Ce Zhang · Jianming Yang

A History of Mechanical Engineering

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Contents

Chapter 1
Introduction

> *With copper as a mirror, you can dress up.*
> *With others as a mirror, you can learn much.*
> *With history as a mirror, you can know prosperity and decline.*
> —Li Shimin (an Emperor in Tang Dynasty of China, 598–649)
>
> *Chasing of relevance and balance between science and art, technology and humanities, is the instinct of human creativity. Exploring the potential of young students is an important task of modern universities.*
> —Tsung-Dao Lee (Chinese-American physicist, Nobel physics award winner, 1926–)

Machines are widely used in almost every aspect of human society, such as industry, defense and daily life. A middle school student can easily speak out a long list of machine names. College students in mechanical engineering around the world are in millions. People working on mechanical related jobs, including production, maintenance, research and education etc. are estimated in the scale of tens of millions. The number of people who have the opportunity to operate a machine is even larger. The automotive vehicles running around the world are estimated more than 1 billion. The industries relating with mechanical engineering contribute 9% of the nation's total GDP in China.

This book intends to describe the historical development and evolution of mechanical engineering. The purpose is to provide a comprehensive reference book for engineers, teachers and students in mechanical engineering who have the interest to learn the history of their profession.

Mechanical Engineering (ME) is a branch of applied science. It studies the theoretical and practical problems arisen in the development, design, manufacturing, installation, operation and maintenance of all kinds of machines with natural science and technological knowledge. ME is highly practical, of which technical experience formed in real production is a integrated part.

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1.1 Historical Stages of Mechanical Development

In human history, development of machines can be divided into three eras: ancient era, modern era and contemporary era.

1.1.1 Ancient Era

The ancient era in this book refers to the period between the early Bronze Age to the Renaissance happened in Europe during the 14th–16th centuries, covering more than 5000 years.

Based on the material from which human made tools, the ancient human history can be divided into the Stone Age, the Bronze Age and the Iron Age. The Stone Age lasted millions of years. In 5000 BC, natural copper was discovered and began to be used. In 4000 BC, People in West Asia started smelting bronze, a copper and tin alloy, and making tools and weapons from it, marking the entrance into the Bronze Age. In 1400 BC, the technology of iron smelting appeared in Anatolian peninsula. In the Bronze Age, the bronze casting industry of the world was concentrated in Egypt and the West Asia, China, Southern Europe (mainly, the ancient Greece and the ancient Rome). These regions became centers of ancient human civilization, also centers of machine development of ancient times.

In history, the turning point from use of tools to use of simple machines was roughly coincident with the starting of Bronze Age. This is one consideration to choose the beginning of the Bronze Age as the starting point of “ancient era” in this book.

Thousands of years ago, human beings were already able to build pretty complicated machines, such as mortars and mills for grain hulling and grinding, shadoof and windlass for water lifting, vehicles, ships and various weapons. Human, animal, water and wind were the main sources of power by which these machines were driven.

There were a lot of clever ideas and brilliant creations embedded in the design of ancient machines, which are still inspiring and enlightening nowadays. However, the development and evolution of ancient machines were obviously very slow. From a purely technical point of view, one of the main reasons for the slowness was the lack of advanced power.

After the Capitalist mode of production appeared in the 14th century, societal evolution, economical activities, and the development pace of machines were significantly accelerated. The European Renaissance occurred in the 14th–16th centuries, as a great ideological movement, became the prelude to a series of great social changes, including the Bourgeois Revolutions and the Industrial Revolution.

In the academic community, there is not a consensus on the dividing line between the ancient and modern eras. In this book, however, the European Renaissance is taken as the separating point between these two eras.

1.1.2 Modern Era

The modern era in this book refers to the period from the European Renaissance to the end of WWII, covering several centuries.

After the Renaissance, science and art were greatly liberated. In the 17th century, the First Scientific Revolution emerged, in which the most representative achievement was the establishment of the classical mechanics. Following that, two ideological liberation movements, the Reformation and the Enlightenment, occurred. The bourgeois revolutions happened later in Netherlands, Britain and France further paved the way to the capitalism.

In this context, two industrial revolutions happened in Europe during the 18th–19th centuries. Power was the core of the two Industrial Revolutions. The First Industrial Revolution brought the world into the age of steam. The new power greatly promoted the use and invention of machines. Railways and steamships began to connect the world as a whole. The Second Industrial Revolution brought the world into the age of electricity. Automobile and aircraft fundamentally changed human society. Inventions went into an unprecedentedly booming period. Machine building was born as an industry and rapidly flourished. Machines were the main pillar of the two Industrial Revolutions. Mechanical engineering, which used to be in the form of personal skills of artisans, was gradually developed into a theory-based, systematic and independent modern discipline.

In view of the historical development, the modern era in this book is divided into three periods: (1) the period from the Renaissance to the eve of the 1st Industrial Revolution, (2) the period between the 1st and 2nd Industrial Revolutions, and (3) the period between the 2nd Industrial Revolution and the end of WWII.

1.1.3 Contemporary Era

Most historians take the turn of the 19th and 20th centuries as the dividing line between the modern and the contemporary eras. This book follows this convention, taking the new physics revolution, which happened at the turn of centuries, as the starting point of the contemporary era in view of the extremely important role of the new physics revolution in the technological revolution after. However, this treat would lead to an overlap of 45 years between the modern and the contemporary eras. Given the development of science and technological is always continuous, clear dividing lines in fact rarely exist. The new physics revolution laid a scientific foundation for the 3rd Technological Revolution, which was mainly triggered by the invention and wide application of computers after WWII. In the center of the 3rd Technological Revolution is information, instead of power which is the core of the 1st and the 2nd Technological Revolutions. After WWII, the universal increase of living standard raised an ever-high demand for high-performance machines, leading to intensive competition in the world market. At the same time, human activities to explore the unknown world were expanded to a much larger scale. These two aspects of demand drove the further development of mechanical technology and machinery industry with an unprecedented speed. The invention of computers along with progresses in relevant fields has provided powerful technical supports to the mechanical engineering. Thus, the contemporary mechanical engineering goes, in both breadth and depth, far beyond the modern counterpart does.

Revolutions in science and technology generally go hand in hand, but sometimes are twisted. During the upper half of the 20th century, a new technological revolution appeared in the horizon inspired by the new physics revolution when the second Industrial Revolution was still in progress. Several iconic achievements of the 2nd Industrial Revolution in either technology or industry production, including the invention of airplane, the development of the automobile industry, and the emergence of mass production mode, were all triggered by internal combustion engines. In view of this fact, the book does not strictly follow the chronological order in presenting the technological progress in the 20th century.

Mechanical engineering evolved into a discipline and further developed with accumulated inventions, technical improvement, and the establishment and growth of the machine building industry. Given that this book is intended for a history of mechanical engineering as a discipline, not for the machine building industry, we trace back to ancient time for inventions and technological improvement of machines for the purpose of completeness. As for the machine building industry, no detail is covered unless it is necessary.

1.2 Key Relations in History of Mechanical Engineering

The history of a technology can be presented in two ways, internal history and external history (Liu et al. 2006). The so-called “internal history” presents the history from the solely viewpoint of the technology itself, while the “external history” takes into account the relationship between the technology and the economic and societal development. This book uses the latter.

To understand the history of mechanical engineering, attention should be paid to the following five important factors:

(1) relation between the nature, society and science and technology,
(2) the driving force behind the development of science and technology,
(3) the influence of society on the development of economy, science and technology,
(4) the relation between mechanical engineering and the natural science,
(5) the relation between mechanical engineering and relevant technological fields.

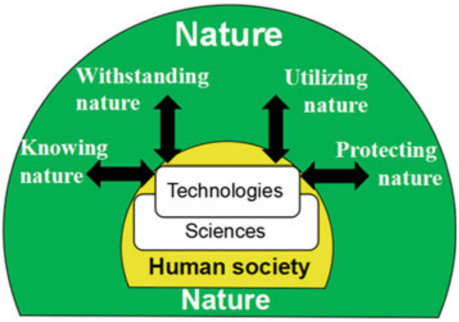


Fig. 1.1 Nature and human society

1.2.1 Nature, Society, Science and Technology

Two lines in parallel exist in human's history. To survive, humans take advantage of the nature, and at the same time, avoid possible harm from the nature.

To take the benefit and avoid the harm of the nature, humans need to know the nature. Science was born in this process. Science in turn greatly enhanced human's ability to understand the nature. To utilize the nature and avoid harm, humans need to rely on technology, which actually appeared before science. After the birth of science, science and technology became interacted. On the one hand, science has provided guidance and support to development of technology; on the other hand, since has gained development in the process of using technology to explore the nature.

After long history of getting along with the nature, humans came to realize that measures should be taken to protect the nature for human's long-term benefit. To protect the nature heavily relies on science and technology (Fig. 1.1).

1.2.2 Driving Forces Behind Science and Technology

Behind the development of science and technology are three important driving forces: the economic development, the national defense, and the scientific exploration of the unknown world.

To survive, ancient humans made tools, simple weaving machines, mortars and mills. Humans also built houses, ships and vehicles. To protect the tribe's benefit and compete for more resources for survival, weapons appeared. Although the standard of living was very low at ancient times, people already began to observe and explore the unknown world, for example, to observe the changes of seasons for planting in time.

The Industrial Revolution started from the textile industry in England. Steam engines were first invented for the purpose of providing power to the drainage pump in coal mines, but led to the establishment of railway transportation. The invention of internal combustion engines made automobile and aircraft a reality.

The impetus behind the development of machines is the economic development and the desire for higher standard of living.

After WWII, the development of the machine building industry was mainly driven by the formation of the global market and the unprecedentedly intensive market competition. The driving force behind the competition is the needs for higher quality and more comprehensive machines.

Humans have started observation of the universe since ancient times. Exploration activities have never been stopped. After WWII, the world has been retained in peace in general. More activities in scientific exploration, such as exploration of the deep sea and outer space, have been conducted. All these activities needed the support of science and technology. Consequently, a variety of high-end machines, such as the spacecraft and special robots, have been invented for these activities.

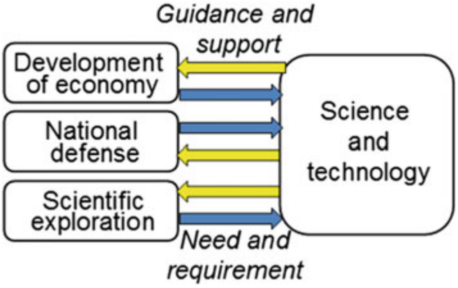
Although some science and technological development, those in ancient time in particular, are driven by the direct need for better life, the thirst for new knowledge is also an important driver for scientific development.

Scientific development, undoubtedly, benefits human society; however, the benefit may not come immediately. For example, some research in number theory and in astronomy, which may not be used in many years, is obviously valuable to the mankind in long term.

Micro-electro-mechanical system (MEMS) appeared in the 1960s was motivated by the etching process of integrated circuits. Initially people did not think of applications; instead applications were envisioned after the invention. For this reason, it is a scientific exploration. Science links with economy, but not as closely as technology does. Science has its own system and follows its own law of development. It is not the case that a direct economical driving force always exists behind science development.

The economic development, national defense and scientific exploration activities put forward requirements to science and technology, which in turn provide guidance and support to the activities in the three areas. This relationship is schematically illustrated in Fig. 1.2.

Fig. 1.2 Driving forces behind science and technology



1.2.3 Influence of Society

What is behind the economic development, national defense, and scientific exploration and technological development?

The answer is the society, more precisely, the development and evolution of the whole society.

The Industrial Revolution happened in England led to the establishment of the machine building industry. Was it possible for the Revolution to come earlier? The answer is "No". The English Revolution outbroke in 1640. As a result, a stable bourgeois regime was established in 1688 after the feudal system was abolished. Combination of the capital, labor and domestic market led to the rapid development of capitalist economy, which laid the foundation for the first Industrial Revolution.

Was it possible that the English Revolution happened earlier? The answer is "No" again. In the dull of the Middle Ages, how could a revolution outbreak suddenly? The premise of revolution is initiation of capitalist mode of production, gradual growth of bourgeoisie, spiritual liberation of the whole society, and public opinion preparation for the revolution.

Why could economy and science flourish after WWII? The core reason was the overall developments of society in the New Era, the long time peace of the world in general, improvement of living standards, ever intensive competition and the cold war, to name a few.

In general, the development of the society is a driving force to science and technology. In specific periods of time or specific regions, however, society may slow down or even stagnate the development of science and technology. The Middle Ages in Europe and the Ming and Qing Dynasties (14th–19th centuries) in China are examples of these periods.

In turn, science and technology may also inspire changes in society. Karl Marx believed that science is "a historically motive, revolutionary force"; it promoted productive forces, and sooner or later would cause changes in production relations and the social system.

Therefore, the history of mechanical engineering is not only compiling the biographies of outstanding inventors and a bunch of invention patents. Behind the grand picture of mechanical engineering history, there is a bigger picture of social development history.

1.2.4 Mechanical Engineering and Natural Science

Mechanical engineering is a discipline of applied science; it is based on the natural sciences, including mathematics, physics (mechanics, thermodynamics, Electromagnetics), and science of systems. Mechanics in particular is the most important theoretical basis.

Classical mechanics founded by I. Newton opened up a new era of science, laying the foundation not only for further development of mechanics, but also for the development of mechanical engineering, civil engineering and some other applied sciences. Today, all the theories of kinematic and dynamic analysis of various machines are derived from the Newtonian mechanics.

In the early days, the two cornerstone subjects in mechanical engineering, mechanism and machine science (MMS) and machine design, were part of applied mechanics. They were not becoming independent subjects until the 19th century.

Every new breakthrough in mechanics theory, such as the rigid body dynamics by L. Euler, the analytical mechanics by J.-L. Lagrange, elasticity by A.-L. Cauchy, and the multibody dynamics and finite element method after WWII, injected new power into the development of mechanical engineering.

In turn, the development of mechanical engineering put forward theoretical problems which need to be solved by the natural science, leading sometimes to the birth of new science. For example, the theory of multibody dynamics was created in response to the needs to study the dynamics of vehicles, spacecraft, robots, and even human bodies. Also, the need for increasingly complex calculation in dynamics promoted the development of new numerical algorithms.

1.2.5 Mechanical Engineering and Related Technological Fields

Development of related fields has significant influence on mechanical engineering. Progress in electromagnetics theory and the invention of motors in the 19th century influenced greatly mechanical engineering. Invention of computers and progress in control theory, after WWII, not only promoted the development of mechanical engineering, but also fundamentally changed the whole picture of machine design and manufacturing.

The 3rd Technological Revolution happened after WWII was characterized by information technology, involving new energy technology, space technology, biotechnology, new materials technology and marine technology. Mechanical engineering is closely related to all these areas and interacts with each other. This relation is illustrated in Fig. 1.3 and discussed in detail in Chaps. 9 and 10.

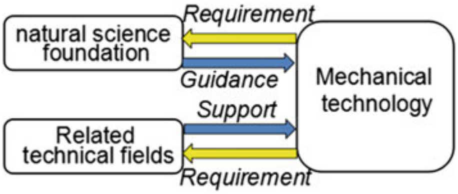


Fig. 1.3 Influence of science foundation and related technical fields

In describing the evolution of mechanical engineering, this book strives to clarify these important relations stated above. Effort is made to illustrate the background of society, economy and the whole science and technology behind the development of mechanical engineering.

1.3 Technological Revolution and Industrial Revolution

In the open literature, the definitions of technological revolutions and industry revolution are not in consensus.

Most of the literature supports that three Technological Revolutions and two Industrial Revolutions have completed in the last 200 years with the third Industrial Revolution ongoing. In some other literature, only the electrical power Technological Revolution is discussed without mentioning the second Industrial Revolution (Rifkin 2011; Jiang 2010). In some other works the 1st Industrial Revolution is termed as English Industrial Revolution, and the rise of the tertiary industry in recent years is called the “new Industrial Revolution”.

This book does not intend to comment on these differences in detail. Instead, focus is placed on the three concepts, namely scientific revolution, technological revolution and industrial revolution, and their relationship.

Scientific revolution means a great leap in understanding of the world by human beings, generally is in the form of a theoretic breakthrough. So far four scientific revolutions have happened as shown in Table 1.1.

Technological revolution is a major change in the means of human being’s transformation of the world. It is generally based on Scientific Revolutions, and leads to Industrial Revolutions.

Industrial revolution refers to the leap in the field of industry, such as radical changes in production mode or industrial structure. Industrial revolutions often directly lead to changes in economy and society.

Nicolaus Copernicus established the heliocentric theory, marking the start of the 1st Scientific Revolution. To the time when Newton founded the theory of classical mechanics, the first Scientific Revolution reached its climax. J. Hargreaves’

Table 1.1 Scientific revolutions in history

	Starting year	Main contents
The first	1543	Astronomy, classical mechanics, mathematics, human anatomy
The second	1755	Cosmology, geology, cytology, biological evolution, thermodynamics, electromagnetics, chemistry
The third	1895	Atomic structure, relativity, quantum mechanics, nuclear physics
The fourth	1946	Biological genetics, system sciences, nonlinear science

invention of the spinning Jenny represented the beginning of the 1st Technological Revolution, which was fully developed to the time when J. Watt invented steam engines. Steam power led to the widespread use of machines. As a result, manual workshops were largely replaced by mechanized factories, indicating that human entered the industrial society from the agricultural society. As such, this was generally regarded as the 1st Industrial Revolution.

Discovery of the electromagnetic induction phenomena by Michael Faraday was one of the most representative signs of the 2nd Scientific Revolution. The 2nd Technological Revolution was symbolized by the invention of electric motors, which brought the world into a new era of electricity. Correspondingly the electric power industry, steel industry, chemical industry and automobile industry rose. The fundamental change in industrial structure was the main sign of the 2nd Industrial Revolution.

Obviously, the 1st Technological Revolution is closely related to the 1st Industrial Revolution. So is the 2nd Technological Revolution to the 2nd Industrial Revolution. Following this convention, this book uses only the terms of the 1st Industrial Revolution and the 2nd Industrial Revolution.

The new physics revolution happened at the end of the 19th century is treated as the 3rd Scientific Revolution. The systems science established after WWII, however, marked the 4th Scientific Revolution. Mainly due to the war time need in WWII, the 3rd Technological Revolution came after the 4th Scientific Revolution. This Technological Revolution has created fundamental changes to the industry, and organization of business. Following the 3rd Technological Revolution, the 3rd Industrial Revolution, however, is still underway (Rifkin 2011).

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Chapter 2
Ancient Machines

Why had China been more successful than Europe in gaining scientific knowledge and applying it for human benefit for 14 centuries? And, given this lead, why did modern science originate only in Europe?
—Joseph Needham (British scientist, historian and sinologist, 1900–1995)

2.1 Introduction

The "ancient times" in this book, refers to a period of about 6000 years from the beginning of the Bronze Age until the European Renaissance in the 14th century. This section describes: (1) the three stages in using tools by ancient humans, and (2) the three main regions in ancient machine development.

2.1.1 Three Stages and Three Regions

Humans differ from animals by the ability of making and using tools. According to the materials of tools, ancient humans experienced three stages, the Stone Age, Bronze Age and Iron Age (Goddard 2010; Singer et al. 1954).

Humans used stone for millions of years. In the Old Stone Age (Paleolithic), all humans lived as hunter-gathers. Wooden and stone tools began to be used in this stage. Those tools, although being simple and primitive, were the ancestors of the "simple machines". Mesopotamia, Egypt and China first entered the New Stone Age (Neolithic). Thereafter people lived by farming and animal husbandry. Agricultural civilization began, and extremely simple farming tools, drawing tools, textile tools and canoes appeared. Virgin copper was already used in this stage.

Natural metals are limited in quantity and metal smelting occurred. Copper smelting was an important milestone in human development. Copper vessels of

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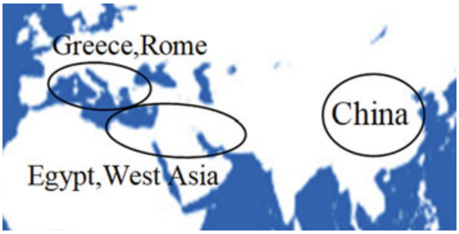
Fig. 2.1 Three main areas of development of ancient machinery



3800 BC were found in southern Iran, being regarded as the earliest items made through metal smelting.

In 3000 BC, southern Iran and Mesopotamia entered the Bronze Age first, followed by Egypt, Europe and China (Tylecote 1976; Ke et al. 1984). The bronze casting industry was also developed around these regions, which became centers of ancient civilization, and centers of ancient machine inventions (Fig. 2.1).

Around 2500 BC, Egyptian already obtained iron from meteorites, and used very small amount of ironware. Around 2000 BC, ironware also appeared in southern India. The Iron Age in the true sense, however, did not come until around 1400 BC, when the Hittite Empire in Asia Minor peninsula mastered the technology of smelting iron, and began large scale production of iron (Hua et al. 1985). Thus, copper was replaced on many occasions by iron. The technology of iron smelting was kept secret by the Hittite Empire, and was spread to the Middle East and Europe only after its demise (Stavrianos 1999).

2.1.2 The Dawning of Civilization: West Asia and Egypt

Human civilization appeared in West Asia and Egypt far earlier than in China and Europe. Thus, these two areas had also simple machines appeared the earliest. In 9000 BC, Jews in Palestine established Jericho, starting city civilization the first time in history (Gates 2003, 18). The earliest wheels maybe appeared at this time.

Many creations were first appeared in these areas, such as vehicles, ships, ploughshares, the shadoof, use of animal and wind power, lost wax casting, forging, primitive lathes and so on. However, further development at early stage was very slow. After the AD, no record was left on advances in tools and machine development in Egypt.

It was not until the 7th–15th century that a new peak came up in West Asia—Islamic civilization reached its golden age. Banu Musa brothers, Persian scholars, and Al-Jazari, a Kurdish scholar, published their books on mechanical devices and automatic machines in the 9th and 13th centuries respectively. The *Book of Knowledge of Ingenious Mechanical Devices* by Al-Jazari, in particular, was well known in the world, which described hundreds of machines and mechanisms. He

Fig. 2.2 Al-Jazari

stated repeatedly that all the devices described in this book were created by himself (Hassan and Hill 1986).

Al-Jazari was an engineering genius of the Islamic world in the Medieval Ages. He had rich inventions in a wide range, including mechanisms, components, automata and many fabrication techniques. He even created the first programmable humanoid robot (Al-Jazari 1973). According to Encyclopædia Britannica, the Italian Renaissance inventor Leonardo da Vinci might be influenced by the classic automata of Al-Jazari (Fig. 2.2).

2.1.3 Brilliance and Straggle of Ancient China

Although started later than Egypt by more than a thousand years, China kept in the top position in the invention of machines for a long time before the European Renaissance. These inventions covered a wide range, including not only various machines, but also many manufacturing technologies (Needham 1986; Liu 1962; Lu et al. 2009b; Lu 2012). In China, plough first appeared early in 3500 BC. Several other tools, including shadoof, windlasses, and blowers etc., were already used in the Shang Dynasty and West-Zhou Dynasty (1600–800 BC). In the late Spring-Autumn Period (about 500 BC), China entered the Iron Age.

After the AD, China rose in terms of creation and invention of machines simultaneously with the decline of Egypt.

Fig. 2.3 Zhang Heng

In the East-Han Dynasty (25–220) and the Three-Kingdoms Period (220–265), the most representative inventions made in China include the armillary sphere, the south-pointing chariot and the mileage drum wagon. Two outstanding inventors in this period are Zhang Heng and Ma Jun (Figs. 2.3 and 2.4).

In Song and Yuan Dynasties (960–1368), China reached the peak in technology of the Ancient time. The two most influential inventions in this period were gun-

Fig. 2.4 Ma Jun

Fig. 2.5 Su Song

powder and movable type printing. The movable type printing technology in particular, invented by Bi Sheng, was one of the greatest inventions in ancient China and had great impact on the development of printing technology around the world. The most outstanding mechanical invention of this period in China was the astronomical clock tower by Su Song (Fig. 2.5).

In 1405, Zheng He, an officer of the Ming Dynasty, led a large fleet of 240 ships and 27,400 crews and visited more than 30 countries over West Pacific Ocean and Indian Ocean. By 1433, Zheng and his fleet made a total of 7 voyages. Zheng's fleet set three world records of that time in sailing time, fleet size and sailing range, reaching the peak of maritime transportation in the ancient world. This achievement was an indicator of the manufacturing level at that time in China (Xin 2009, 98–102).

In 1637 (in Ming Dynasty), Song Yingxing published the book *Heavenly Creations* (Song 2009), which was the world's first comprehensive book on the production of agriculture and handicraft in the infancy of capitalism. It covered wide scope, including mining and smelting, casting and metal forging, operation of tools and machines, structure and application of ships, vehicles and weapons. This work was translated into many languages later. Due to its extremely important position in the world history of technology, it is referred to as "the encyclopedia of technology in China's 17th century" by European scholars (Fig. 2.6).

Zheng's fleet and Song's book could be regarded as two marks of the final glory of ancient Chinese technology.

Fig. 2.6 Song Yingxing and his *Heavenly Creations*

Liu Xianzhou (1890–1975), the first scholar on ancient history of machinery in China, pointed out (Liu 1962; Zhang et al. 2004): "*Generally, China's invention before the 14th century was not only superior in terms of quantity, but also far earlier in time. However, after the 14th century China fell gradually behind the Western. The basic reason for this was related to the social system*".

In a long period, rulers in China did not pay attention to development of industry and handicraft technology. Technical inventions were often regarded as "diabolic tricks and wicked craft". In the Ming Dynasty, the imperial examination became more rigid and dogmatic. As a result, intellectuals only focused on passing the exam and squeezing in government, with no interest in anything related to technology and practical knowledge.

Zheng and his fleet reached only the east coast of Africa, without getting a glimpse of Europe. Everywhere he saw was less developed in comparison with China. The information he collected from overseas only increased the hubris of Chinese rulers and the people.

In the mid and late Ming Dynasty, China adopted the "closed door policy". Qing Dynasty went even further to strictly limit trade with foreign countries. The rulers knew little about the change of society and development of science and technology taking place in the Western. The closed door policy not only prevented the trade and culture exchange between China and other countries, but also obstructed the path for China to learn the development of science and technology from the outside world. More importantly, it hindered the growth of the capitalist sprout in China.

At the same time, however, Europe was experiencing fundamental social and economic changes. After the Renaissance, ideology was being emancipated, scientific spirit was being disseminated, and productive forces were developing. Europe was well prepared to rise up.

2.1.4 Twists and Turns in Europe's Development

Balkans began to use the copper ax in 3000 BC, later than Egyptian by almost a thousand of years. In 1000 BC, the iron tools were widely used throughout Europe.

The classical Greek culture was booming from 600 BC to 400 AD, a number of famous philosophers and scientists emerged during this period.

Aristotle, the Greek philosopher and scientist, published *On the Heavens* in 350 BC. This was the earliest publication on mechanics in the world, in which he explained the role of air on projectiles, and discussed the motion of falling bodies. However, one of his conclusions, velocity of a falling body is proportional to its weight, was proved wrong later. This wrong statement affected the academia for thousands of years (Wu 2000).

Archimedes of Syracuse was a master of science in ancient Greece with outstanding achievements in many subjects, such as mathematics, mechanics and astronomy (Archimedes 2002). He first used the term "simple machine". His publication with the title of "*On the Equilibrium of Planes*" was the earliest work on statics, in which he explained the law of the lever. He also calculated the areas and centers of gravity of various geometric figures. In another publication "*On Floating Bodies*", he listed many hydro-static and fluid balance theorems, including Archimedes' principle of buoyancy. He is the founder of the hydro-statics (Figs. 2.7, 2.8 and 2.9).

Hero of Alexandria was the most famous mechanical inventor in ancient Greece. His inventions were reported in his works "*Mechanica*", "*Pneumatica*" and "*Automata*".

Fig. 2.7 Aristotle

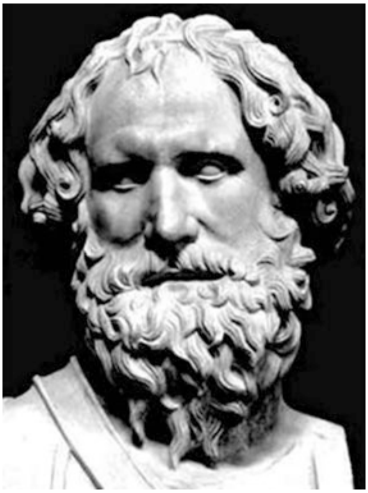


Fig. 2.8 Archimedes of Syracuse

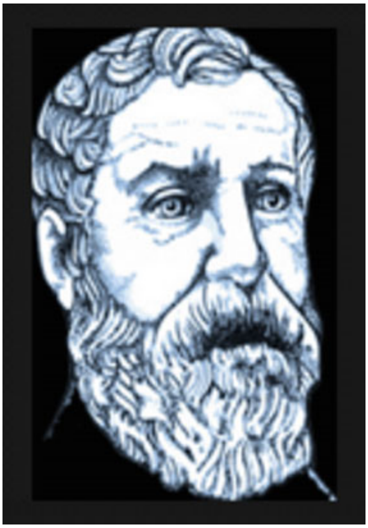


Fig. 2.9 Hero of Alexandria

With the decline of ancient Greece and ancient Rome, brilliant ancient European culture was silenced. The one thousand years, from the 5th century AD (collapse of West Rome Empire) to the 14th century (the Renaissance) is often called the Medieval Age of Europe by historians. During this period, no country in Europe was governed by strong secular regimes, and feudal separation caused frequent wars. Rome Catholic Church strictly controlled the spread of scientific thought, and established the inquisition to punish “heresy”. School education was required to serve theology strictly. In the 14th century, the Black Death spread to the whole Europe, resulting in 30% mortality and a sharp decline in the population. The feudal separatist rule, theology’s control and the plague spread were thought to be the critical three factors leading to stagnation of technology (including mechanical technology), slowing down the productivity in Medieval Europe.

Wu (2006) listed the most important 100 publications in the history of mechanics, in which 7 articles in ancient Greece by Aristotle, Archimedes and Hero were included. In 1543, Copernicus published his historical work, *De revolutionibus orbium coelestium*, in Latin (*On the Revolutions of the Celestial Spheres* in English). After this publications were booming up. In the almost 1200 years between the ancient Greece and Copernicus, however, it was almost blank without any publication referred.

Slowness does not mean full stagnation. In fact, mechanical technology in Europe began recovering and developing in the late Medieval Ages in the fields of agriculture and handicraft. The main progress was made through absorption of the advanced Chinese and Islamic technologies.

In the late Medieval Ages, the capitalist mode of production budded first in Italy. The change of the economic foundation led to the entire transformation of superstructure. In hundreds of years, the Renaissance and a series of ideological liberation movements took place in succession. The world began to enter the Modern period (Stavrianos 1999).

Greece, Rome, Egypt, and parts of West Asia are all on the Mediterranean coast. Through the spread of Christianity, frequent trade and the Crusades, cultural and scientific exchange already started between these ancient civilizations very early. In the process, they were kind of blended with each other. On the other hand, contacts and exchanges between China and the Western were rare in a long period due to the long distance and the inconvenience of traffic. However, China got in contact, and exchanged science and technologies with the Islamic world as early as in the 1st century when the Silk Road was opened. In Ming Dynasty, some European missionaries came to China, gradually disseminating western knowledge to China, which is often called “Western learning spreading to the east”.

2.2 Various Ancient Machines

Ancient machine inventions involved almost all aspects of human life, but primarily driven by the basic necessities: farming, irrigation, grain grinding, textile, vehicle and boats. Due to the need of agriculture, it was necessary to understand the astronomical phenomena. Thus, astronomical observation instruments were invented. To protect the basic life necessities of tribes, weapons were created. Metals were needed for manufacturing tools and machines. Blowers appeared for smelting the metals.

2.2.1 Simple Machines

Lever, pulley, wheel and axle, inclined plane (ramp), screw and wedge are called "the six simple machines". These simple machines were the wisdom of ancient humans formed in the practice of using tools. They formed the foundation of more complicated machines in later development (Fig. 2.10).

The stone axe used in Paleolithic is an example of "wedge", and the shadoof is a "lever" (Fig. 2.13).

The first record of pulley application dates back to 1500 BC when people in Mesopotamia used rope pulleys for hoisting water. Archimedes pulled a boat ashore by himself with a compound pulley set. The windlass used for farmland irrigation is a "pulley" as well. It was also the embryo of the winch later used in the construction and mining industry. A windlass shaft made in the Spring-Autumn period (8th–5th centuries BC) was unearthed in the 1970s at Tonglushan (Copper Hill) site, in Hubei Province of China (Zhang 2018).

In 2600 BC, Egyptians began to build the Pyramid. Huge rocks for constructing the pyramid weigh several tons, even dozens of tons. They had to be lifted up from the ground and transported to the top; the height was more than 100 m. It is believed that rolling logs (i.e. simple wheels), inclined planes, crowbars (levers) and other simple machines might have been used for handling and lifting the huge rocks (中山秀太郎 1975) (Fig. 2.11).

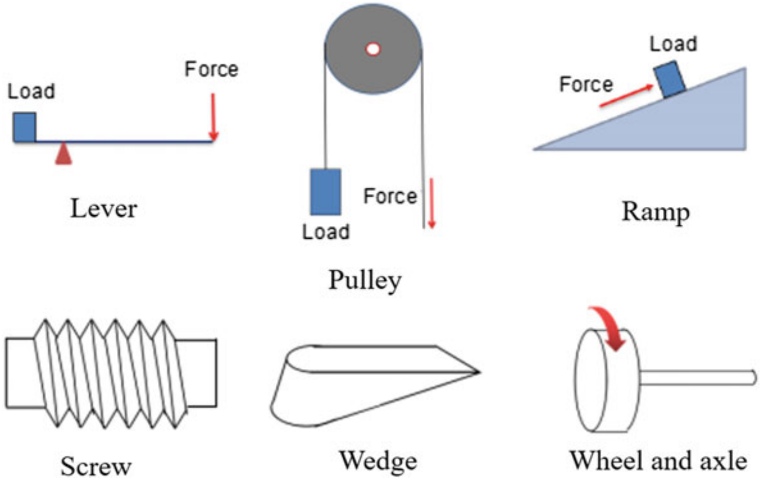


Fig. 2.10 Six simple machines

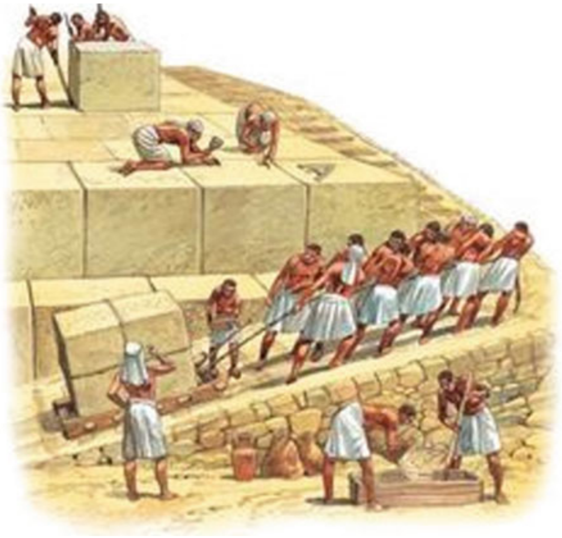


Fig. 2.11 Building of a pyramid (http://www.thirteendimensions.com)

Although Egyptians used the simple machines first, collection and summarization of those machines were mainly conducted by scholars in the ancient Greek. In fact, the word “simple machines” was first coined by Archimedes, the famous Greek scientist. The simple machines he defined only include the lever, the pulley and the screw. He also revealed the concept of mechanical gain in leverage (Archimedes 2002). The famous motto, *Give me a place to stand on, and I will move the Earth*, was believed to be generated from his research on leverage.

Later, the Greek philosopher Hero of Alexandria, born in the 1st century AD, added the axle and the wedge into the simple machines. He described production and application of the 5 kinds of simple machines in his book *Mechanica*, which was the first important book to describe machinery in ancient world.

An inclined plane was added into the simple machines in the later Renaissance period (Anderson 1914, 112–122). In fact, both the wedge and the screw are variations of an inclined plane. A screw formed by wrapping an inclined plane on a cylinder. Thorough theoretical analysis on simple machines was completed by Galileo Galilei, the great Italian scientist.

2.2.2 *Agricultural Machines*

In the Neolithic, people lived on farming and animal husbandry. Some very primitive farming tools and machines were created in this period for different farming work, such as ploughing, seeding, water-lifting, milling and winnowing. However, the development in general was very slow in thousands of years.

2.2.2.1 Tools for Ploughing and Seeding

In about 3500 BC, primitive ploughs appeared in both China and Egypt and simple seeding tools appeared in Mesopotamia.

Multi-tube iron seed drills (Fig. 2.12) were invented by the Chinese in the 2nd century BC. In the Qin and Han Dynasties (about 200 BC–200 AD), drill ploughs which could continuously complete trenching, seeding and covering, were widely used in China. This multi-tube seed drill was credited with giving China an efficient food production system that allowed it to support its large population for millennia (Needham et al. 1987, 48–50). After many years, this multi-tube seed drill might have been introduced into Europe. The first known European seed drill appeared in 1566. Seed drills of this type and its successors were expensive, unreliable and fragile; thus, they were not widely used in Europe until the mid-19th century (Temple and Needham 1986).

2.2.2.2 Water-Lifting Devices

In the dry and windy West Asia and Egypt, agriculture is largely dependent on irrigation. Most ancient water-lifting devices, such as the shadoof, the noria and the sakia, were first used in these areas. The shadoof emerged first in Mesopotamia and Egypt in about 3000 BC (Fig. 2.13).

Fig. 2.12 Chinese double-tube seed drill (Song 2009)

Fig. 2.13 Shadoof (www.lookandlearn.com/history)

In about the 15th century BC, Mesopotamians began to raise water with pulleys and rope. As early as in about 1100 BC the windlass (Fig. 2.14) appeared in China, and became very popular by the Spring-Autumn Period (770–476 BC).

In the 3rd century BC, Archimedes lifted water to high altitude with a screw, as shown in Fig. 2.15 (Oleson 2000). Later, a screw water machine of this kind was used for water supplying of Rome city, which was regarded as the ancestor of today's helical conveyor.

According to Wikander (2008, 141), both the compartmented wheel and the hydraulic noria appeared in Egypt by the 4th century BC. The animal powered sakia (Persian wheel), as shown in Fig. 2.16, was invented also there a century later. This is supported by archeological finds at Faiyum. Later development of the water wheel was credited mainly to engineers in Mediterranean region of the Hellenistic era between the 3rd and 1st centuries BC (Oleson 2000, 217–302).

Around 300 AD, the Romans created the noria (Oleson 1984) by replacing the wooden compartments with separate ceramic pots attached to the outside of an open-framed wheel. Later the norias were adopted by Muslim engineers (Hill 1996b) with some improvements.

Muslim engineers used norias to discharge water into aqueducts carrying water to towns and fields. Some of the norias used in the Medieval Islamic world were as large as 20 m in diameter. The norias at Hama on the Orontes River in Syria, as

Fig. 2.14 Windlass

Fig. 2.15 Archimedes' screw

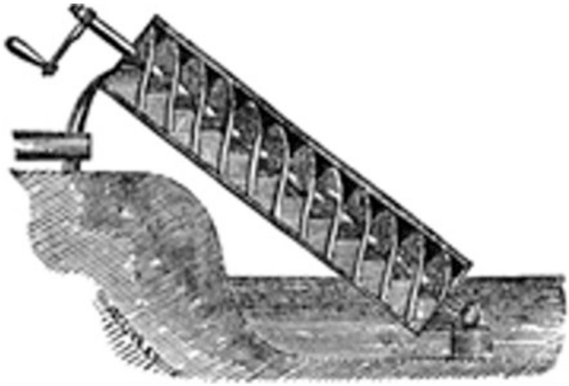
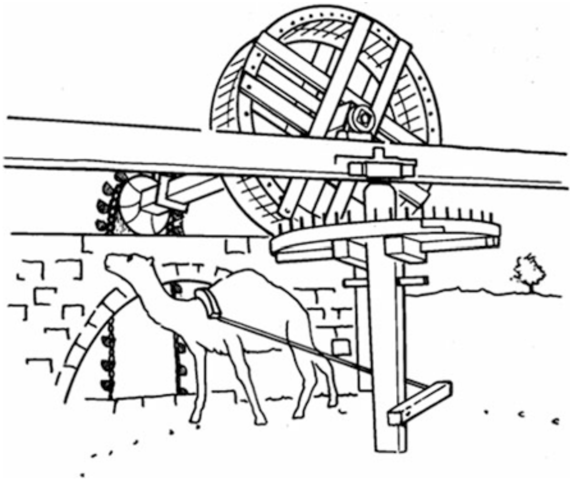


Fig. 2.16 Camel-driven Persian wheel (Fraenkel 1986)



shown in Fig. 2.17, being surviving examples, are still in use, although only serving aesthetical purposes. The noria has 120 water collection compartments and could raise more than 95 L of water per minute. A noria in Iraq in the 10th century could lift as much as 2550 L per minute (Hill 1996a).

Wind pumps have also been used in South-eastern Asia and China for much longer time than in Europe, mainly for irrigation and/or sea salt production which needs pumping sea water into drying pans. The Chinese sail windpump (Fig. 2.18) was first used thousands years ago (Fraenkel 1986). The traditional Chinese design was constructed from wire-braced bamboo poles carrying fabric sails. Many Chinese windmills rely on the wind generally blowing in one direction, because their rotors are of fixed orientation.

Fig. 2.17 Norias at Hama on the Orontes River in Syria

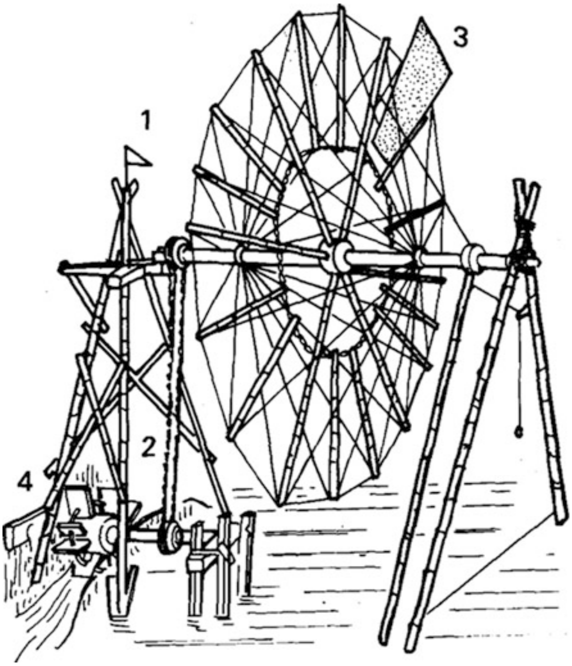


Fig. 2.18 Chinese chain windmill

Al-Jazari invented five machines for raising water; all were described in his book in 1206 (Al-Jazari 1973). An example of them is shown in Fig. 2.19.

The dynamic scale model, shown in Fig. 2.20, depicts five famous water-raising devices made by Muslim engineers, including al-Jazari's reciprocating pump, one-scoop pump, chain-of-pots, four-scoop pump, and Taqi-al-Din six-cylinder pump.

2.2.2.3 Mills and the Winnow

During the 15th and 14th centuries BC, Egyptians used the earliest primitive mill for grain crushing. Europeans used lever-type pressing machines to press grapes and olives.

In China, the winnower for separating grain from husk with wind power, shown in Fig. 2.21, was used at latest in the West-Han Dynasty (202 BC–8 AD) (Li 2018). Around the mid. 3rd century animal driven grinding mills (Fig. 2.22) appeared in which gear trains were used (Wang 1981; Lu 2012, 178).

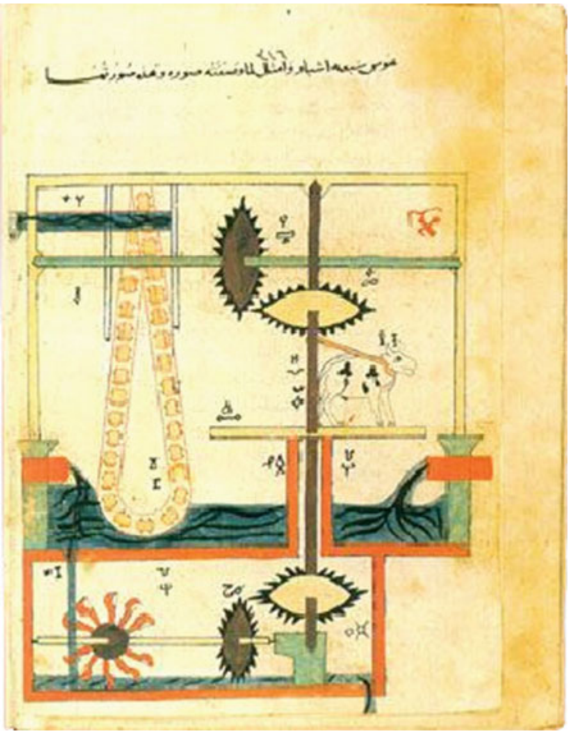


Fig. 2.19 Al-Jazari's Sakia, both animal- and water-driven

Fig. 2.20 Model of water-raising devices made by Muslim engineers (http://museum.kaust.edu.sa/explore-4-technology.html)

Fig. 2.21 Chinese winnower

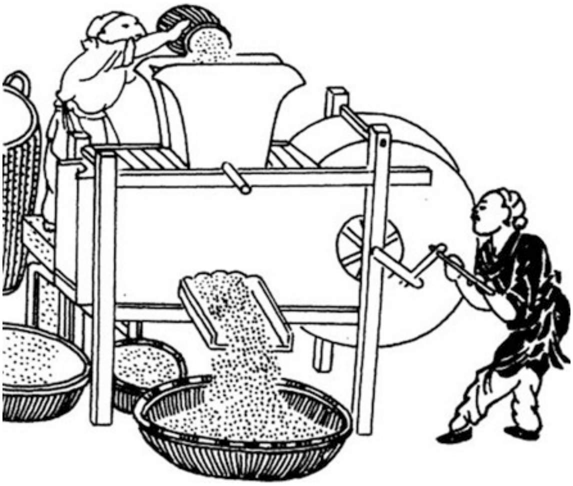
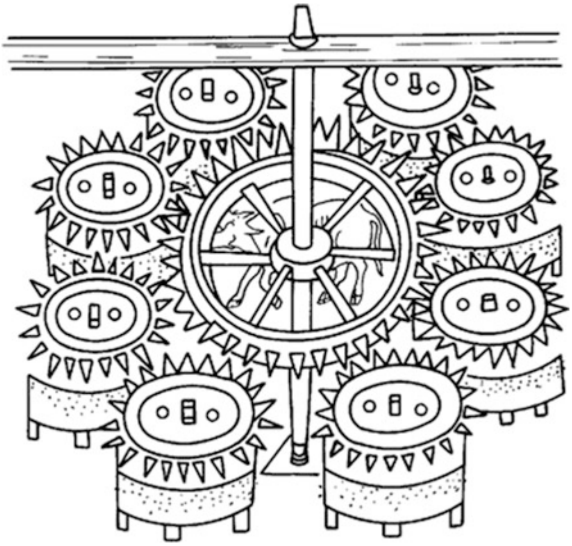


Fig. 2.22 Animal driven grinding mill



2.2.3 *Blowers and Blast Technology*

Blowers played an important role in ancient metallurgy. A powerful blower was critical for making the temperature in a furnace high enough to extract metals from ores. Thus, tools and weapons of high quality could be forged.

Four types of blowers appeared in the ancient time, namely blowpipe, leather bag, wooden fan and bellow (Huang and Qian 2013).

Fig. 2.23 Using of blowpipes, in a tomb at Saqqara

Fig. 2.24 Using of leather bags in a tomb at Thebes

Blowpipes were the earliest wind blower. In a blowpipe air blast was created through a pipe with the pressure of human's breath. There was a scene of using blowpipes on a relief in a tomb at Saqqara site in Egypt (Fig. 2.23), dated 2500 BC (Huang and Qian 2013). Blowpipes were also used in Mesopotamia, China, India and Southeast Asia.

A bag was made of horse or cow leather, and was pressed by the weight or limb strength to form air blast. This was the first significant improvement on blowers. There was a scene (Fig. 2.24) of using pedal leather bags on a relief in a tomb at Thebes in Egypt, dated 1500 BC (Huang and Qian 2013). Archaeology showed that simultaneous air supply with multi-bags appeared in the West-Zhou Dynasty of China. The leather bag could be driven by humans, animals and/or water power. A manual bag shown in Fig. 2.25 was the remote ancestor of modern air compressors, and still in use in some cases nowadays.

Air supply could also be achieved through the reciprocating swing of a wooden fan, driven by humans or water power. In 31 AD, a Chinese officer Du Shi invented a water driven blower (Wang 1981; Lu 2012, 132–134), as shown in Fig. 2.26. At that time, it was a very advanced water driven blower. From the point of view of modern mechanism analysis, it consists of a planar sheave mechanism, a spatial four-bar linkage and a planar four-bar linkage combined in series.

Double-acting piston bellows, dated back at least to the 5th century BC (Temple 2007, 46–49), were one of the most important inventions of ancient China. They

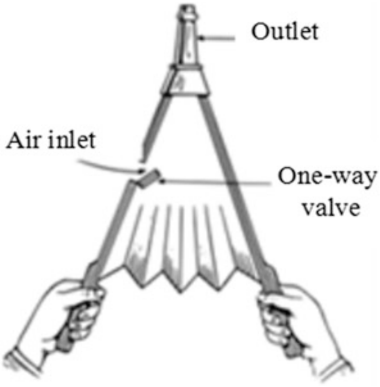


Fig. 2.25 Manual air bellow

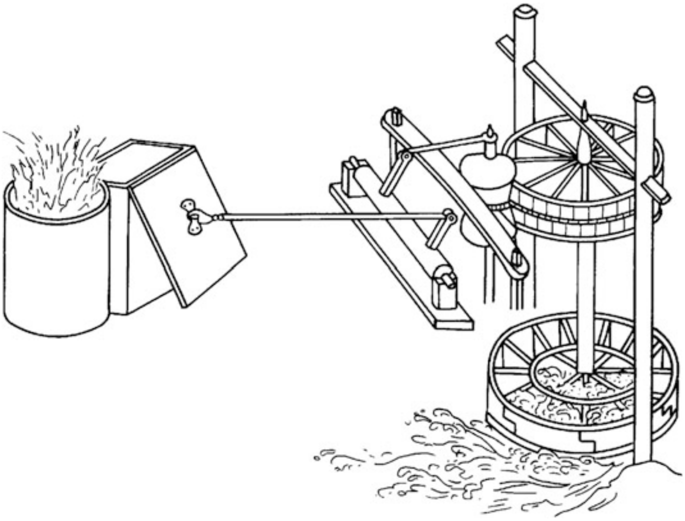


Fig. 2.26 Du Shi's water driven blower (Wang 1981)

provided continuous airflow, and greatly improved the efficiency, representing a significant progress in the blast technology.

These bellows were spread to Europe by the 16th century. In 1550, the wooden box-bellow was invented by Hans Lobsinger of Nuremberg, and the leather bellow was replaced (Beckmann 1846). A similar machine, the double-acting piston water pump, was invented in Europe in 1716, which opened a road toward the piston type machines nowadays.

2.2.4 Boats and Ships

The oldest boats found by archaeological excavation were the log boat and the wooden raft. The Pesse canoe, which is believed to be the oldest known boat in the world, was found in a bog in the Netherlands, being carbon dated to 8040 BC–7510 BC (McGrail 2001). A 7000-year-old seagoing boat made from reeds and tar was found in Kuwait as well (Lawler 2002, 1791–1792). Boats were also used between 4000 BC–3000 BC in Sumer, Egypt (McGrail 2001) and the Indian Ocean. Sailing boats and anchors appeared first in Egypt around that time.

Phoenicia was an ancient civilization located along the coast of the Mediterranean Sea. It became a center of maritime trade and manufacturing during 1500–332 BC. The Phoenicians were highly achieved in maritime technology, ship-building in particular. The mighty ships they built were well known in the world. One of them shown in Fig. 2.27 was built around 1200 BC with a dimension of 25–35 m long and 4–5 m wide (Rawlinson 1889).

In the 1st century, rudders were invented in China (Goddard 2010).

In 200 AD, Rome became the trade center in Mediterranean. Figure 2.28 shows a Rome merchant ship found on an unearthed relief. A small square sail hangs on the bow mast of the ship, indicating the Romans already knew at that time how to control the ship under a certain wind direction. This was a great progress in sailing and navigation (Xin 2009, 32–33).

China was already able to build huge ships in the Spring-Autumn period (770–476 BC). The warship *Big Wing* built by the Wu Kingdom in 515 BC was 19 m long and 3 m wide with a crew capacity of 90 (Xin 2009, 21). In the East Han Dynasty (206 BC–24 AD), towered ships with 3–4 floors were built (Fig. 2.29). In 42 AD, General Ma Yuan commanded a fleet of 2000 towered ships in the war to unify the South (Xin 2009, 33–34).

All the ancient ships were made of wood. Iron or steel were not used as materials for ship-building until the 19th century.

Fig. 2.27 Phoenician ship in 1500–1000 BC (http://www.oocities.org/capitolhill/parliament/2587/ships.html)

Fig. 2.28 A Roman trade ship (http://www.nabataea.net/sailing.html)

Fig. 2.29 Copying model of the towered ship in Han Dynasty

2.2.5 Vehicles

The emergence of wheels was a major event not only in the history of machine, but also in the history of human civilization.

Evidence indicated that camel pulled wheeled vehicles appeared in the Arabian area around 4000–3000 BC (Bulliet 1990, 63–64).

About 2500 BC, Sumerian in Mesopotamia had vehicles with four solid wooden wheels pulled by single horse. A two wheeled chariot found in an ancient Egyptian tombs was believed being made about 1500 BC (Bu 2018).

In 2000 BC, China already had primitive vehicles with solid wooden wheels. Several books described that Xi Zhong in Xia Dynasty (2100 BC–1600 BC) made the horse pulled chariot of two wheels in which spokes were used the first time in human's history. The earliest archaeological evidence of chariots in China was 18 wooden two-wheeled chariots unearthed in Anyang, Henan Province, dated back to

Fig. 2.30 Model of cart in museum of the First Emperor of Qin Dynasty

the late Shang Dynasty (about 1200 BC). A bronze chariot and horses, shown in Fig. 2.30, were unearthed from the tomb of the first emperor of Qin Dynasty of China in Shaanxi Province.

The Diolkos was a 6–8.5 km long wagonway constructed by the Greece and used to transported boats across the Isthmus of Corinth since around 600 BC until the first century AD. Wheeled vehicles pulled by men and animals ran in the parallel grooves of limestone which worked as the track preventing the vehicles from leaving the intended route. It is widely believed that The Diolkos was the origin of the modern railway (Lewis 2011, 8–19).

The special vehicles invented by Chinese have raised great interest among researchers around the world on ancient machines.

The south pointing chariot was a remarkable invention in ancient China, in which a wooden doll or figure always pointed the South with an outstretched arm, as shown in Fig. 2.31, no matter how the chariot turned. It is believed that the earliest chariot was invented in the West-Han Dynasty (202 BC–8 AD). Unfortunately the detailed construction and working mechanism were lost. Zhang

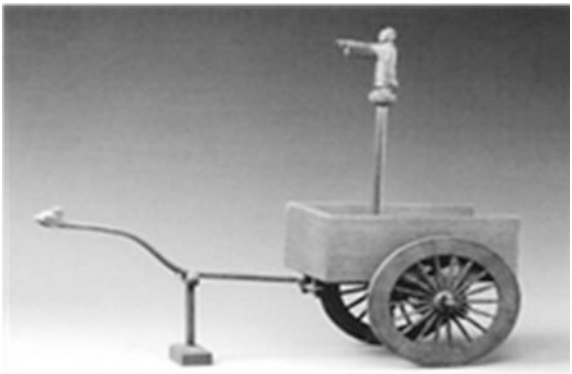


Fig. 2.31 Model of the south pointing chariot

Heng in the East-Han Dynasty and Ma Jun in the Three-Kingdom period re-invented the chariot independently using pure mechanical structure. However, both were lost again due to war and changeover of the ruling regime (Lu 2012, 154–156). In the Song Dynasty (10th–13th century), it was reconstructed again and the structure was described in the *History of Song Dynasty*. There is a widely believed hypothesis that the chariot worked on differential gears. Joseph Needham, a famous expert on Chinese history of technology, credited the chariot as the world's "*first cybernetic machine*." (Needham 1954). In the last 100 years, Chinese and foreign scholars made great effort to re-build the chariot, putting forward several restoration models (Lu 2012).

Another important vehicle invented in ancient China was the mileage-measuring drum wagon (Lu 2012, 156–157). The wagon was constructed with two stories. The upper was with a bell and the lower a drum, as shown in Fig. 2.32. When the wagon goes over 5 km, a wooden dummy beats the drum once, and after the drum is beaten ten times, the dummy strikes the bell once. Zhang Heng or Ma Jun was widely accepted as the inventor of this device. The drum wagon experienced the zigzag that the south pointing chariot did, being created, lost, recreated and re-lost and so forth. In the Song Dynasty, it was reconstructed again and documented in the *History of Song Dynasty* as well.

In the 6th century, China was already able to build huge war wagons as high as several meters with 20 wheels (Bu 2018).

Before the 1st century BC, the Celts, Europe's earliest inhabitants, created the 4-wheel chariot and the steering device, opening a new era of vehicles. On the basis, the Roman made some improvements, such as adding suspensions, enforcing the structure and reducing friction. Thus, the performance of the 4-wheeled chariots (Fig. 2.33) was greatly improved (Bu 2018). To the 200 AD, the speed of horse pulled mail cart reached 6.6 km/h.

The 4-wheeled vehicle is far more complicated than the 2-wheeled vehicle, and has higher requirement on road condition. The 2-wheeled vehicle was the mainstream until the 14th century. However, the Bohemian war in the 15th century changed the game. The Tabor uprising army of Czech tactically used 4-wheeled

Fig. 2.32 Mileage drum wagon

Fig. 2.33 A cameograph of a 4-wheeled chariot in ancient Roma, unearthed in Klagenfurt, Austria (Bu 2018)

chariots as a powerful weapon, beating the German cavalry heavily. Since then, 4-wheeled vehicles became dominant in Europe, laying the foundation for further development of modern vehicles in Europe (Bu 2018).

2.2.6 Textile Machinery

Evidences suggested that humans may have begun wearing clothing as far back as 10,000–50,000 years ago in the Palaeolithic Age (Goddard 2010; Kvavadze et al. 2009, 1359). The earliest definite examples of needles were from the Solutrean culture which existed from 19,000 to 15,000 BC and located at Solutré, in east-central France. Archaeological evidences proved that all the great ancient civilizations, such as those in Switzerland, Egypt, northern Europe, Mesopotamia, China and India, already used textiles in the Neolithic era, dating back to about 5000–5500 BC.

2.2.6.1 Thread Spinners

At latest in 4400 BC, Egyptians started using original weaving looms to make linens (Goddard 2010). It is speculated that they also had spinners to make flax fiber at the same time. In China spinning wheels first appeared in Qin and West-Han Dynasty, the period around the 3rd century BC–1st century BC.

Huang Daopo, a famous Chinese lady and textile expert, invented the pedal spinner with multi-spindles.

Wang Zhen described a large spinner consisting of 32 spindles, and a water-driven spinner as large as 6.1 m long and 1.54 m wide (Fig. 2.34) in his book *Treatise on Agriculture* in 1313 (Wang 1313; Lu 2012, 187–188). At that time, China undoubtedly was on top of the world in textile machines. The water-driven spinner was earlier than a similar machine invented by R. Arkwright during the British Industrial Revolution by about 4 centuries.

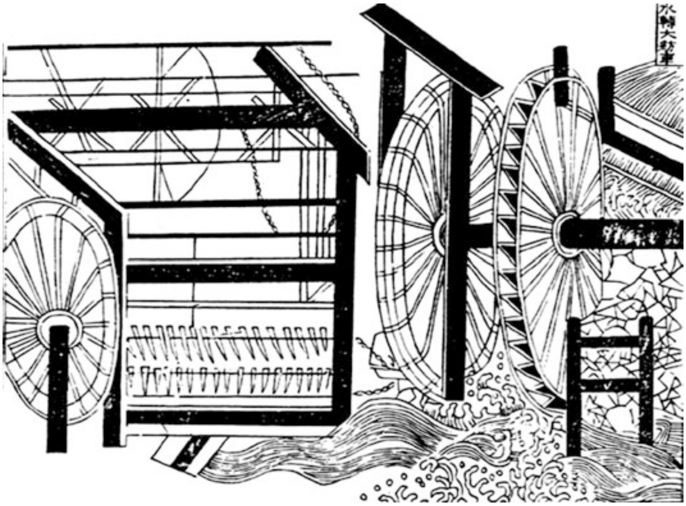
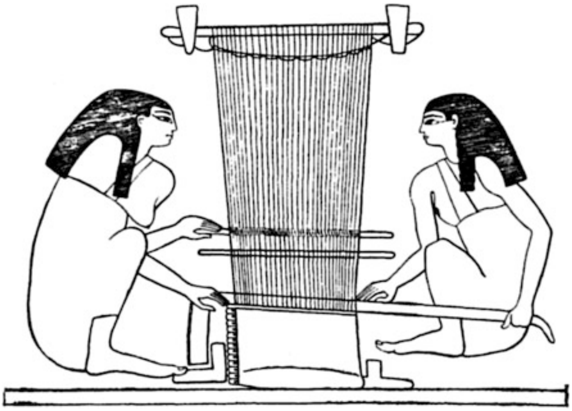


Fig. 2.34 Water driven spinner in 14th century, China (Wang 1313, 1981)

2.2.6.2 Looms

In the Neolithic Age, flax fibers were used in clothes in Northern Europe. A primitive loom, the waist loom, appeared in China around the same time. In the waist loom there was no frame. One end of the cloth-rolling shaft was tied around the waist of the weaver and the other end tied to the feet pedal so that the fabric could be in tension. Looms without frame also appeared in Egypt around 3000 BC (Singer et al. 1954). In Fig. 2.35 is a wall painting of a horizontal loom with two weavers, unearthed from the tomb of Chnem-hotep at Beni Hasan, dated back to XII Dynasty (21–18 centuries BC) (Roth n.d.).

Fig. 2.35 Egyptian horizontal loom in Neolithic (Tomb of Chnem-hotep)



From the Pre-history through the early Middle Ages, two types of looms, namely the warp-weighted loom and the two-beam loom, were dominant in most of Europe, the Near East and North Africa. The warp-weighted loom is vertical probably originating from the Neolithic Era. The earliest evidence of looms came from sites belonging to the Starčevo culture in modern Serbia and Hungary, and from late Neolithic sites in Switzerland (Barber 1991). This type of looms was also used in ancient Greece, and spread north and west throughout Europe later. The double-beam vertical loom was first developed by Egyptians in 1500 BC (Harris 2011), which had two vertical uprights and two horizontal beams to hold the warp.

In Shang Dynasty (about the 16th–8th century BC), China already had looms with fixed frame. Pedal looms appeared in China in the Warring-States period around the 5th–3rd century BC. To the Middle Ages such types of devices also appeared in Persia, Sudan, Egypt and possibly the Arabian Peninsula. In 700 AD, horizontal looms and vertical looms could be found in many parts of Asia and Africa. By the 12th century it spread to Europe (Pacey 1991).

Drawlooms were first appeared in China in the Warring-States period (5th–3rd centuries BC), enabling incredibly complex fabrics to be woven. The evidence came from the brocade of that period unearthed from a tomb of the Chu Kingdom, at Jiangling, Hubei Province, in 1982 (Lu et al. 2009b, 294).

The large drawlooms made in the Ming Dynasty of China (14th–17th century) marked the peak of hand loom age (Pan and Wang 2005).

2.2.6.3 Silk Reeling Machines

In about 3500 BC, Chinese already knew making silk from silkworm cocoons. Silk items unearthed from an ancient tomb in China date back to 2700 BC. They have very complex and intricate patterns and are dyed, showing high-level technical skills and craftsmanship. In Qin and Han Dynasties, hand and foot silk reeling machines were widely used in China (Pan and Wang 2005).

In the Roman Empire, wool, linen and leather were widely used materials for making clothes. Silk, imported along the Silk Road from China, was also used, but being an extravagant luxury.

In the whole ancient times, evolution of textile machines was very slow. However, two inventions, the flying shuttle and the spinning Jenny, made in 1733 and 1764 respectively were revolutionary. They greatly improved productivity. Consequently the UK was brought to the very leading position of the world in the textile industry.

2.2.7 Timers and Astronomical Instruments

About ten thousand years ago, humans already knew how to determine the best growing season of a year through timekeeping. The timekeeping was achieved for a long time through direct observation of astronomical phenomena or continuous movement of some flowing materials, such as the gnomon, the sundial, water clocks and the sandglass, etc. (Pan and Wang 2005). Mechanical timers did not appear until the 14th century.

Ancient humans began making astronomical instruments very early, such as the celestial globe and the armillary sphere. Some of them also had the function of timer. This book does not intend to explain the detail of all ancient astronomical instruments, which requires a fully understanding of the astronomical perspective of the time. Instead we briefly introduce several of the most representatives as a clue for further reading.

2.2.7.1 Antikythera Mechanism

Figure 2.36 shows the remains of an ancient bronze instrument, the so-called "Antikythera mechanism" found in a sunken wreck off the Antikythera island in Greece (Williams 2003). Research on the mechanism indicated that the instrument was made around 87 BC (according to a more recent view, in 205 BC). The discovery has inspired wide curiosity among scholars on history of science and technology. Many of them devoted great effort to study this mechanism. A paper on the journal *Nature* concluded that it was a solar system instrument for predicting the position of celestial bodies (Freeth et al. 2006, 587–591). The Antikythera mechanism was also the earliest known gear device in the world, in which 30 gears were preserved until now.

Archimedes (3rd century BC) created the compound pulley, and the screw to raise water. Hero (1st century AD) created some less complex mechanisms. When the two great scientists were working on these relatively primitive mechanisms, Antikythera mechanism appeared, exhibiting a much higher level of design and

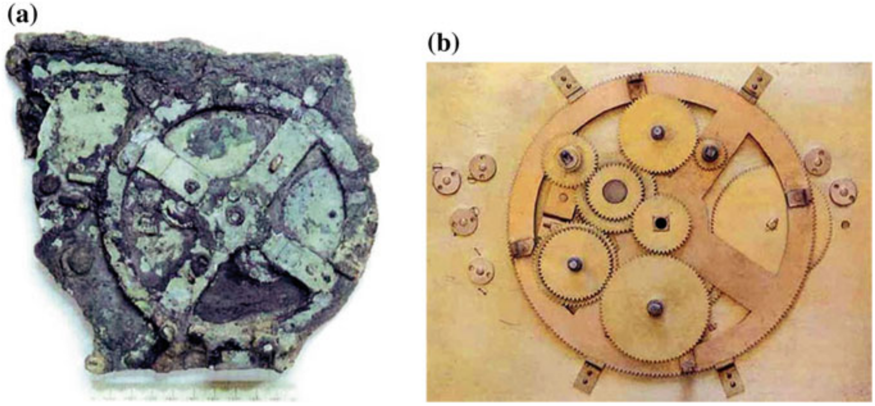


Fig. 2.36 Antikythera mechanism. **a** Mechanical gear assembly constructed from the remains. **b** M. Wright's reconstruction (Paz et al. 2010)

workmanship. This fact simply tells us that many mysteries in the history of ancient machines are waiting for us to crack.

2.2.7.2 Armillary Spheres

Eratosthenes of Cyrene (276–194 BC), a Greek astronomer, was the earliest inventor of the armillary sphere (Couprie et al. 2002).

Since the 4th century BC, a few astronomers in China made effort to build the armillary sphere. Zhang Heng (78–139 AD), the famous astronomer and inventor of the Han Dynasty, invented his version in 125 AD (Fig. 2.37). This was the first water-powered celestial globe of the world (Needham 1987a).

The armillary sphere was a complex instrument, invented separately in ancient Greece and ancient China, for demonstrating astronomical phenomena. Based on the isochronous clepsydra, it used water to drive a gear train, which further rotates the celestial globe (demonstrating part of the instrument) one revolution around the north-south polar axis each day at a constant speed. The main component of Zhang's device was a globe of about 1.5 m in diameter. On the globe's surface painted the equator, the ecliptic, the 24 solar terms and the 28 stars, etc. The detailed structure was already lost.

Zhang Heng made indelible contributions to the development of astronomy, mechanical technology and seismology of ancient China. In recognition of his contribution in astronomy, an asteroid was named after him.

Fig. 2.37 Armillary sphere by Zhang Heng

2.2.7.3 Astronomical Clock Towers

At the end of the 11th century, Su Song, a Chinese astronomer, made the "Astronomical clock tower". It was a comprehensive instrument integrating many mechanical devices, not only for observation and demonstration of astronomical phenomena, but also for measurement and report of time (Needham 1986; Lu 2012).

The clock tower is about 12 m high and 7 m wide (Fig. 2.38). It combines the principles of the waterwheel, the shadoof, the cam and the scale arm. In the tower a lot of wooden puppets are arranged, each has a predefined duty. After a certain time, a puppet beats a drum or rings a bell to report time. The center of the tower

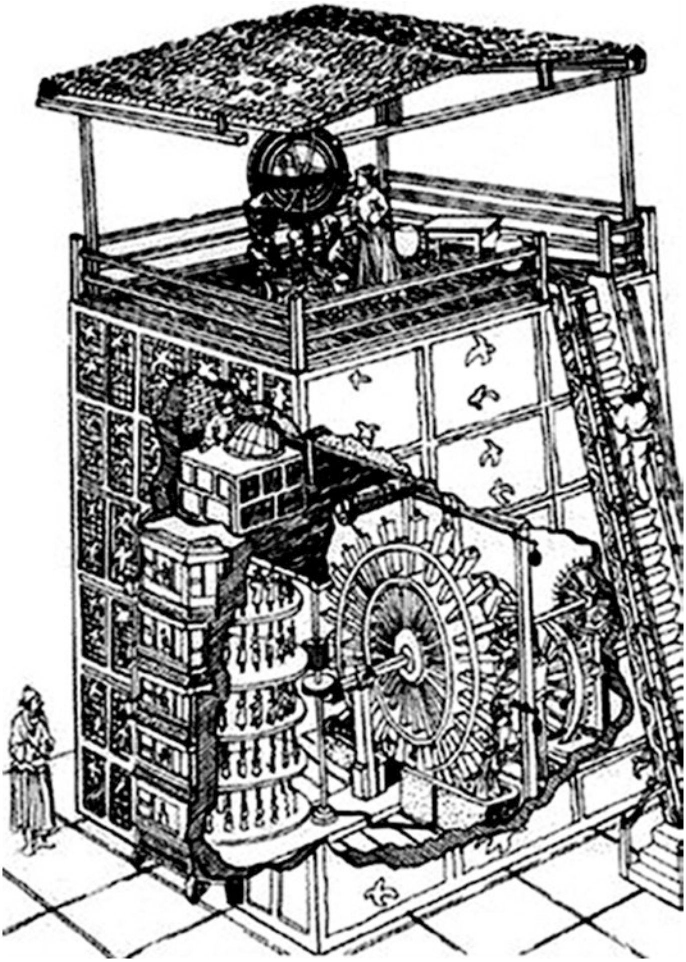


Fig. 2.38 Astronomical clock tower by Su Song (Lu and Gao 2000)

lays in the mechanical transmission. Water impulse of the clepsydra is used as the power to drive all of devices, enabling the tower to perform its function in a prescribed order.

An escapement mechanism was used in Su's clock tower. This mechanism was invented in 725 AD by a Buddhist monk, Yi Xing, and a government official, Liang Lingzan, for the purpose of operating a water-powered armillary sphere (Needham 1987a).

Su Served in many important positions in the government; the highest was as the prime minister. Therefore, he had the opportunity to read many books in the Royal library and wrote out from memory after going home. He was a well-known polymath with excellent contribution and knowledge in a wide range of subjects, making outstanding achievements in astronomy, machinery and pharmacy.

Su Song's treatise on the clock tower, *Xin yixiang fayao*, has been read by many historians, including J. Needham. The international academic community highly evaluated his clock tower for its vivid demonstration of astronomical phenomena, crediting it as the ancestor of the modern observatory. The escapement mechanism used in his clock tower became a key component in later clocks, J. Needham put it as "*it may be the direct ancestor of medieval European astronomical clocks*" (Needham 1986). Since 1958, some scholars from China and other countries have attempted to reconstruct Su's model.

2.2.7.4 Al-Jazari's Clocks

Al-Jazari, the Kurdish scholar, made a lot of clocks with various forms and dimensions (Hassan and Hill 1986). His largest astronomical clock is called the "castle clock" with a height of about 3.4 m. This complex device has multiple functions besides timekeeping, including display of the zodiac, and the solar and lunar orbits. It had the ability to reprogram the length of day and night in order to account for their changes throughout the year. Another feature of the device is that five automata musicians who automatically play music when moved by levers operated by a hidden camshaft attached to a water wheel (Wiedemann 2010).

2.2.8 Lifting Machines

Crane for lifting heavy loads was invented by the Ancient Greeks in the late 6th century BC (Goddard 2010). Archaeological record indicated that no later than 515 BC distinctive cuttings for both lifting tongs and lewis irons began to appear on stone blocks of Greek temples. They were regarded by archaeologists as the positive evidence required for the existence of the crane (Coulton 1974, 1–19).

Introduction of the winch and pulley hoist soon led to a widespread replacement of ramps as the main means of vertical motion.

Fig. 2.39 Reconstruction of a Roman treadwheel crane, the Polyspaston, at Bonn, Germany

By using a number of pulleys to multiply the force, Archimedes once drove a boat onto the beach himself. Hero designed cranes with single or double columns, on the top of which a pulley was fitted.

The heyday of cranes in ancient times came during the Roman Empire, when construction activity soared and buildings reached enormous dimensions. The Romans adopted the Greek crane and developed it further. There were also two surviving reliefs of Roman treadwheel cranes, with the Haterii tombstone from the late 1st century AD being particularly detailed.

The Roman Polyspaston crane (Fig. 2.39) could lift 3000 kg if operated by four men at both sides of the winch. If the winch was replaced by a treadwheel, the capacity could be doubled to 6000 kg with half the crew. In the construction of the Egyptian Pyramids, about 50 men were needed to move a stone block of 2.5 ton up the ramp (50 kg per person). In comparison with the lifting device used in building the Pyramids, the capability of the Roman Polyspaston is 60 times more efficient (3000 kg per person) (Dienel and Meighörner 1997).

2.2.9 *Weapons*

In the evolution of human society, civilization has been intertwined with barbarism. From the Stone Age, through the Bronze Age to the Iron Age, any progress in using materials, metal processing and construction of machines had been used in fighting, killing, wars and revolutions.

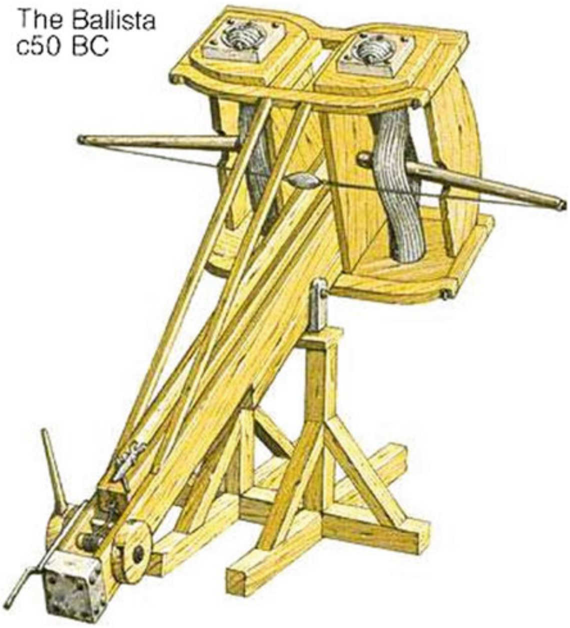


Fig. 2.40 A picture of Greek stone thrower “Ballista”

The earliest weapons humans developed are “cold weapons”, such as swords, bows, spears and shields etc. Among the cold weapons, chariots, stone throwers and crossbows etc. could be regarded as machines (Lu et al. 2009b; Lu 2012).

Stone axes and wooden spears could be traced back to the Paleolithic. Single bow appeared in the Neolithic. To the Bronze Age, metal arrows replaced stone ones.

Around 1000 BC, bronze dagger appeared in many parts of the world.

Around 2000 BC, the Nubian mercenaries in the 11th Dynasty of Egypt first used stone throwers, which work on the principle of lever. Thereafter, they were spread to Greece, Rome, Persia, India, Assyria, Macedonia and other countries. Archimedes made giant stone throwers in his later years to fight against Rome’s military invasion of Syracuse. Figure 2.40 shows a Greek stone thrower “Ballista” (Gurstelle 2004).

At the end of the 14th century BC, Egypt and the Hittites kingdom set out about 2000 war chariots in the battle of Syria, which was the earliest written record of war chariots.

The earliest archaeological evidence of repeating crossbow was from a tomb at Qinjiazui in Hubei Province, China. It was dated back to the 4th century BC, the Spring-Autumn Period (Lin 1993). To the Three-Kingdoms Period, a type of repeating crossbow which shoot ten arrows successively (Fig. 2.41), and igniting rockets appeared.

Gunpowder was invented by Chinese in Tang Dynasty, but the earliest record of a written formula appeared in the book, *Wujing Zongyao*, in Song Dynasty (Wang

Fig. 2.41 A picture of repeating crossbow

1947). Gunpowder brought revolutionary change to weapons, having an epoch-making significance on warfare.

A depiction of the early vase-shaped cannon dates back to around 1350. The illustration in Fig. 2.42 is taken from the book *Huolongjing* published in 1403, in the Ming Dynasty of China (Needham 1987b).

Fig. 2.42 Vase-shaped cannon in ancient China

The first documented record of artillery with gunpowder propellant used on the battlefield was in 1132, when General Han Shizhong of the Song dynasty captured a city in Fujian Province (Toqto'a and Alutu 1346). In 1332 (Yuan Dynasty), the Yuan troops were equipped with bronze blunderbusses (with 34.7 cm long and 10.5 cm of diameter), which were the world's oldest artillery known so far. Gunpowder spread to Arabia and Europe by Mongols (Lu et al. 2009b, 182–190). Thereafter hot weapons were rapidly developed in Europe, various guns and artilleries appearing in succession.

After spreading to the West, gunpowder caused fundamental changes to European society. The rise of capitalism, along with the gunpowder weapons, led to revolution. "*The stone walls of the noblemen's castles, hitherto unapproachable, fell before the cannon of the burghers, and the bullets of the burghers' arquebuses pierced the armour of the knights. With the defeat of the nobility's armour-clad cavalry, the nobility's supremacy was broken*" (F. Engels: Anti Dühring). Victory of capitalism inspired further improvement to guns and artillery, and expanded the production of them. In China, however, the picture was totally different. Following the policy of isolationism in long times, Governments cut off almost all connections with the outside world. A direct consequence of this policy was the slowing down the development of economy, science and technology. Improvement and production of firearms remained stagnant. From backwardness to being beaten, China was degraded from a great power to a semi-feudal and semi-colonial country.

2.2.10 Machines for Rituals and Entertainment

2.2.10.1 Entertainment Machines by Hero

Hero, the ancient Greek scholar, developed several mechanical devices for religious rituals or entertainment.

In the book *Automata*, he described a machine that could automatically turn the gate of the temple, and a machine that could automatically poured wine.

The working mechanism of the gate-turning machine is illustrated in Fig. 2.43. The believers first light the fire on the altar A, which is in front of the temple generally. The air pressure in the altar is therefore increased, pushing the water in the hollow sphere B into the storage bucket C through the water pipe. After the weight of the bucket and the water within reaches a certain threshold, the bucket starts to move downward, and turns the door slowly open or close through the rope winded around the shaft D (Singer et al. 1956).

In another book, *Pneumatica*, he described machines working on air, steam or water pressure. Hero also made a simple steam turbine (Fig. 2.44), which can be regarded as the origin of modern reaction steam turbines. Actually Hero's turbine was too primitive to any actual application. It could be regarded only as a toy from nowadays perspective (Mokyr 2001, 11).

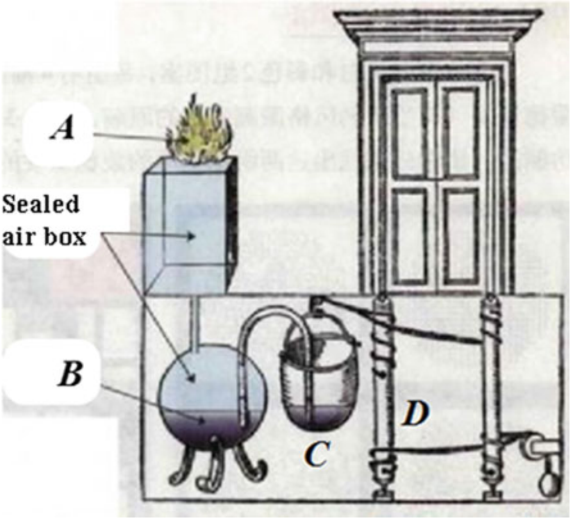


Fig. 2.43 Hero's mechanism for opening and closing temple door

Fig. 2.44 Hero's aeolipile (a steam turbine)

2.2.10.2 Water-Driven Opera by Ma Jun

In the Three-Kingdoms Period of China, Ma Jun developed the “water-driven opera” (Lu 2012, 251–253). When a water-driven wheel was rotating, all the wooden puppets on the wheel were moving up and down and doing extremely complex things, such as drumming, dancing, playing a sword or riding a horse etc. Although it was only an entertainment device made for the emperor, it exemplified Ma Jun’s excellent skills and knowledge in mechanism, hydraulics and mechanical transmissions. Unfortunately the water-driven opera was lost.

2.2.10.3 Al-Jazari’s Automat

Al-Jazari, the Islamic genius, also made some ingenious automatic devices for entertainment (Hassan and Hill 1986).

He created a musical machine, which was a boat with four automatic musicians floating on a lake to entertain guests at royal parties. It is thought to be an early programmable automat (Sharkey n.d.).

Al-Jazari’s “peacock fountain” was a more sophisticated hand washing device featuring humanoid automat as servants which deliver soap and towels (Fig. 2.45). Pulling a plug off the peacock’s tail releases water out of the beak, the water from the basin fills the hollow base. Then a float rises and actuates a linkage which makes a servant figure appear from behind a door under the peacock and offer soap. When more water is used, a second float at a higher level trips and causes the appearance of a second servant figure—with a towel (Rosheim 1994).

The Arabian scholars displayed an interest in creating human-like machines for practical purposes but lacked real impetus to pursue their robotic science (Rosheim 1994).

2.2.11 Mechanisms and Transmissions

The rope drive was the earliest transmission humans ever used. It could be seen in bow drills (Fig. 2.54), spinners and water-driven blowers (Fig. 2.26).

In the 1950s, archaeologists in China found an iron ratchet gear of the 3rd century BC to the 1st century AD, a bronze ratchet gear and metal gears of the 3rd century BC, and herringbone gears (Fig. 2.46) of the 1st century (Needham 1987a).

The gear trains in the Antikythera mechanism (Fig. 2.36) and in the south pointing chariot (Fig. 2.31) were very complicated.

The worm drive was an evolution from the screw, one of the ancient simple machines. Although It is not clear who invented the worm drive, humans noticed the unique features of worm drives very early, such as the large reduction ratio, the force amplification, and self-locking. At first, the rudder of a sailboat was driven with rope wound on a drum. Steering of the sailboat needed a few boatmen to pull

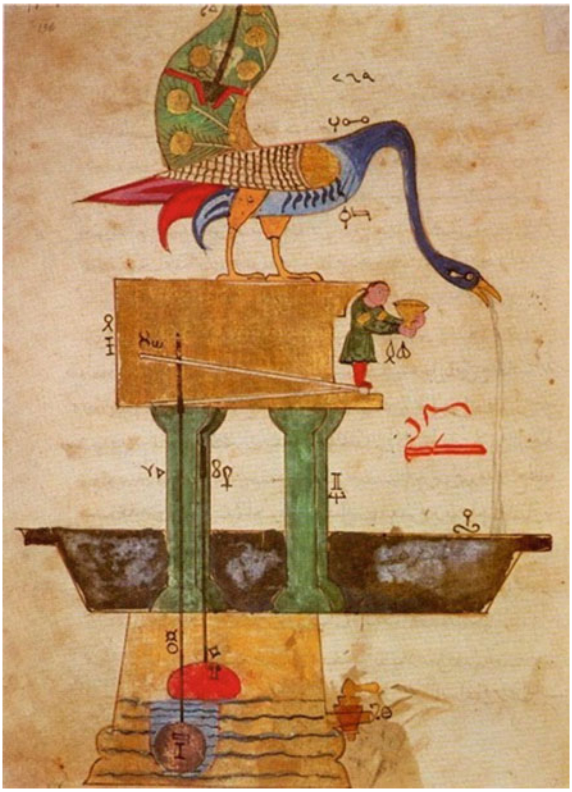


Fig. 2.45 Peacock fountain

Fig. 2.46 Herringbone gears in the 1st century, China

the rope. Controlling the rudder with a worm drive was an important improvement in the history of sailboats.

The oldest known application of a chain was described by a Greek engineer in the 3rd century BC, but it was not used to transmit power from shaft to shaft. The first continuous and endless power-transmitting chain was depicted in the written horological treatise of Su Song, who used it to operate the armillary sphere of his astronomical clock tower (Needham 1986).

Al-Jazari described a cam mechanism in his book published in 1206, which is believed to be the first publication on cam mechanism. In addition he employed camshafts in his automata, water clocks and water-raising machines (Al-Jazari 1973). In 1276, Guo Shoujing, an astronomer and officer in Yuan Dynasty of China, made a quite complex cam mechanism used in an automatic timekeeping machine. Cam mechanisms appeared in Europe much later in the 14th century.

The handle mounted eccentrically on a rotary quern-stone of the 5th century BC in Spain which spread across the Roman Empire constitutes a crank (Ritti et al. 2007, 138–163).

The earliest evidence of the crank-rocker mechanism was that used in a pedal spinning in China, in the East-Han Dynasty (25 AD–220). The crank also appeared in the mid-9th century in several of the hydraulic devices described by the Banū Mūsā brothers in their *Book of Ingenious Devices* (Beeston et al. 1990). The crank-slider mechanism was first used by Al-Jazari. He also created an escapement. Segmental gears was clearly described the first time in his book.

The principle of flywheels could be found in the Neolithic spindle and the potter's wheel. The use of a flywheel as a general mechanical device to even the speed of rotation was recorded by Theophilus Presbyter, a German artisan, who applied the device in several of his machines (Lynn 1964, 224–233). Actually, a little earlier, Ibn Bassal, an Islamic Spanish scientist, pioneered the use of the flywheel in the noria and the saqiya (Hassan n.d.).

2.2.12 Power for Ancient Machines

Human was the earliest power for ancient tools and machines. In many applications, such as spinning, weaving, watering and driving vehicles, this situation was not changed until the Modern Times.

Waterwheels appeared in Egypt and Greece during the 4th and 3rd century BC respectively. Initially water power was used to drive millstones and blowers. In the 1st century AD, hydraulic pestles were widely applied in Italy. In 226 AD, waterwheels were used to supply water to the city in Rome (Goddard 2010). In the 3rd–4th century, water powered flour mill and saw mills emerged in Europe. The power used in the Rome's largest waterwheel reached 36 kW.

As early as in 4000–3500 BC, people in Middle Asia and West Asia began to use animals for dragging heavy objects and pulling the plough. There is evidence indicating that camel was also used for pulling wheeled vehicles about 4000–3000 BC.

Human began to use simple windmills thousands years ago. In 400 BC, irrigation systems driven by a windmill were used in India. In 200 BC, windmills with vertical wing plates were found in the border area between Afghanistan and Iran. Later, windmills with horizontal plates also appeared in the area. Since the 7th century, Persians applied windmills for driving millstones, raising water and pressing sugar canes (Hassan and Hill 1986).

In the middle 14th century, wind power was applied in Dutch and Belgium to drain out the water trapped in the lands below sea level. A European proverb says, *God created the world, but the Dutch created the Netherlands.*

None of the human, animal, water and wind is able to produce a great power. The limitation greatly restricted the development of ancient machines. Also due to the limit of power, machines were in general operated at very lower speed, thus no real need to consider dynamics in ancient machines.

Over the past 300 years, the revolution in power promoted the rapid development and wide application of machines.

2.3 Ancient Manufacturing Technology

2.3.1 Casting

The technology of copper casting was an attendant of copper smelting (Singer et al. 1954; Beeley 2001).

Copper was the earliest metal used in human history. Bronze is an alloy of copper and tin or lead. Bronze largely improves the strength of copper, and reduces the melting point. It was the earliest metal alloy in the history of metallurgy. The earliest bronze item of the world appeared in 4000 BC, in Mesopotamia. One of the earliest bronze products in Egypt was the statue of Sargon the Great of the Akkadian Empire (Fig. 2.47), which was cast with lost wax process in 2300 BC (Mallowan 1936). The Bronze casting technique was developed around the same period in Europe, China and India.

Bronze was frequently used to cast containers such as cups, urns, and vases. People also made battle-axes, helmets, knives, shields, and swords with bronze. Ornaments and, sometimes, primitive stoves, were common items made from bronze as well.

A bronze knife, unearthed at Majiayao sites of Gansu Province, China, in 1975, indicates that it belonged to nomadic people in the 2800 BC (Hua 1999). This showed the bronze production technology was already introduced into China at that time. The rapid development of bronze casting in China, however, appeared in the Xia Dynasty (21st–16th century BC). All the bronze items from Xia Dynasty were unearthed at Erlitou site in Yanshi, Henan Province (Linduff and Mei 2008) (Fig. 2.48).

By the late Shang Dynasty and early West-Zhou Dynasty (1200–1000 BC), bronze casting entered its heyday in China, reaching very high level in technique and craftsmanship. The bronze casting technology at that time of China enjoyed a high reputation in the world, one of the most famous items cast in the Shang Dynasty was the “Queen Cauldron” (Fig. 2.49a). It weighs 832.8 kg and has magnificent shape, momentum of grand, ornate decoration, reaching very high level

Fig. 2.47 Statue of Sargon the Great

Fig. 2.48 Bronze cup unearthed at Erlitou site in 1963

in technology. It is the heaviest bronze item unearthed so far in the world (Tian 1987, 16–17).

In 1978, exquisite bronze castings, including the "Symbol of the dynasty" (Fig. 2.49b) and the "Great chime bells" (Fig. 2.49c),were unearthed from Zenghou Yi's tomb, who was a duke in Hubei Province of China in the 5th century BC (Tian 1987, 209–210, 111–114). The bells with different sizes make up a set of music instruments.

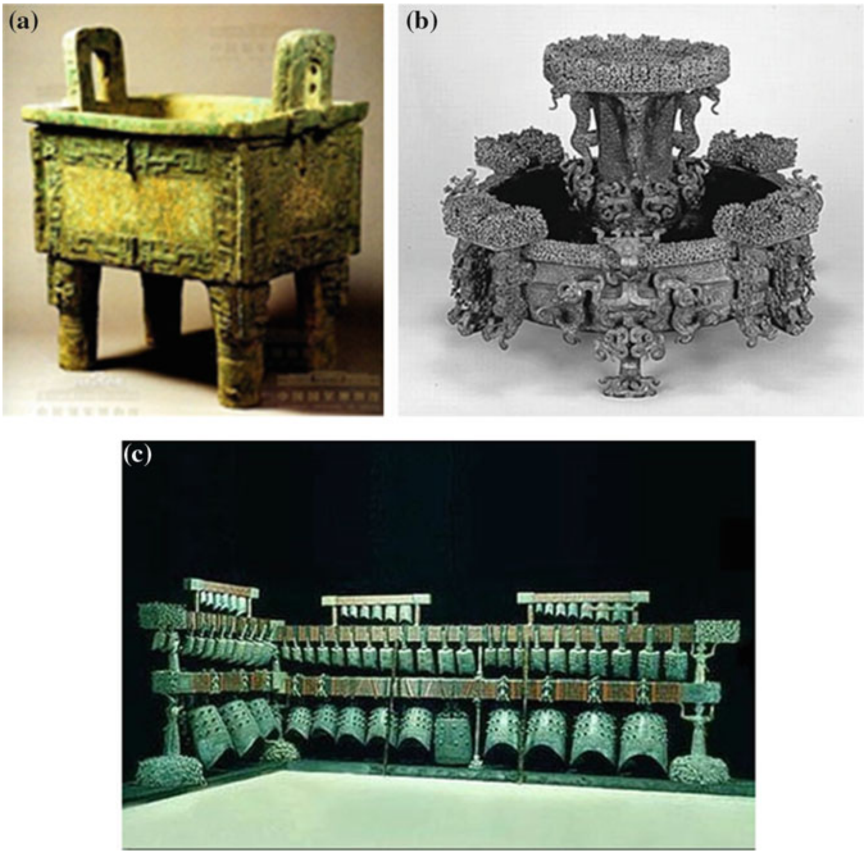


Fig. 2.49 Ancient Chinese bronze castings. **a** Queen Cauldron. **b** Symbol of dynasty. **c** Great chime bells

In 3000 BC, Europeans could cast axes of simple shapes from bronze in open molds. Exquisite bronze statues was produced in Europe before Christ. By the time of late Medieval Ages, decorative bronze and tin casting products were widely used in European churches and households.

Iron casting, however, developed along a route different from that of the bronze casting.

The melting point of iron (1535 °C) is much higher than that of bronze (800–1000 °C). Due to lack of technical knowledge, melting furnaces in ancient times could not reach temperature of the melting point of iron. So, forging was first developed in the production of iron because it requires a much lower temperature than casting. Iron ore could be reduced with carbon at a temperature of about 1200 °C to a porous body, known as block iron. Block iron, containing many impurities, had to be heated and forged repeatedly for at least 20 times at high temperature in order to remove the impurities. At that time, people in many areas

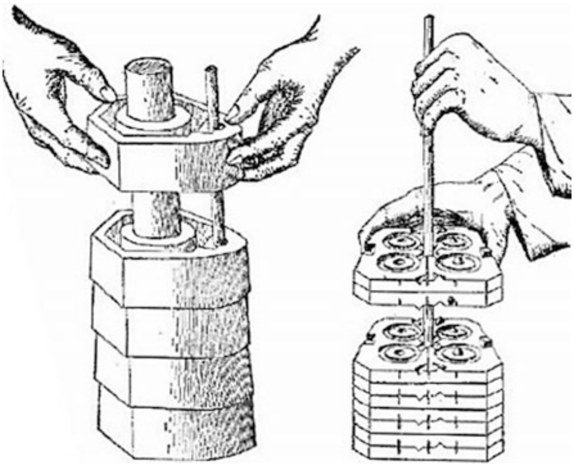


Fig. 2.50 Stack casting

had not yet mastered the hardening and tempering process, hardness of forged iron was not higher than bronze. Block iron was not desired at that time due to its time-consuming and labor intensity, thus, quality and production volume were very low. In Europe, smelting of pig iron did not appear until the 14th century after the invention of the hydraulic blast furnace, it took more than 2000 years to develop from block iron to pig iron.

Chinese, however, took a completely different route. The smelting technology of pig iron appeared in the late Spring-Autumn Period, shortly after the appearance of block iron. In 513 BC, Chinese made the world's first recorded iron casting "Jin cauldron", weighing about 270 kg. It was recorded in *Zuo zhuan*, a famous work of history in ancient China. Thus, the iron casting technology in China appeared earlier than in Europe by about 1900 years (Tian 1987, 144–147). This great achievement is mainly credited to the development in blowing device and iron making furnace in ancient China, which enabled the high temperature required for iron smelting.

In the 8th century, Europeans began to produce iron castings which largely expanded the range of application of castings. During the 15th–17th century, cast iron pipes were laid in Germany, France and other countries to supply drinking water to the city residents.

The earliest casting method appeared in history was the sand casting. Sand is cheap, abundant, and easy to make into a mold. Sand casting is still in use as the basic process of casting until now.

In ancient China, three special casting technologies, clay mold casting, metal mold casting and lost wax casting, were developed. Clay mold casting was developed with the technology of pottery making. Archaeological evidences of both molds of white pig iron and casting products in the Warring-States Period were discovered (Hua 1978).

Lost wax casting, also known as investment casting, was passed down from the ancient times for precision casting of bronze. This technology appeared in many parts of the ancient world. The earliest example was discovered in south Israel, a famous casting item dated back with carbon 14 method to 3700 BC (Muhly 1988). In China, lost wax process appeared in the Spring-Autumn Period. This casting technique is still widely used for making art products nowadays (Hua 1978).

During the Warring States Period (475–221 BC), stack casting (Fig. 2.50), in which several casting molds were stacked together and shared one sprue cup, appeared in China. With this process, multi castings could be obtained in one operation (Tian 1987, 200–205), productivity being greatly improved and materials being saved. It was widely used in casting of coins and parts of vehicle and is still used even today.

2.3.2 Forging and Other Press Processing

Forging of metal appeared earlier than smelting and casting. In the late Neolithic times, humans had used virgin copper before the emergence of copper smelting technologies. The natural form of copper exists on the surface layer of the copper mine. During mining, people found the brightly colored “stone” was unusual, easy to be forged and formed. Cutting, bending, forging, annealing, sharpening and some other primitive processing and forming techniques were developed thereafter (Hua 1999). The world’s earliest metal product was a forged copper decoration unearthed in northern Iraq, dated back to 9000–8000 BC. Ornaments made of virgin copper also appeared in Mesopotamia in 6000 BC and Egypt in 5000–4000 BC respectively. Among them the small items were directly forged and the large ones were cast from the melted virgin copper (Pan and Wang 2005). Egyptians forged natural gold, silver and copper with stones; bronze was forged under normal temperature to make the work hardening and used as weapons or tools (五弓勇雄 1978).

During the late Bronze Age, bowls were made by continuously hammering the inner wall. A close look at the statue of King Pepy I of the sixth dynasty of Egypt, shown in Fig. 2.51 (Bongioanni and Croce 2001, 81), may find some clues of the hammering, such as the unevenness on the skull and face.

In the mid. West-Han Dynasty, a kind of forged iron, called “100-forged steel” meaning that it was produced by repeated heating and forging of block iron, appeared in China. The sword of the King Liu Sheng, unearthed in Mancheng County of Hebei Province in 1968, was an early item made of the 100-forged steel. After quenched, the sword acquired excellent toughness and hardness (Tian 1987, 176–177). A knife made in East-Han Dynasty of China was unearthed in Tenri City, Japan. In the Three-Kingdoms Period (220–265) and Jin Dynasty (265–420) this steel reached its heyday.

Fig. 2.51 Status of King Pepy I

Heavenly Creations (Song 2009) published in Ming Dynasty described the process of forging a big and heavy anchor (Fig. 2.52). Forging remained a manual operation in China for a long-term.

In ancient Rome, drop hammers were used. The hammer was lifted up by human or animal power and then dropped down rapidly. In the 14th century hydraulic hammers emerged, with which large pieces could be forged. The drop hammer was in use until the 19th century (五弓勇雄 1978).

The earliest forging die appeared in 1600 BC, which was made by ancient Greeks from stone with grooves on one side. It was used to forge gold or silver plate into a jewelry. During the 8th–5th century BC, coins were embossed with similar dies. In 1250, people forged iron decoration with a single flat die. In the late Medieval Ages, dies were used to forge bullets of artillery and musket, or the gun barrel in Europe (Lange and Mayer-Norkemper 1977).

In Rome, punching was used to make coins at the latest in the 5th century BC. But the skill was lost during the several hundreds of years after the fall of Rome.

In the Shang Dynasty, Chinese used pottery wheel to make ceramic products. In the early 10th century, spinning, a metal forming technique, was hatched from the pottery. With this technique, silver, tin, copper and other metal sheets were made into various bottles, plates, pots and other utensils and decorations (Wang et al. 1986). To the 13th century, this technique was spread to Britain and other European countries.

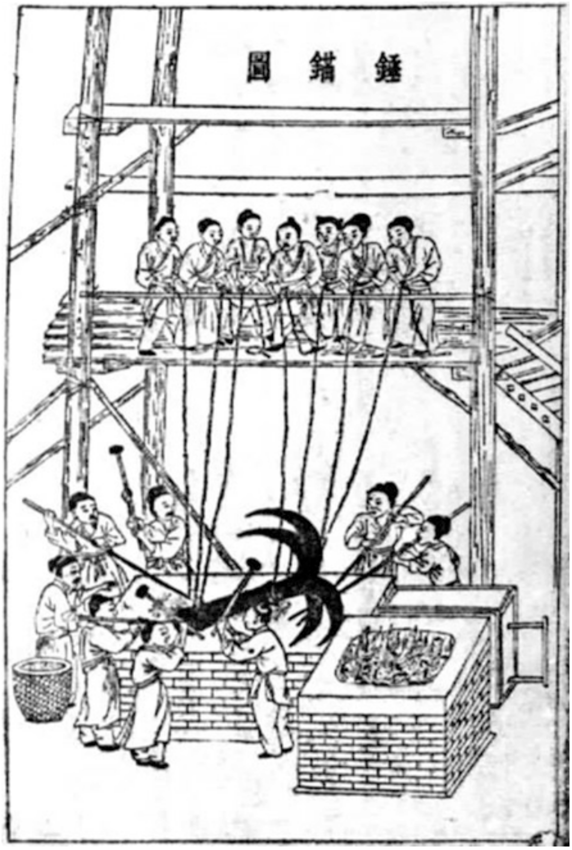


Fig. 2.52 Forging of a large anchor in China (Song 2009)

2.3.3 Welding

In about 3000 BC, the forge-welding technology, in which two heated metal blocks were repeatedly beaten until they were welded together, appeared in Egypt. Some iron and bronze items discovered in a Pyramid have complex forging-welding lines clearly seen (Cary and Helzer 2004).

In Shang Dynasty (2000 BC), the cast-welding technology was applied for making weapons in China. Chinese also had mastered brazing process of bronze and forge-welding process of iron before 200 BC.

The Middle Age saw advances of forge-welding in Europe. In 1540, *De la pirotechnia*, the first book on metallurgy published in Europe, included descriptions of this forging operation (Biringuccio 1959). Renaissance craftsmen were skilled in the process, and the industry continued to grow during the following centuries.

The Delhi pillar of India (Fig. 2.53), made in 310 AD, is 7.25 m in height, 400 mm in diameter and 5.4 tons in weight, marking the largest manufactured piece of metal in ancient world. It was forge-welded from many smaller pieces of

Fig. 2.53 Delhi pillar of India and its top part

wrought iron billets (Cary and Helzer 2004). However, it seemed being made by casting if observing the patterns on the top.

Most modern welding methods we are familiar today were invented after the 19th century.

2.3.4 Machining

Humans used stone cutters early in the Paleolithic Period. The oldest known cutters were found in Olduvai Gorge in Tanzania, being made 1.8 million years ago. Stone beads used for drilling 28,000 years ago were discovered in Shanxi Province, China (Ren 2018).

In the Neolithic Period, very fine perforated stone axe and stone knife with multi holes appeared, some of them were polished by grinding with hard sand.

The bow drill was the first machine drill (Fig. 2.54) in history, which was traced back to around 10,000 years ago. It converted reciprocation to rotation, and was mainly used to create fire by drilling on wood. It was also used in ancient woodwork, stonework and dentistry (Ren 2018). Archeologists discovered a Neolithic grave yard of around 7500–9000 years ago in Mehrgrath, Pakistan. In the 9 adult bodies, 11 teeth were found being drilled (Coppa et al. 2006).

In a tomb at Thebes, hieroglyphs were found depicting Egyptian carpenters and bead makers using bow-drills. The earliest evidence of these tools being used in Egypt dates back to around 2500 BC (Needham 1954). The bow drill was widely

Fig. 2.54 Bow drill

spread throughout Europe, Africa, Asia and North America, during ancient times and is still in use today.

Core drill was developed in ancient Egypt by 3000 BC. The pump drill was invented during the Roman times, which consisted of a vertical spindle aligned by a piece of horizontal wood and a flywheel to maintain accuracy and momentum (Singer et al. 1954).

In the Bronze Age, saw was widely used in wood processing. Ancient Egyptians sawed stones with copper tool.

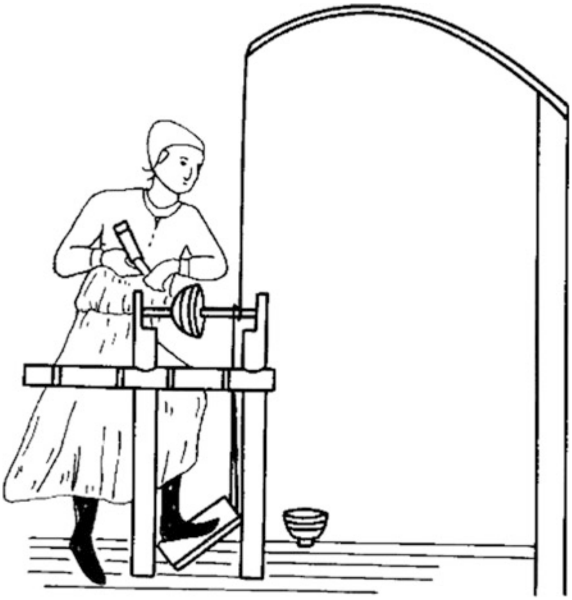
As early as 3000 years ago, Babylonians made the tree lathe, which was the earliest form of lathe. The operator presses the rope ring at the lower end of the work by feet. Due to the flexibility of the sticks the workpiece is rotated by the rope. A shell or sharp piece of stone hold by the operator moves along the slab to cut the work. Egyptian monuments illustrated (Fig. 2.55) one worker used a strap to rotate a wooden workpiece while another held the cutter (Stephenson and Agapiou 2005). The earliest strap lathes were developed in 1300 BC in Egypt (Holtzapffel 1976). Chinese, Persian, Arabian and Roman had their own variations of the strap (or bow) lathe (Wood 2005).

Ancient Roman improved the Egyptian design with the addition of a turning bow (Fig. 2.56). In Europe of the Middle Age, a pedal replaced hand-operated turning, allowing a single person to rotate the piece while working with both hands (中山秀太郎 1975). This system is called the “spring pole” lathe nowadays, which was in use until the early 20th century.

Since the ancient times, human has been making screws. For many centuries, however, the thread was only manually cut out or filed out on a log stick (中山秀太郎 1979).

Fig. 2.55 Lathe cutting wooden workpiece in 1300 BC, Egypt

Fig. 2.56 Pedal type woodworking lathe in the 13th century in Europe



Initially, the object of cutting was wood. After the Bronze Age, there appeared a need for metal cutting, correspondingly, tools were also made from metal. However, the development of cutting technology was very slow. It began to speed up during 1500–1750 before the Industrial Revolution.

2.3.5 Heat Treatment

To the Bronze Age, the value of heat treatments was gradually recognized. For example, Annealing of virgin copper was used in about 4200 BC (Singer et al. 1954). Also, iron from meteorite was forged and annealed in Mesopotamia in 3000 BC.

In *Kaogong Ji*, a treatise on specifications and techniques of various handicraft processes in the Spring-Autumn Period of China, it was described the first time in history that how the composition of the bronze alloy influenced its properties. This was the world's earliest metallographic concept and profoundly impacted the development of heat treatment technology in China (Tian 1987, 71–72).

The development of heat treatment was more closely related to the appearance and development of iron and steels.

Quenched steel knives were unearthed at the Hallstatt culture site in Austria, which dated back to about 1000 BC. In Egypt, two quench-hardened axes unearthed dated back to 900 BC. At the edge of the axe martensite structure was discovered. In the Odyssey by Homer in the 8th century BC, quenching was vividly recorded: "*As a blacksmith plunges a glowing ax or adze in an ice-cold bath and the metal screeches steam and its temper hardens*". In the Spring-Autumn Period, Chinese mastered the annealing technique to prevent iron's brittleness, obtaining a kind of ductile iron which could be forged to make a variety of farm implements. In the 6th century BC, iron weapons were used and the quenching process was developed. Archaeological analysis of a sword unearthed from a tomb in West-Han Dynasty, dated to 113 BC, indicated that the carburizing-quenching process had been used then (Tian 1987, 233–240).

To the 17th century (the Ming Dynasty), Chinese became the world's largest steel producer, and accumulated more experiences in heat treatments, which were recorded in *Heavenly Creations*, the famous work by Song Yingxing. However, knowledge of heat treatment at that time remained mainly empirical, instead of theoretical level.

As a scientific subject, theory of heat treatment was not established until the period between 1840s and 1860s. With the metallographic analysis technique, the theory of metal phase transition and the iron carbon state diagram appeared in succession.

2.4 Discussion on Ancient Machines

In the ancient times, the theory of mathematics was just budding and the theory of mechanics was not born yet, to say nothing of theories of mechanism and innovative design. As such, progress and improvement of machines came from practice, rather than theoretical development. Machines in ancient times were created by some skilled craftsmen, relying on intuition and inspiration.

Design relying on intuition and inspiration is classified as the first stage in the history of mechanical design.

Intuition and inspiration are important links in creative thinking activities. Although nowadays computers are powerful and software is sophisticated, there is no way for computers and software to displace intuition and inspiration. From ancient times, numerous inventor's practices have been accumulated, becoming an invaluable bank of wisdom sparks, from which nowadays creative study (creatology) has been developed.

Many ancient machines were so ingeniously conceived that it is not an easy task to rebuild today. For example, Zhuge Liang, a famous inventor and a prime minister in the Three-Kingdoms Period of China, invented the wooden ox which was lost later. Much effort has been made to rebuild it; however, no one has been successful to make a convincing model to date.

Gear trains in both the Antikythera mechanism of Greece and the south pointing chariot of China were very complicated. Many modern machines, such as lathes, steam turbines, hydraulic turbines and screw conveyors, have their ancestors in ancient times. The basic principle of a modern machine is often interlinked to that of its ancestor, which may be simple and primitive. Ancient machines laid the foundation for later inventions and improvements.

The concept of robots also existed in ancient times. Literature and legends indicated that machine dolls were already made in China of the West-Zhou Dynasty and Greece of the 2nd–3rd century (Needham 1987a; Zhang 1998).

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Chapter 3
Social, Scientific and Technological Progresses of Europe Before Industrial Revolution

> *In late medieval and early modern times, ……, modernization comprised the Renaissance and Reformation, economic expansion, emerging capitalism, state building, and overseas enterprise. These developments set off a chain reaction in the form of the great scientific, industrial, and successive political revolutions that have molded human history from the seventeenth century to the present.*
> —Leften S. Stavrianos (Greek-Canadian historian, 1913–2004):
>
> *A Global History: From Prehistory to the 21st Century*
> *To the Master's honor all must turn, each in its track, without a sound, forever tracing Newton's ground.*
> —Albert Einstein (German-born theoretical physicist, Nobel physics award winner, 1879–1955)

After the long medieval darkness, the world entered the modern times, the era of birth and rapid growing of Capitalism. Europe experienced a series of great social changes. During the several centuries, a series of important events, including the birth of Capitalist mode of production, great geographical discoveries, the Renaissance, the Reformation, the Enlightenment and Bourgeois Revolutions, took place successively.

3.1 Social Development Before Industrial Revolution

3.1.1 Emergence of Capitalist Mode of Production

Emergence of the capitalist mode of production laid the foundation for a series of social changes following.

In the 14th century, manual workshops, the sprout of capitalist mode of production, appeared in Italy first. At that time, there were more than 3000 wool textile workshops in Florence alone. The boatyards in Venice could build a thousand of galleons every year.

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To the 15th and 16th centuries, manual workshops were gradually formed also in England, France, Germany and other European countries. Great progresses were made in brewing, textile, glass manufacturing, mining, metal processing and other handicraft industries. In Germany pumping machines with hydraulic and horse-power drive appeared, making pit mining possible. In the middle 16th century, textile factories with more than 2000 workers appeared in Britain.

The emergence of the capitalist production mode called for 1) liberation of human spirit from the Catholic tyranny, and 2) development of science and technology as the basis of new productive forces.

3.1.2 *Great Discoveries of Geography*

In the second half of the 15th century, the Age of Discovery started. Under the full support of the king of Spain, the Italian navigator, Christopher Columbus, sailed westward, and reached America in 1492, which was uncharted then and thus a New Continent from the European perspective. In 1522, the Portuguese navigator, Fernão de Magalhães, sent by the king of Spain, completed the voyage around the world for the first time. These two events in Europe are known as the "the Great Geographical Discoveries" (Fig. 3.1).

The Great Discoveries were not accidental, behind which were a variety of driving factors, including the enthusiasm to spread Christianity to the unknown world, and the eagerness to explore colonies etc. Among the many, economic consideration, of course, was in the center. After economic boosting, the emerging bourgeois needed gold to further develop the economy, strengthening East-West trade and finding markets for their industrial products.

Both Columbus and Magalhães believed in "round Earth theory". The Great Geographical Discoveries changed human's understanding of the Earth and started the formation of a world market. They greatly promoted the social and economic development of Europe. In addition, the need for navigational positioning at that times required knowledge of astronomy, which accelerated, directly or indirectly, the development of astronomy and mechanics.

Fig. 3.1 Global route of F. de Magalhães

3.1.3 The Renaissance

The ancient Greece and ancient Rome had a very high achievement in literature and art, and people could express all kinds of academic thoughts freely. This formed a sharp contrast with the dark Middle Ages. In the 14th century, requirement of "restoration of the culture and art of ancient Greece and ancient Rome" was spreading through Italy, like a spring breeze blowing. By the 16th century, an ideological culture movement formed and diffused throughout Europe.

With revival of classical culture as the means and a slogan, the Renaissance was substantially an ideological liberation movement. Its foundation was rooted in the commodity economy in Italian cities at that time.

In commodity economy, activities in operation of business, such as purchase, sale and contract, are characterized of freedom, which further requires the freedom of ownership of the means of production. A common premise of all these freedoms is the freedom of people. Economy achieved unprecedented prosperity in the cities. With the economic success, the emerging bourgeoisie were confident, desiring for win and being full of spirit of adventure. All these brought up a need for ideological liberation movement of free spirit to the stale Europe.

It was the greatest progressive revolution that mankind had experienced. This great time called for giants and produced giants—giants in power of thought, passion, and character. The representative figures of the Renaissance include Alighieri Dante (1265–1321), Leonardo da Vinci (1452–1519), Buonarroti Michelangelo (1475–1564), Sanzio Raffaello (1483–1520), and William Shakespeare (1564–1616).

The poems, paintings, sculptures and drama works by these cultural giants reflected the Ideological kernel of Renaissance, which was characterized with promoting human rights, fighting theocracy, singing praises of secular, despising of the heaven, esteeming of rationality and refuting God inspiration.

In essence, the Renaissance was a cultural liberation movement against the theology, which created a favorable cultural atmosphere for modern development of economy and the birth of modern natural science. Human society entered a new era full of creative spirit. Western European countries began to set up universities, develop natural sciences, humanities, and cultivate talents, preluding to the modern history of Europe.

3.1.4 Religious Reform (the Reformation)

The religious reform movement (the Reformation) was originated in Germany. At the end of the 15th century, Germany was in the state of feudal separation, and a huge amount of wealth was flowed into the Church of Rome each year. The German Reformation was symbolized with Martin Luther (1483–1546), a theological professor. He wrote an official accusation to his bishop in October of 1517, directly criticizing the Church of Rome. The accusation spread quickly throughout Germany through posting publicly and received the endorsement and support of the general.

The religious reform then swept the whole Western Europe. It stroke the theocratic rule and deprived the privilege of the Church of Rome in the Western Europe. It was conducive to the development of nation states. If the Renaissance was an ideological liberation movement under the cloak of culture and art, the Reformation was also a social movement against feudalism and religious theocracy, but under the cloak of religion.

After the Reformation, the Protestant, a new branch of Christianity, was formed.

3.1.5 The Enlightenment

The Enlightenment refers to a movement of thought happened nearly a hundred years before the French Revolution occurred in 1789. France was the center of the Enlightenment. The representative figures were a group of philosophers and thinkers, such as Voltaire (1694–1778), Montesquieu (1689–1755), Denis Diderot (1713–1784) and Jean-Jacques Rousseau (1712–1778).

The Enlightenment, different from the Renaissance and the Reformation, threw away the cultural and religious mask, directly criticizing the feudal autocratic system and opposing against the authority of the Church. The Enlightenment hold high the banner of freedom, equality and human rights, opened the power of people intellect and called on the people to build a modern society of human nature. The Enlightenment could be regarded as an ideological mobilization and public opinion preparation of the French Revolution.

3.1.6 Bourgeois Revolutions

The war Hollands seeking independence from the Spain during 1566–1609 was the first Bourgeois Revolution in modern history.

In 1640, the British revolution broke out. Then a bourgeois regime of constitutional monarchy was established (known as the “Glorious Revolution”) in 1688.

The revolution happened in France in 1789. This revolution publicized the spirit of freedom, equality and fraternity. Napoleon’s troops trampled Europe, also spread the revolution spirit throughout Europe.

The English Revolution abolished the feudal system. Primary accumulation of capital provided financial base to the development of industry. The breaking-down of the traditional economy which was based on family owned small farms provided sufficient labor force and domestic market to the industry. In addition, long-term development of handicraft workshops prepared basic technical conditions for the emergence of large machine production. Thus, improving of technological level became the key for capitalist economic development. This was the social background of the 1st Industrial Revolution which began in Britain in the 1760s.

3.2 Mechanical Science and Technology Before the Industrial Revolution

Isaac Newton founded the classical mechanics in 1687. Before Newton, several astronomers and scientists already did some groundwork for classical mechanics. Their contributions are presented in Sect. 3.3 along with the contributions of Newton.

In this section, the development of mechanical science and technology in Europe between the Renaissance and the Industrial Revolution is introduced. It consists of two parts. The first is focused on theoretical researches and inventions represented by Leonardo da Vinci and other scientists. The second part is on progresses in mechanical technology, some of which directly led to some important inventions in the First Industrial Revolution.

3.2.1 Leonardo da Vinci

Leonardo da Vinci (Capra 2007; Scriba et al. 1975) was an outstanding representative figure with the Renaissance spirit, one of "the most brilliant minds of that era" (Fig. 3.2).

Born in 1452 in Vinci, a small town near Florence in Italy, he was a great artist, and an excellent engineer and inventor. As an artist, da Vinci was good at

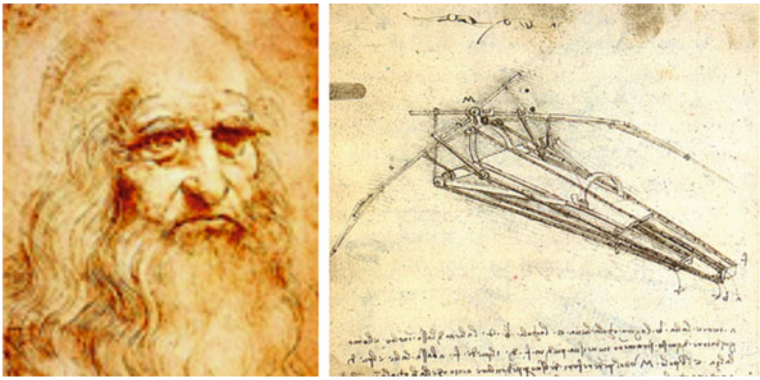

Fig. 3.2 Leonardo da Vinci and his sketch of aircraft

observation. He'd rather describe a phenomenon with great detail than verify theory through experiments. A notebook of tens of thousands of pages densely filled with sketches and notes was his legacy left to the world. He drew conceptual sketches for lathe, boring machine, thread cutting machine, and grinder. In these concepts, many mechanical components such as crank, flywheel and bearing etc., were utilized. He also designed a variety of pumps. In 1490, da Vinci sketched the concept of CVT, which is widely used in automobiles today.

L. da Vinci was a polymath, having "unquenchable curiosity" and "feverishly inventive imagination". Some representative machine concepts he conceived include flying machines, adding machines, robots (Leonardo's mechanical knight) and concentrated solar power etc. His concepts were original and too much ahead of time; thus, most of them, except for a few, were not practical to be built at that time.

Serving as a military engineer, he also completed several designs of military machines, including machine guns, tanks, shrapnel, parachute, submarine etc. Da Vinci was also fascinating with flight. He planed several flying machines based on observation on birds, including a flapping ornithopter and a machine with a helical rotor. In 1496, he constructed one, but ended up with failure in the experiment.

Due to the language barrier, da Vinci's achievements in engineering did not catch much attention from scholars in Europe at that time. To the 20th century, many of his inventions were made into models, and exhibited in the L. da Vinci Museum at Florence, thanks to the sponsorship of the International Business Machines Co. (IBM).

3.2.2 Progresses of Machine Theory Before Industrial Revolution

3.2.2.1 Improvement of Theory on Simple Machines

Greeks summarized the simple machines, but did little theoretical analysis. During the Renaissance, people began to look at how much useful work simple machines could accomplish. This eventually led to a new concept, the mechanical work. In 1586, Simon Stevin, a scientist in the Netherlands, derived the expression of the mechanical gain of an inclined plane. However, the complete mechanical theory of the simple machines was worked out by Galileo Galilei, an Italian scientist, in 1600. This was stated in his book *On Mechanics*. Galileo Galilei was the first to understand that simple machines do not create energy, only transform it (Krebs 2004).

3.2.2.2 Progresses of Mechanics Related to Machines

On the basis of experiments, G. Galilei put forward firstly in 1638 a formula for the strength of beam, marking the beginning of mechanics of materials. In 1678, Robert

Hooke, a British scholar, proposed the well-known Hooke's law, indicating that the elastic deformation was proportional to the applied force. This was the bud of elastic mechanics (Timoshenko 1953).

The classic law of sliding friction was first discovered by L. da Vinci, recorded in his notes and unpublished. He also studied the wear problem in a journal bearing. The classical law of friction was rediscovered by a French scientist, Guillaume Amontons, in 1699 and further developed by C.-A. de Coulomb, also a French physicist, in 1785. Coulomb investigated the influence of main factors on friction, including the nature of the materials in contact and their surface coatings; the extent of the surface area; the normal pressure (or load); and the length of time that the surfaces remained in contact (Dowson 1997). He also introduced the concept of friction coefficient and explained the phenomenon of dry friction by his theory of mechanical engagement. His explanation had been dominating until the early 20th century. A further discussion on friction will be presented in Chap. 13.

3.2.2.3 Early Research on Gear Theory

After the Renaissance, the watch industry developed in Swiss. Though speed of watch gears is very low, the uniformity on wear and motion of the hands is required. On the other hand, in order to reduce the size, metal gears were developed. Cycloidal profile was first used in clocks at the beginning of the 17th century. Wear of gears was a critical problem for clocks and windmills at that time, engineers in the Renaissance period was not able to solve this problem due to inadequate geometric knowledge. In the 18th century, several mathematicians explored new tooth profiles.

In 1733, C.-É.-L. Camus, a French mathematician, first proposed the famous theorem of gear meshing, well known as the Camus Theorem. In 1765, L. Euler studied the instantaneous transmission ratio of gearing and first presented the involute tooth profile (Singer et al. 1957, 345).

The increase of machine speed required high performance gears. The involute profile guarantees a constant instantaneous transmission ratio, greatly improving the performance of mechanical transmission. Today, the involute is still the most common profile used in gears.

3.2.3 Mechanical Technology Before the Industrial Revolution

During the late Middle Ages, manual workshops appeared in Europe, and mechanical technology was recovering slowly. The birth of the most representative technologies of the first Industrial Revolution, such as the spinning Jenny, the steam engine and the machine building industry, was closely linked to the development of textile, mining, and watchmaking industry during the several centuries before. This is the production background of the first industrial revolution.

Early in the 15th and 16th century, the patent system was established in Italy, France and England. The Britain patent system was regarded as the first in the world that recognized intellectual property in order to stimulate invention. This was the crucial legal foundation upon which the Industrial Revolution could emerge and flourish (MacLeod 1989).

3.2.3.1 Clocks, Watches and Watch Making Industry

After the High Middle Ages, a landmark in the mechanical technology was the invention of clocks and watches, and the rising of their manufacturing industry.

Clocks were developed from the early astronomical timers. The verge escapement is the heart of a clock, which differentiates a clock from timers.

The escapement was firstly used in the astronomical clock tower by Su Song, a Chinese inventor, in the 11th century. Needham (1987), a British scientist, pointed out that it may be a direct ancestor of medieval European astronomical clocks. Al-Jazari, the Islamic scholar in the 12th century, also designed a variety of clocks.

Astrarium, the earliest astronomical clock in Europe, was made by an Italian, Giovanni de’ Dondi (Singer et al. 1957, 654). Dondi was known as the father of the European clock. In 1350, he created the first simple mechanical tower clock (Fig. 3.3) which had only a hour hand. The daily error of this clock was 15–30 min. He built another clock with more functions in 1364.

At that time, clocks were driven by the weight of an object, and equipped with the verge escapement.

Peter Henlein, a German clock maker, used a mainspring the first time to replace the weight-driven mechanism in 1500–1510 (Milham 1946), making it possible to significantly downsize the clocks. In the 16th century, table clocks appeared in Germany.

In 1582, G. Galilei, at the age of 18, discovered the isochronism of pendulum. In 1658, Christiaan Huygens, the Dutch scientist, invented the pendulum clock based on Galilei’s discovery (Singer et al. 1957, 654). Huygens’ clock reached an accuracy with an error of less than 5 min per day, far more accurate than any other clocks of that time.

After the invention of pendulum clock, effort to improve accuracy was focused on the escapement mechanisms. During the two centuries following, about 300 kinds of escapements were invented, marking the golden age of clock and watch making industry. Among them only about 10 found real application (Milham 1946). These constituted the foundation for the development of more accurate clocks.

In 1675, C. Huygens and R. Hooke invented the spiral balance, or the hairspring, for the purpose to control the oscillating speed of the balance wheel, laying the foundation of more accurate pocket watches. Watches appeared in France and Germany as early as at the beginning of the 16th century. The most famous was the

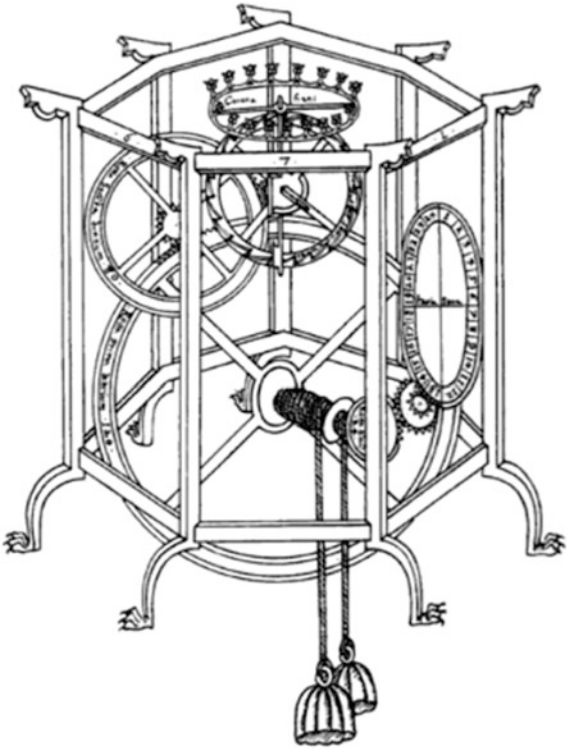

Fig. 3.3 A part of the Astrarium by Dondi

German "Nuremberg egg", which was the initial form of pocket watches (Fig. 3.4). The 18th century was the golden period of pocket watches. In 1704 jewel bearings were invented. In about 1760, the French Jean-Antoine Lépine devised a new watch-movement, known as the "Lépine movement", making thinner pocket watches possible (Bu 2018).

Fig. 3.4 Nuremberg egg (https://commons.wikimedia.org/wiki)

John Harrison, a self-educated English clockmaker, invented the marine chronometer during the 1720s to 1760s, a long-sought after device for solving the problem of calculating longitude while at sea. His solution revolutionized navigation and greatly increased the safety of long-distance sea travel (Carter and Carter 2012).

The European clock and watch industry first developed in Italy at the beginning of 16th century, and later spread to France, Germany and Switzerland. By the 18th century, watchmaking became the pillar industry in Swiss. Swiss watches feature accurate timing, precision manufacturing, beautiful shape, being a symbol of the noble value and pride of the Swiss industry.

The watchmaking industry was a prelude to the European modern machine building industry. First, to meet the needs of manufacture watch parts, human powered machine tools were developed for machining screws and gears. Second and more importantly, the watchmaking industry prepared technicians and craftsmen for the machine industry. For example, J. Watt, R. Arkwright, the inventor of steam engine, the inventor of textile machine, and R. Fulton, the inventor of steamboat, were all apprentices in watchmaking in their youth.

The first wristwatch of the world was made in 1810. To the end of the 19th century, wristwatch had been on the product lines of most watch manufacturers.

3.2.3.2 Early Steam Engines

The invention of the steam engine was initially for the needs of deep mining.

Mining industry in the Middle Ages developed dramatically (Friedel 2007). In the 14th century, demand for weapons and armors was greatly increased. Medieval knights often wore armors of about 100 lb, and were equipped with swords, spears and other weapons. At that time, gun and artillery already started development. Military obviously had strong demand for iron. Iron was also used as a building material. In the Medieval, the mining industry initially focused on iron and copper, and later extended to lead, tin and zinc. Precious metals were mainly used to make jewelry and coins. Although paper currency was already in use, gold and silver were still in high demand as a form of currency. These developments pushed the mining industry ahead, which further demanded for more fuel. It was reported that the forest in Britain was once cut much faster than its growth. As a result, coal mining grew dramatically to meet the increased fuel demand.

In the Middle Ages, drainage of water was the primary challenge to the mining industry. At first, open-pit mining was the main form which does not have the water problem. After the resources of surface mining became rare, underground mining became an option and the depth of mines went deeper and deeper. In underground mining, effective draining of water became a real barrier. In 1465, a silver crisis occurred in Europe. The reason of this crisis was that the draining technology then did not meet the requirement to mining operation, and significantly affected the silver production. Although pumps at that time were all driven by animals, every

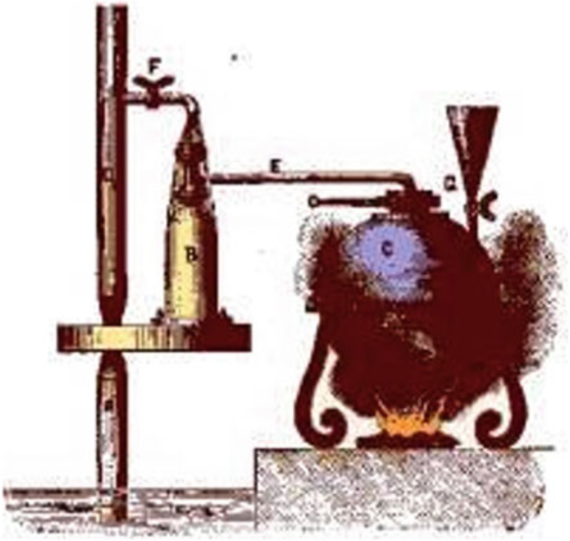

Fig. 3.5 Steam pump by T. Savery

progress in the pump technology was transformed to improvement in mining efficiency.

Since 1690, 100 years before Watt's success, several inventors had made contribution for creation of steam engine (Singer et al. 1958; Hills 1989).

In 1690, Denis Papin, a French physicist, made the first experimental steam engine, in Germany. This engine had a piston and a cylinder. In 1698, Thomas Savery, a British mining engineer, patented a steam pump, the Miner's Friend. This was a manually operated simple device, which was able to discharge water out of a pipe using steam pressure (Fig. 3.5). The steam pump was put in commercial production around the end of 18th century.

On the basis of the inventions of Papin and Savery, Thomas Newcomen, a British blacksmith, invented the atmospheric engine, or the Newcomen engine (Fig. 3.6). The Newcomen engine was applied in mine drainage and farming irrigation in 1712. The engine was later in common use in Britain, Germany and France.

Both the Newcomen engine and Savery's Miner's Friend had very low efficiency, consuming large amount of coal. In addition, the output was a reciprocating linear motion. However, their work laid the foundation for Watt's improvements.

3.2.3.3 Materials for Machines

Prior to the invention of the steam engines, wood had been the main material of engineering structures for a long term. Metals (mainly copper and iron) were used only for instruments, locks, clocks, pumps and small hardware in the wood structures.

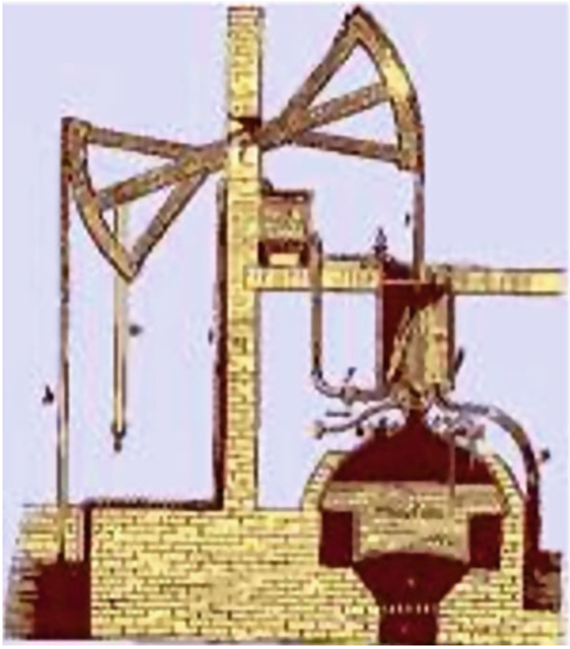

Fig. 3.6 Newcomen's steam engine

After the 16th century, Europe began to cast cannons with pig iron, thus, technology of smelting of iron in blast furnace was developed. In 1709, Abraham Darby I, a British man, developed a method of producing pig iron in a blast furnace fueled by coke rather than charcoal (Weissenbacher 2009, 194). This was a major step forward in the production of iron, which was the most important raw material of the Industrial Revolution. The cast iron obtained in this method was then made into wrought iron through decarburization in a refining furnace. The machines in the iron industry then were driven by hydraulic power; therefore, all blast furnaces were built along fast flowing rivers (Jiang 2010).

With the development of iron melting, pig iron replaced wood, becoming the main material for machine parts.

In 1740, Benjamin Huntsman, an English engineer, invented the crucible process for steel-making. However, the output of this method was very low (Singer et al. 1957). In the second half of the 18th century, the puddling process was invented and gradually matured, in which malleable steel was obtained with blowing the flame in the furnace. This method had been in use until the mid-19th century, and was replaced by more advanced methods later.

Between the end of 17th and mid-18th centuries, the technology of rolling steels became almost mature.

3.2.3.4 State of Machining

Although lathes driven by human or animals were already in use as early as BC in Egypt and many places in Europe, the progress in machine tools and cutting tools before the Middle Ages had been very slow. A few types of machine tools, including lathes, were devised; however, they were all made from wood and for making wood parts.

The lathes before the time of Watt were all operated in such a way that the operator spun the work by foot pedals, and at the same time hold the cutting tool by hand. The accuracy of the machining was mainly dependent on the operator's skill. When machining metal parts, it was hard to achieve high accuracy.

To the late Middle Ages, real machine tools in modern sense appeared. This was probably driven by the need of more accurate machining from the watch-making industry. These machines were different from their predecessors in two ways: (1) they were made for machining metals, not wood, (2) the cutting tools were moved and guided by mechanisms, not the operator's hands. To the 18th century, the main structure of lathes gradually changed from wood to metal.

The first lathe completely made from metal was built in 1751 by Jacques de Vaucanson, a French inventor (Singer et al. 1958). Many components in a lathe, such as the lead screw and cross slid, had existed for many years; thus, this machine was not a completely new invention. Some parts in it were from very old concepts, and experienced continuous evolution. A few of inventors in the Middle Ages, whose name might not be documented, also made obvious contribution to the lathe concept. L. da Vinci made drawings of a screw lathe in his notebook. It is not clear if da Vinci's design was built or not; however, one fact is certain that screw-making machines already appeared in France in the 16th century.

3.2.3.5 Textile Machines

The British textile industry used to be wool focused. Because cotton products were cheaper than wool, the East India Company in India started in the second half of 17th century to produce finished cotton goods in large quantity for the UK domestic market aiming to replace the wool and linen products. This hurt the interest of the local textile business, and led to petitions of local weavers, spinners, dyers, shepherds and farmers etc., requiring the government for a ban on the importation and sale of woven cotton goods. In 1700, the British Parliament issued a decree banning import of foreign cotton. Thus, the cotton textile industry in Britain developed dramatically and became the most important industrial sector of the country (Jiang 1988, 422–423).

The increasing market demand required to grow production greatly. The cotton textile, as a burgeoning new industry, did not have stereotypes and obstacles, leaving more room for technological innovation and competition.

The pedal spinning and hand loom used at that time were handed down from the Middle Age; few improvements had been made ever since.

Fig. 3.7 Shuttle https://en.wikipedia.org/wiki/JohnKay(flying_shuttle)

In 1733, John Kay, a British watchmaker, invented the flying shuttle (Fig. 3.7), greatly improving the efficiency of hand looms (Singer et al. 1957). By 1760s, shuttle looms were widely applied. Due to the dramatic increase of efficiency, the yarn needed by a weaver had to be provided by 10 spinners. This situation, in turn, triggered the birth of spinning Jenny, which greatly improved the efficiency of spinning and became the symbol of beginning of the First Industrial Revolution.

At that time, hydraulic power was predominant for the cotton textile machines. Therefore, the location of plants must be limited to areas near rivers as was the coal mining industry. This location limitation restricted the further development of the cotton textile industry, calling for new types of power.

3.2.3.6 Printing and Printing Machines

The printing technology was originated in China. Bi Sheng, a Chinese inventor, invented the movable type printing in the 11th century, being a tremendous progress in the history of printing. This technology spred to Europe after the 13th century. European, however, invented the printing machine, making many important improvements on the Chinese technology.

The demand for printed matters grew fast during the Renaissance. Then the techniques of paper making were already popular in Europe. In 1434, Johannes Gutenberg, a German jewelry artisan, began to study the movable type printing. He invented a lead-tin-antimony alloy as the cast material of characters, and a printing machine which was pressed by a screw and capable of double-sided printing (Steinberg 1974; Jiang 2010).

In 1450, he established a printing house in his hometown, Mainz. In 1455, he printed the famous “Gutenberg Bible”. Due to the high quality and low price, his printing press spred quickly to the whole Europe. In half a century, about 1000 printing factories at 250 places were established in Europe. The printing technology became one of the pillars to support the Renaissance and the religious reform movement. The screw pressed, manual printing machine by Gutenberg was, although simple, kept in use for 300 years (Fig. 3.8).

Fig. 3.8 Printing press by Gutenberg (Wolf 1974)

3.2.3.7 Construction Machines

Technology was fallen into disuse in Western Europe after the demise of the Western Roman Empire. During the High Middle Ages, however, the treadwheel crane was reintroduced on a large scale (Matthies 1992, 510–547). This might be attributed to the construction of many Gothic architectures, especially cathedrals. Figure 3.9 is the local of a painting “The Tower of Babel” in the 16th century, in which a treadwheel crane was shown.

Generally, vertical transport could be done more safely and inexpensively by cranes. Typical areas of application were harbors, mines, and, in particular, building sites. Nevertheless, historical documents, such as archives and pictures, of the time suggested that these machines, like treadwheels or wheelbarrows, did not completely replace the traditional, more labor-intensive methods like ladders, hods and handbarrows. Rather, the old methods and new machines coexisted on the Medieval construction sites and harbors (Matthies 1992, 510–547).

Apart from treadwheels, cranes operated by hands were also used in the Medieval, which had windlasses with radial spokes and cranks. Flywheels are known to be in use as early as in 1123 for smoothing out the operation and getting over the dead-point in the lifting operation (Matthies 1992, 510–547).

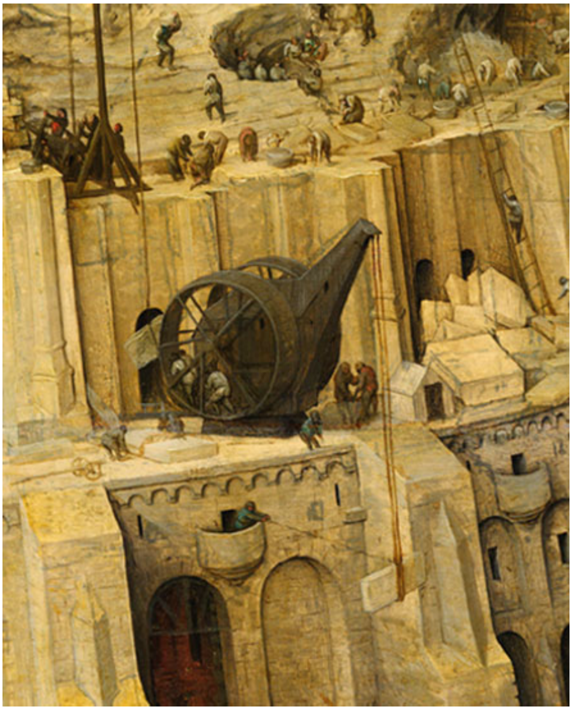

Fig. 3.9 Treadwheel crane in a painting (https://en.wikipedia.org/wiki/Treadwheel_crane)

The reappearance of the treadwheels crane may be related to the development of windlasses. The treadwheels experienced improvements structurally and mechanically inspired by the windlasses (Matthies 1992, 510–547).

Stationary harbor cranes are considered a new progress of the Middle Ages, which was related to the development of navigation. The earliest record of using port cranes was in the second half of the 13th century, mainly in Holland, Belgium and Germany (Matheus 1996, 345–348). Two types of harbor cranes, the gantry crane and the tower crane, were used.

A lifting tower similar to the one that the ancient Romans used was utilized by a Renaissance architect to relocate the Vatican Obelisk in Rome in 1586, which was as heavy as 361 tons. His report clearly indicated that to make the lifting ropes evenly loaded the 40–50 pulling teams (Fig. 3.10) had to work in extremely careful coordination. If the force was not applied evenly, the excessively stressed ropes might rupture (Lancaster 1999, 419–439).

In the 14th century, jib cranes appeared in West Europe (Shen and Zhang 2004), which had a tilted arm with a pulley mounted on the top of arm, and was capable of both lifting and rotating. All the lifting machines before the 18th century, although different in shapes and forms, were powered by humans or animals. The lifting capacity, application range and efficiency were very limited.

Fig. 3.10 Erection of the Vatican Obelisk in 1586 by means of a lifting tower (https://en.wikipedia.org/wiki/List_of_obelisks_in_Rome)

3.2.3.8 Artillery

As early as in 1332, the troops of the Yuan Dynasty of China, were equipped with the world's earliest cannons. In 1378, cast bronze cannons appeared in Germany.

A major change occurred in the 1420s, when artillery became powerful enough to make real attack on strongholds and fortresses. The power of cannons was tripled through making the canon longer and improving the gunpowder. In 1453, the walls of the Constantinople with a thickness of 4.7 m were destroyed by the stones launched by siege cannons. These cannons reached 5.18 m in length and 63.5 cm in bore diameter, being a landmark in the history of cannons (McNab 2011).

As the cannon was very heavy at that time, it was difficult to relocate during combat. This greatly limited its role in the battlefield. During the Thirty Years' War, movable field artillery appeared in Europe. The initiator was the Swedish commander Gustavus Adolphus. Under his influence, more troops began to use lighter and more maneuverable artillery (Dastrup 1994).

In the 14th or 15th century, Europeans developed mortars (Ágoston 2005), which fired explosive projectiles known as bombs at low velocities, short ranges, and high-arcing ballistic trajectories (Fig. 3.11). During the Hussite War (1419–1434), howitzers, which had a longer barrel and larger ratio of length to bore diameter, appeared (Turnbull 2004). The modern howitzer was invented by the Swedish around the end of the 17th century.

A cartridge which combined the shot and powder into a single unit occurred during the 1620s in Europe, and was quickly adopted by many nations. It made quicker loading and was safer. In fact, bombs with cast iron shell filled with gunpowder was already used in China as early as in the 13th century in the war between Song Dynasty and Jin Kingdom (Li 2013). But the bombs were launched by stone throwers.

Fig. 3.11 Mortar in 1500

3.2.3.9 Water Power and Pumps

During the 12th and 13th centuries, water mills were transformed into turbines (not the modern turbines yet) to supply power in mining, crushing and smelting operations. To meet the demand in city water supply and mine drainage, water pumps experienced great development during this period. Rotary and centrifugal pumps emerged in 1588 and 1689, respectively. Water became the main source of power for industry. This situation remained until the end of the 18th century when steam power appeared.

At the end of 16th century, rudiments of gear pumps appeared in France. In 1636, a double deep toothed rotary gear pump was invented in Germany, and used to supply water to a fountain. Today, gear pumps are widely used in many applications, including in lubricating systems.

3.2.3.10 Information Machines

In 1642, Blaise Pascal, a French mathematician and physicist, invented a mechanical calculator. Later, Gottfried von Leibniz, a German mathematician, worked on adding automatic multiplication and division to Pascal's machine, and invented the pinwheel calculator. He also refined the binary number system, which is the foundation of all modern digit computers (Smith 1929).

3.3 Establishment and Development of Classical Mechanics

The Renaissance, as an ideological liberation movement, created a favorable cultural atmosphere for the birth of modern natural science. In the 16th and 17th centuries, the First Scientific Revolution in modern history of the world took place. Starting from the heliocentric theory of Copernicus, a modern science system began to be formed, which was completely different from the medieval theology and the experiential philosophy. The main contents of the Scientific Revolution included astronomy, mathematics, anatomy and classical mechanics (Wu 2000). In this section only the establishment of Newton's classical mechanics is presented.

3.3.1 Breakthrough in Astronomy and Liberation of Scientific Spirit

To meet the need of maritime transport after the great discovery of geography, astronomy developed up, becoming the first breakthrough of modern science, and the background of the establishment of classical mechanics.

Representatives of the astronomers at that time include the Polish Nicolaus Copernicus and the German Johannes Kepler (Figs. 3.12 and 3.13).

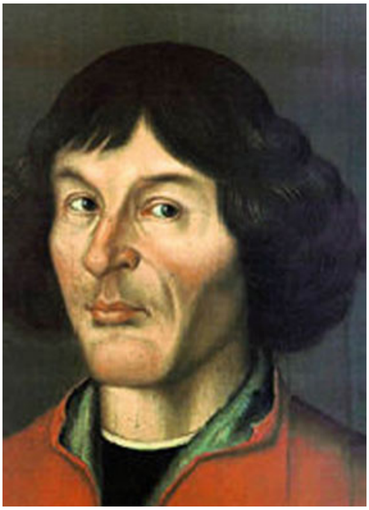

Fig. 3.12 N. Copernicus

Fig. 3.13 J. Kepler

N. Copernicus was a priest in a Polish church. He devoted himself to compose his famous work *On the Revolutions of the Heavenly Spheres*. Realizing that his doctrine was completely opposite to the Catholic Church, he chose to publish his work in 1543, shortly before he died. Copernicus's theory marked a fact that science was getting rid of the shackles of Theology.

J. Kepler served as a royal astronomer in Austria. After long time of observing and studying the Mars movement, he summarized the "three laws of motion of planets" which was published in 1619.

Although the Renaissance created the social precondition for liberation of natural science from theology, this liberation was far from achieved yet. The heliocentric theory caused a great panic to the Catholic Church. In 1600, an Italian scientist, Giordano Bruno, was burned to death in Rome under the accusation of advocating the heliocentrism. G. Galilei defended the heliocentrism through astronomical observation, extending the influence of the heliocentrism. He was tried by the Roman Inquisition, being accused of "vehemently suspect of heresy".

The Heliocentric theory, after breaking the ice of the Geocentrism, was widely accepted. A social atmosphere for the development of modern science was formed. Beginning from the early 17th century, academic institutions were established in Italy, Britain and France successively, which broke through the ideological confinement of Church and conducted scientific discussion and communication freely. A golden age of scientific research and discovery was coming.

3.3.2 Theoretical Background

Before the creation of classical mechanics, astronomy, mechanics and mathematics had experienced great progress already, laying a foundation for Newton' mechanics.

Although there were preliminary studies on mechanics early in ancient Greece, they were scattered in different areas and far from systematic. Mechanics, as a subject of science, did not come into being until the Renaissance.

G. Galilei (Fig. 3.14), the Italian scientist, considered the priesthood at young age, enrolled in medical school for some reason, but ended up as a polymath in science. He was a mathematician, astronomer, physicist, and engineer, making many groundbreaking contributions in science. To name a few, he was the first to put forward the concepts of velocity and acceleration with clarity; he drew the conclusion that the motion of a freely falling body was with a uniform acceleration; he presented the principle of inertia and the projectile motion for the first time in history, and found the isochronism of a pendulum. In fact, the motion of free falling body and the projectile motion are two special cases of Newton's second law, namely the uniformly accelerative motion under the constant gravitation. Also, he was the first person in the world to observe stars with a telescope. Galilei was both a theoretical master and a practical observer. He was known as the father of modern science for his many contributions.

It became a fashion, after G. Galilei, to explore motion of bodies. The activities focused on the celestial motion, simple pendulum motion and impact problems. These became later the main contents of "particle kinematics". Compared with vehicles, machines and other constrained systems, the motion of a particle is much simpler.

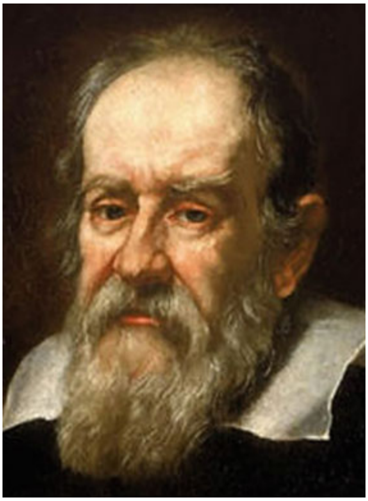

Fig. 3.14 G. Galilei

Fig. 3.15 R. Descartes

Fig. 3.16 C. Huygens

In the early 17th century, J. Kepler introduced the theorem of angular momentum when studying the Mars movement.

During the period of 1637–1638, Rene Descartes (Fig. 3.15), a French scientist, proposed the Cartesian coordinate system and created the analytical geometry. He introduced the concept of variables and opened the field of variables mathematics. F. Engels evaluated Descartes's contributions highly as: "*Descartes's variable* *quantity was a turning point in mathematics. It brought motion and, thereby, dialectics into mathematics. As a result, differential and integral calculus quickly became necessary...*" (F. Engels: *Dialectics of Nature*).

In 1668, the British Royal Society posed the collision problem of bodies. Christian Huygens and two other scientists got similar solutions which were all correct and formed the early expression of the law of momentum conservation (Fig. 3.16).

Besides the impact problem, C. Huygens also studied the pendulum motion and invented the pendulum clock. In studying circular motion, he introduced the concept of centripetal force, and correctly expressed the centripetal acceleration in terms of velocity and radius of the circle. This result came very close to the law of universal gravitation.

In 1686, A German scientist Gottfried Leibniz proposed the kinetic energy law. To this point all the three laws of conservation, which are the foundation of the classical mechanics, were formed with initial shapes.

The research results in the fields of astronomy, mathematics and mechanics by a series of scientists, from Copernicus to Leibniz, made well preparation in theory for I. Newton to create the classical mechanics.

3.3.3 Establishment of Classical Mechanics

I. Newton was born in a peasant family. During his college years he already mastered the mathematics and optics knowledge most up-to-date of that time. At the age of 30 he was elected as a fellow of the Royal Society, which was then the Britain's highest scientific honor. His achievement in optics was the discovery of the seven colors forming sunlight and the proposal that light, in essence, is made up of particles like any ordinary matters. In mathematics he discovered the binomial theorem and created the calculus.

Newton's greatest achievement was his work *Philosophiae Naturalis Principia Mathematica* published in 1687. In this work he stated the three universal laws of motion, laying the foundation for classical mechanics (Fig. 3.17).

The creation of classical mechanics opened a new era of scientific development, and laid the foundation of mechanics, mechanical engineering, civil engineering and many other applied sciences. Today, all the theories of kinematic and dynamic analysis of mechanical systems are derived from Newtonian mechanics.

During the two hundred years after Newton, classical mechanics was continuously developing along two lines. One was the study on problems with finite degree of freedom and general principles of mechanics. The other was research on continuum mechanics, including solid mechanics and fluid mechanics.

Fig. 3.17 I. Newton

In 1743, Jean D'alembert, a famous French mathematician and dynamicist, did research on the motion of constrained bodies the first time in history. He divided the forces applied on a system into external forces and internal forces between particles. Further he combined the equilibrium in statics and the Newton's second law by taking the inertia forces into the static equilibrium. This was the well-known D'alembert principle, which elegantly integrated dynamics and statics into a unified model and became an important modeling method still in use today in machine dynamics (Fig. 3.18).

Leonhard Euler, a Swiss scientist, became an academician of the Petersburg Academy of Sciences at the age of 26. Being a scientific generalist, he made contributions in many areas, and dozens of, or even more, achievements were named after him. In 1760, he introduced the "Euler angle" to describe a rigid body rotation. In 1765, he put forward the concept of inertia moment for deriving of the dynamic equation of rotation of a rigid body around a fixed point. Then he extended the Newton's second law from particles to rigid bodies, laying the foundation for rigid body dynamics (Fig. 3.19).

3.3.4 Limitations of Classical Mechanics

3.3.4.1 Scope of Application of Classical Mechanics

In the classical mechanics, two basic assumptions are taken for granted. First, the time and space are assumed to be absolute, and the measurements of length and time intervals are independent of the observer's movement. Second, all the

Fig. 3.18 J. D'alembert

Fig. 3.19 L. Euler

observable physical quantities, in principle, can be measured with infinite precision. Later development of physics since the 20th century has revealed the limitations of classical mechanics. The first assumption is suitable only if the motions are at a speed far below the speed of light. The second assumption is only applicable to macroscopic objects. In micro systems, all physical quantities, in principle, may not be determined simultaneously and accurately. Therefore, the classical mechanics is just an approximate description of low speed motion for macroscopic objects.

By the end of the 19th century, it came out that the classical mechanics could not explain some important scientific problems. This triggered the so-called "physics crisis", leading to a new revolution in physics represented by the emergence of the theory of relativity and quantum theory.

All the machines humans have built so far have a speed well below the light speed; thus, the classical mechanics is applicable in dealing with these mechanical problems.

3.3.4.2 Limitations of Mechanical Determinism

Adapting to modern natural sciences represented by Newtonian mechanics, mechanical materialism became the prevalent natural view in the 16th–18th centuries. Although great achievements were made in mechanics, other science branches had not yet been developed. People tended to explain all natural phenomena using the mechanics principle. The concepts in mechanics were extended then to every field, such as electromagnetics, chemistry and biology. F. Engels (1820–1895) called this as "*the craze to reduce everything to mechanical motion*" (*Dialectics of Nature* 1883). The complex and advanced motions were interpreted by the simple mechanical motion behind which external forces were considered the reason. This opposed to the fact that the core reason of motion for any system was from internal, rather than external,resulting in the mechanical determinism, which exaggerated the inevitability and negated contingency. One of the most representative figures of the mechanical determinism, a French mathematician Pierre-Simon Laplace, put it as: "*We may regard the present state of the universe as the effect of its past and the cause of its future. An intellect which at a certain moment would know all forces that set nature in motion, and all positions of all items of which nature is composed, if this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movements of the greatest bodies of the universe and those of the tiniest atom; for such an intellect nothing would be uncertain and the future just like the past would be present before its eyes*" (*A Philosophical Essay on Probabilities* 1814).

Beginning from the second half of 18th century, a series of achievements in the field of astronomy, biology and chemistry broke the metaphysical view of nature, one after another, and provided an important scientific basis for the establishment of dialectical materialist view of nature.

3.4 Calculus and Differential Equations

To discuss the modern history of mechanical engineering, it needs to go back to the establishment of classical mechanics. In addition, to understand the mathematical theories and methods being used today in the mechanical science, it is necessary as well to trace back the development of related mathematical theories. When the

Newtonian mechanics was established mathematical theories were also in blossom. More precisely, the theory of mechanics has always gone hand in hand with mathematics. In this section, the calculus and differential equation theories, which are regarded as great achievements of mathematics in Newton's era, are introduced (Boyer and Merzbach 2011; Katz 1998). More advanced mathematics theories commonly used in mechanical engineering, including the variation method, probability theory, linear algebra and graph theory, are left to Chap. 6.

3.4.1 Establishment of Calculus

Beginning from the second half of the 16th century, mechanics was playing a more and more important role in science. Driven by the needs from mechanics, many mathematical problems were put forward. Among the many problems the most urgent were as follows, which ultimately led to the creation of calculus theory.

(1) Given a distance as a function of time, to calculate the velocity and the acceleration. Or the other way around to calculate the distance and speed with a given acceleration as function of time.
(2) To obtain the tangent of a curve at a point for the need to determine the instant moving direction of an object along its orbit.
(3) To calculate the length of a curve and the area under a curve for the need from the study of planet motion. To compute the volume of a solid of arbitrary shape in order to determine the gravity center of bodies.
(4) To find the extreme value of a function for the need of mechanics and other physical subjects.

In the century before Newton, many mathematicians had done active research on the above problems. Three problems calling for urgent solutions were: (1) clarifying the concepts, especially the establishment of the concept of the rate of change, (2) summarizing and generalizing the methods for finding the tangent, extremum, area and volume; (3) changing the geometric presentation for tangent and velocity into analytical forms for the purpose of general application (Boyer and Merzbach 2011).

I. Newton and G. Leibniz developed the calculus theory independently about the same time, giving solutions to the above three problems.

3.4.2 Theory of Differential Equation

The mathematical model for static analysis is a set of linear algebraic equations. While the one for dynamic analysis is a set of differential equations. The problem of differential equations and the concept of integral appeared simultaneously. The theory of calculus was proved a powerful tool in solving physical problems. The first step in solving any problem was to develop the differential equations representing the problem.

During the 1690s, some Swiss mathematicians, including Bernoulli brothers, Jacob Bernoulli and Johann Bernoulli, studied some curves encountered in mechanics, such as isochron, catenary and brachistochrone. As usual, they always derived the differential equations first, and then solved the equation by integration. Their studies became famous examples of early development of differential equations.

After obtaining the differential equation, the next problem is to solve them properly. Initially, attention was focused on the solution of certain types of special equations in view of the difficulty and complexity. To the 1740s, the general method for solving first-order differential equations was proposed by G. Leibniz, and L. Euler.

Research on second-order differential equations was driven by mechanics problems. In 1728, L. Euler transformed a kind of second-order equations into first-order ones using variable substitution. This work had an important implication, marking the start of research on second-order differential equations. It is still playing a fundamental role presently in numerical solution of second-order differential equations and in the state space theory. Euler proposed the concept of characteristic equation and characteristic roots in the studying of higher-order homogeneous linear differential equations with constant coefficients. Then the problem solving a differential equation set could be transformed into solving an algebraic equation set. The important role of this concept in vibration theory has been widely acknowledged. But the differential equation studied by Euler was of only single argument, thus he did not touch the concept of characteristic vector.

During the period of 1762–1765, J. Lagrange came into contact with homogeneous linear differential equations with variable coefficients in the research on the movement of sun-earth-moon three bodies. He extended the result for equations with constant coefficients obtained by L. Euler to the new equations. In 1877, a periodic solution of linear homogeneous equations with variable coefficients was obtained by an American astronomer George Hill in his study on the motion of the moon. During the period of 1881–1883, a French mathematician, Gaston Floquet, proposed the general theory of differential equations with periodic variable coefficients, which is of great significance on dynamic systems.

Partial differential equations were originated from the vibration of strings. In 1747, J. D'Alembert obtained a partial differential equation in dealing with the shape of a string in vibration, which was later called wave equation. Euler began to study partial differential equations in 1765 from mathematics perspective.

In 1807, Joseph Fourier, a French mathematician, proposed that a periodic function could be expressed as trigonometric series, the famous Fourier series. It came out later that Fourier series not only were a solution method of partial differential equations, but also played an important role in electrical theory and vibration theory. Vibration of linear systems under periodic excitation is solved with this method. Fourier analysis has already become an indispensable tool for signal analysis.

The most important contributions to the study of nonlinear differential equations were made by H. Poincaré and A. Lyapunov (Александр Ляпунов) in the late 19th century (see Sect. 6.2.5).

In 1768, L. Euler proposed the earliest numerical method for solving ordinary differential equations, known as the Euler method. Around 1900, two German mathematicians, Carl Runge and Martin Kutta, proposed the Runge-Kutta method, which greatly improves the precision compared with the Euler method. After some other improvements later, the method has been widely used so far for solving differential equations numerically.

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Chapter 4
First Industrial Revolution

Since steam, machinery, and the making of machines by machinery transformed the older manufacture into modern industry, the productive forces evolved under the guidance of the bourgeoisie developed with a rapidity and in a degree unheard of before.
—Friedrich Engels (German philosopher, social scientist, 1820–1895): *Anti Duhring* (1877)

4.1 A Brief Review

In the second half of the 18th century, a Technical Revolution, characterized with several ground-breaking technological inventions, such as steam power, happened in Britain. The Industrial Revolution happened the same time, which brought wide application of machines to the industry and dramatic changes to the society, transforming the agriculture-based society to an industry-based one. Since then, the world started fast development in all aspects.

4.1.1 Background of English Industrial Revolution

It was not accidental that the First Industrial Revolution first took place in England. England then possessed all the conditions required by the Revolution.

4.1.1.1 Political Background

In 1588, Britain defeated the Spanish Armada and became the global hegemon. Thereafter it began to expand its overseas colonies, reaching a height being called "The Empire on which the sun never sets" (Fig. 4.1). Alongside the territory expansion, its commodities were sold to Europe, Asia, Africa and America; thus, abundant wealth was accumulated.

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Fig. 4.1 The Empire "on which the sun never sets"

In 1640, the English Revolution outbroke, and in 1688 a constitutional monarchy regime was established. Different from the French Revolution one hundred years later, the English Revolution ended up with a compromise between the bourgeoisie and the nobility. As a result, the social order was restored rapidly after the wars, and the society was kept long term stable. The living standard was greatly improved and population grew continuously.

The Revolution abolished the feudal system. Capitalist primitive accumulation and the long-term success of the overseas business provided the necessary capital for the development of industry. Elimination of small-scale peasant economy provided sufficient labor force and a domestic market. Thus, the promotion of technology became the main task for the development of capitalist industry.

These factors constituted the political background of the Industrial Revolution in the 1760s.

4.1.1.2 Production Background

The long-term development of the manual workshop, which was the main form of production before the Industrial Revolution, provided the initial technological conditions for the mechanized large-scale production. Two specific factors in the production of that time became the direct cause of the outbreak of the Industrial Revolution.

(1) Bottleneck in the development of cotton textile industry

The Industrial Revolution started first from the Britain's cotton textile industry. Due to the relatively lower price, the market demand for cotton textiles was very large. However, the home-based production manner and labor-based technology in the 17th–18th century were not efficient enough to meet the huge market demand. The cotton textile industry, as a young industry then, was free of old traditions of guilds, being easier to adopt innovative technologies and competition. Thus, this industry urgently needed technical innovation.

In 1733, John Kay invented the flying shuttle which greatly improved the efficiency of the loom (Singer et al. 1957). In the 1760s the shuttle loom got widespread applications, leaving the low efficiency of spinning a problem to be solved.

(2) Mining in need of the new power

Dewatering in mines in the 17th century was the impetus behind the development of steam engines. Steam engines were invented by T. Savery and T. Newcomen (see Sect. 3.2.3), and initially a lot of technical flaws existed in the new invention.

4.1.1.3 Scientific Background

After the second half of the 17th century, Britain became the leader of science and technology in Europe. Classical mechanics not only affected the development of science, but also provided a theoretical guidance for the Technical Revolution. In 1654, Otto von Guericke, a German scientist, proved the existence of vacuum and atmospheric pressure through a famous experiment in which 16 horses, 8 on each side, could not separate two 20-in. diameter hemispheres which was vacuumed in advance and tighten up by the outside atmosphere (Singer et al. 1958b) (Fig. 4.2). In 1662 and 1679 respectively, a Irish scientist, Robert Boyle, and a French physicist, Edme Mariotte, independently found the so-called Boyle-Mariotte law for ideal gas. According to this law, if a certain amount of gas is closed in a container of certain volume and heated, the pressure will rise. If the gas is then released, it can drive a machine (West 2005). These scientific findings paved the way technically for the birth of steam engine. Boyle's law also greatly influenced the French inventor D. Papin who invented the steam digester, the forerunner of the steam engine (Singer et al. 1958b; McConnell 2004).

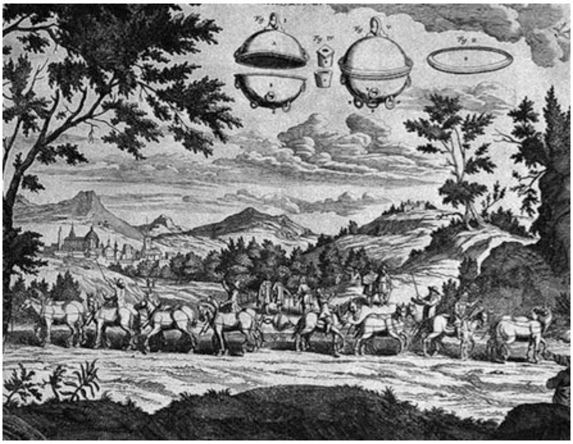


Fig. 4.2 Guericke's experiment

During the First Industrial Revolution, Britain's higher engineering education was not yet established, and science and technology were not yet tightly combined either. Contributors in machine inventions, such as J. Watt, were all craftsmen and/or experimentalists who accumulated rich experiences in practice. However, we should not underestimate the role of science. On the one hand, these craftsmen were already learning scientific knowledge apart from their practical experience. More importantly, thanks to the popularization of education after the Scientific Revolution, the workers in the period of Industrial Revolution were much better equipped with scientific knowledge than the medieval artisans in workshop handicraft industry period.

4.1.2 Introduction to First Industrial Revolution

In 1761, the Royal Society put forward premiums of £50 and £25 for "the invention of a machine that will spin 6 threads of wool, flax, hemp, or cotton at one time and that will require but one person to work and attend it (Smelser 2013)." Three years later in 1764, James Hargreaves, a weaver, invented the Spinning Jenny, which increased productivity by dozens of times although still with a manual operation (Rübberdt 1972; 中山秀太郎 1987) (Fig. 4.3). Thereafter, improvements on spinning machines and weaving machines were alternated, pushing the Britain's textile industry to the world's largest sector of light industry.

The textile industry set up an example for other industries, causing a wave of invention and application of machines in the metallurgy, coal mining and other industrial sectors. Thus the invention of Spinning Jenny is generally considered as a symbol of the starting of English Industrial Revolution.

Fig. 4.3 Spinning Jenny (https://www.thinglink.com)

With the wide application of various machines, power became the bottleneck to the further development of machine production. This led to the invention and improvement of the steam engine.

Steam power replaced humans, hydraulic and animals, leading to a series of consequences. Powerful machines replaced manual tools and primitive simple machines. Home-based scattered workshops were concentrated to factories. Power, machine and factory are the three key words of the First Industrial Revolution (Singer et al. 1958b).

The First Industrial Revolution started first in the UK, and then spread to France, the United States, Germany and some other countries. In terms of time, it covered the period from about 1760 to somewhere between 1820 and 1840. This chapter extended the period to the start of the Second Industrial Revolution in about the 1860s.

4.2 Steam Engine and Transportation Revolution

4.2.1 Long Process of the Invention

The invention of steam engine was a long process (Hills 1989; Singer et al. 1958b; Rübberdt 1972). The development before James Watt was introduced already in Chap. 3. Watt made a series of improvements on the basis of the engine of T. Newcomen.

The working cycle of Newcomen's engine is as follows (Fig. 4.4):

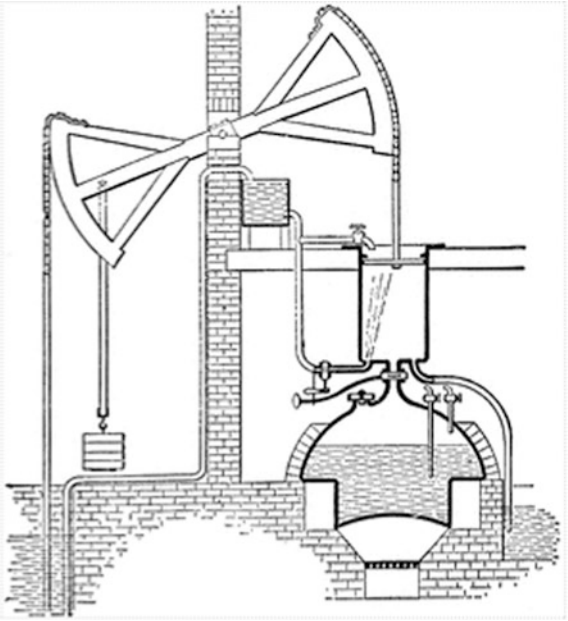
(1) the pump rod drops and the piston in the cylinder lifts,
(2) the steam valve opens and the cylinder beneath piston is filled with steam,
(3) the piston reaches the top, steam supply is cut off,
(4) the water output valve closes and the input valve opens, cold water is sprayed into the cylinder,
(5) the steam is condensed and the pressure within the cylinder is quickly reduced, the piston moves downwards under the atmospheric pressure, so the pump on the left side moves upward and the water is lifted.

The Newcomen's engine was of low efficiency, consuming large amount of coal. Also its output motion was limited to straight reciprocation only.

4.2.2 Watt's Contributions

James Watt was born in Scotland and worked once as an apprentice (Fig. 4.5). His father was a carpenter and shipwright. In his childhood, Watt exhibited great interest and skills in geometry, metalworking, woodworking and model making.

Fig. 4.4 Newcomen atmospheric steam engine (http://etc.usf.edu)



When working in a laboratory of the University of Glasgow, he got in contact with the Newcomen's steam engine and became interested in this machine. After 1759, Watt made a series of tests to improve the steam engine (Hills 1989).

The main Improvements Watt made are as below.

Fig. 4.5 J. Watt

4.2.2.1 Separated Condenser

In the Newcomen's engine, the steam entering into the cylinder heats up the cylinder and then cold water is injected into the cylinder to reduce the temperature. This repetitive heating and cooling wastes considerable amount of energy; thus, the machine was of very low efficiency. To overcome this shortcoming, Watt added a separated condenser outside the cylinder. Thus, the cylinder could always maintain a high temperature and the efficiency was significantly improved. A prototype of this improvement was made in 1769.

4.2.2.2 Rotation Output

Watt also noted that Newcomen's engine could only output straight reciprocating motion which, he thought, was a critical limitation to the machine. Then he tried to convert the linear motion into rotation with a slider-crank mechanism; however, this mechanism had already been patented by someone else. Watt, alternatively, turned to a planetary gear mechanism to realize the motion conversion. A steam engine with rotation output and larger power was eventually made in 1782. After the patent right of the slider-crank mechanism expired in 1794, Watt replaced the planetary gear train with the relatively simpler slider-crank mechanism.

4.2.2.3 The Double Action Cylinder

As shown in Fig. 4.3, Newcomen's machine could only work in one direction because the steam enters the cylinder in only one end. If the steam can enter and discharge from the cylinder at both ends, work can be done by the steam in both upward and downward strokes of the piston. Thus, the efficiency could be improved. In 1782, Watt changed the single action cylinder into a double action one, and replaced the low-pressure steam with high-pressure steam. This was Watt's third leap in improving the steam engine.

4.2.2.4 The Flywheel

As can be seen, the force applied on the piston by the steam is periodically changed, resulting in fluctuation of the rotation speed. For this issue, Watt installed a flywheel to smooth out the speed fluctuation of the output rotation.

4.2.2.5 The Centrifugal Governor

The speed of the engine output is also affected by the amount of steam into the engine. Without proper control, the amount of steam, also the output speed of the

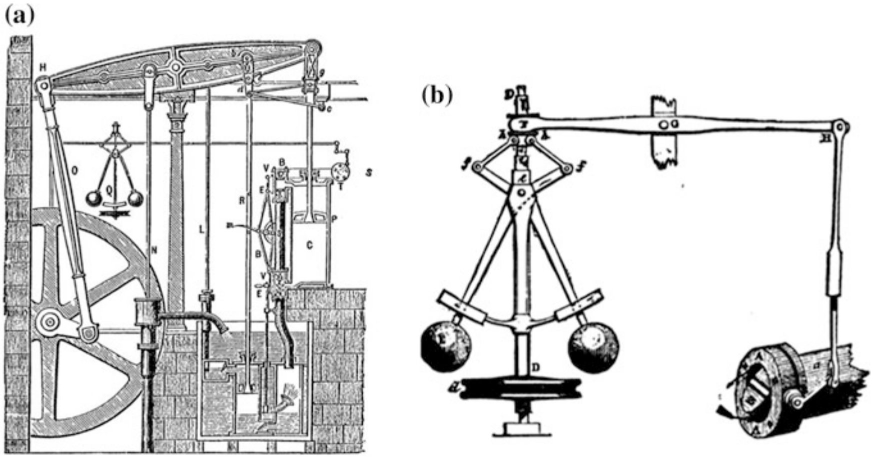


Fig. 4.6 J. Watt's steam engine. **a** Watt's engine (https://dazeinfo.com), **b** centrifugal governor (https://en.wikipedia.org/wiki/Centrifugal_governor)

engine, can't keep constant. In 1782 Watt made another important improvement. Under the suggestion of Matthew Boulton, an entrepreneur and his partner, he installed a centrifugal governor in his engine, making the amount of steam supply close to a preset value (Fig. 4.6b). Thus, the output speed of the engine could be kept stable. This improvement paved the way for the engine to be applied in trains and ships.

Neither flywheel nor centrifugal governor was Watt's invention. Governors had already been applied in mills of Europe since the 17th century while flywheels first appeared in Germany early in 1430. About the centrifugal governor, another two things are worth of mentioning. First, it is the early application of the modern automatic control theory. Second, further application of and investigation on centrifugal governors triggered an extremely important topic of system stability in mechanics, see Sect. 6.2 (Wu 2009). Both flywheel and governor are still covered in most current textbooks of theory of machines and mechanisms.

To the year of 1790 when he invented the cylinder indicator, Watt completed the invention of steam engines in about 30 years, obtaining a series of patents.

4.2.3 *Watt: A Creative Genius*

J. Watt was an outstanding and very creative genius. His successful career and great accomplishment gave us important inspirations.

(1) During his childhood, strong curiosity and thirst for knowledge were formed.
(2) He had no formal and systematic education; however, he studied diligently. To collect materials of steam engines, he learned Italian and German by himself.
(3) He chose the steam engine as his research object, which was in urgent need of that time.
(4) He kept an open mind and kept in contact with all walks of life to acquire new knowledge. He became acquainted with university professors to learn theoretical knowledge. He participated in the "Lunar Society". In fact, the idea of using the planetary gear mechanism to convert motion was inspired from his experience there.
(5) Watt encountered great financial difficulty initially when trying to commercialize his invention. This issue was not solved until he met his life partner, Matthew Bolton, in 1775. With the help of Bolton, Watt found some of the world's best manufacturing craftsmen. One of them developed the precision boring technique, and solved the critical problem in manufacturing the engine.
(6) Watt was persistent. During the 30 year continuous improvement to the engine, he experienced numerous failures. However, Watt did not give up, and finally completed a series of important innovation to Newcomen's engine.

4.2.4 Epochal Significance

Watt's improvement and innovation to the steam engine created revolutionary effect on the modern technology and production, being of epoch-making significance. Before Watt production mainly relied on human, animal and hydraulic power. The steam engine provided unprecedented power, marking a new era of steam power. Consequently it led to the rapid development of the First Industrial Revolution.

The wide application of steam engines greatly increased the demand for coal, promoting the rapid growth in coal production. With blowers equipped with the new power, the capacity of blast furnace enlarged and the smelting temperature was increased. Thus, the quality of iron was greatly improved, and the output increased exponentially. In addition, the steam engine also solved the problem of mine drainage.

The emergence of steam powers inspired the application of machines in almost all sectors of industry, far beyond the traditional engineering machines. Even tractors were equipped with steam engines. More importantly, it stirred a wave of invention of new machines.

The steam engine directly led to the invention of steam locomotives and steamboats; bring revolution to railway and water transportation. The significance of steam power went far beyond only economic growth. It sped up the development of every aspect of the society, and promoted international exchanges. An era of globalization started.

4.2.5 Railway Age

The steam engine technology triggered a revolution in transportation. Railway already existed in mines and some other applications of Europe before the emergence of the steam engine; however, horses were used to draw the carts along the rail track. After Watt's invention, people attempted to use steam engines as the pulling power (Rübberdt 1972; 中山秀太郎 1987). In 1804, Richard Trevithick (Fig. 4.7), a British engineer, tested the world's first railway steam locomotive, which loaded only 15 tons with a speed of 8 km/h. Trevithick's work was not acknowledged at that time. Eventually he died of pneumonia in absolute poverty in 1833.

In 1814, George Stephenson designed his first steam locomotive, *Brücher* (Fig. 4.8), and made a successful test run. In September 1825, Stephenson's another steam locomotive, named *Locomotion*, was tested hauling an 80-ton load of coal and flour 15 km in two hours. In the test, the speed reached 39 km/h. In addition, a purpose-built passenger car, called *Experiment*, was attached, carrying dignitaries on the opening journey. This was the first documented passenger traffic running on a steam locomotive railway (Davies 1975). This historical experiment opened an new era in land transport, the "era of railway". Soon after, a wave of railway construction appeared in Britain. After 1840, this construction wave stretched to mainland Europe and America.

Railway caused revolution in land transport, and changed the industry chain in the whole world. As a product of modern industrial civilization, it in turn greatly promoted the development of industrial civilization. In 1840, the total railway

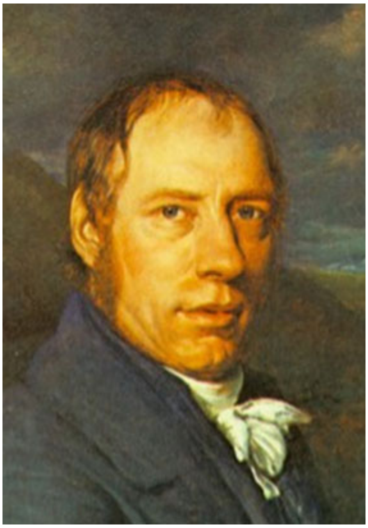


Fig. 4.7 R. Trevithick

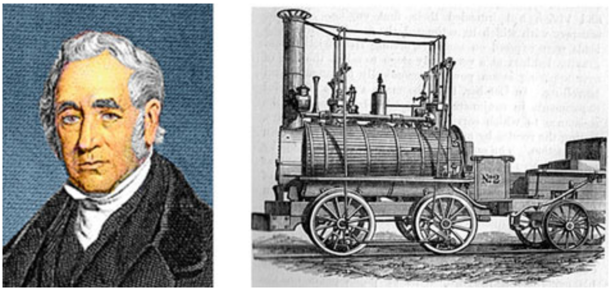


Fig. 4.8 G. Stephenson and his steam locomotive (https://en.wikipedia.org/wiki/George_Stephenson)

length in operation was only 8000 km in the world; while to the year of 1870 the number reached 210,000 km. In 1913 the number further expanded to more than 1.1 million km. The major European countries and the U.S. formed their national railway networks. In 1869, the first transcontinental railroad across the United States was completed (Vernon 1870). It not only brought the western states and territories into tightly alignment with the northern Union states, but also made transporting passengers and goods coast-to-coast much quicker and cheaper. Thus, it played an irreplaceable role in the establishment of the modern capitalist system in the U.S. Tens of thousands of Chinese workers participated in the construction of this transcontinental railway.

4.2.6 Steam Ships

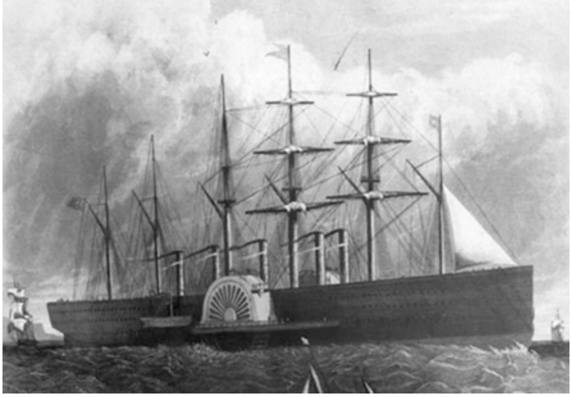
In 1807, an American engineer, Robert Fulton (Fig. 4.9), developed a commercially successful steam boat called *The North River Steamboat of Clermont*. His passenger boat, driven by a steam engine imported from Britain, voyaged in the Hudson River for a round trip of 300 miles in 62 h (Buckman 1907). This historical event was a prelude to the steamboat era.

In 1812, Henry Bell, a Scottish engineer, constructed the steam-boat, *Comet*, and introduced the first successful passenger steamboat service in Europe (Wood 1885).

The first steamship purpose-built for crossing the Atlantic was the British side-wheel paddle steamer, *SS Great Western*, designed by the great engineer Isambard Brunel, which inaugurated its maiden voyage to New York in 1838 (Fig. 4.10), marking the era of trans-Atlantic ocean liner (Gibbs 1952).

Fig. 4.9 R. Fulton

Fig. 4.10 Maiden trans-atlantic voyage of the SS Great Western (http://www.ikbrunel.org.uk/ss-great-eastern)



4.2.7 Significance of Transportation Revolution

Production and circulation are two important segments in social reproduction process. To shorten the time of social reproduction, we must shorten the circulation time, which can be mainly achieved by improving the transportation means.

The transportation revolution changed the state of isolation between regions on the earth. It expanded rapidly the scope of human activities and strengthened the communication between different areas and countries. The British ocean ships transported consumer goods produced in Britain to every corner of the world, and took back industrial raw materials needed, creating the conditions for the formation of a world market.

Railway is called “the industrial crown”. The Industrial Revolution transformed the shop-based industry into large factory-based one which laid solid material and technical foundation for the capitalist economy. While the transportation revolution accelerated the agglomeration and centralization of capital, forming a new starting point of rapid development of the capitalist economy.

4.3 Mechanical Inventions in First Industrial Revolution

The Spinning Jenny set a good example for all industries, clearly demonstrating the power of machines to increase productivity. On the other hand, steam engines offered massive power, greatly pushing the wide application of machines, and inspiring invention of new machines (Goddard 2010; 中山秀太郎 1987). Table 4.1 listed examples of machines invented under the motivation of the First Industrial Revolution until the 1850s (The invention of machine tools is not included in the table, see Sect. 4.4). As can be seen the majority of the inventions concentrated in the UK, involving the textile industry, agriculture, the construction industry, and the mining industry. Britain became the first ‘Factory of the world’ (Palmer et al. 2010).

At the same time, the U.S. started industrialization as well. The French Revolution in 1789 and the Napoleon’s war to conquer Europe intermitted the trade between the U.S. and Britain as well as France (中山秀太郎 1979). Americans had to produce what they need by themselves. This greatly inspired the development of manufacturing in the U.S. and raised an upsurge of invention of new machines.

4.3.1 Wide Application of Steam Power

Steam engines were already used in many applications before Watt made the critical improvements. In 1785, Germany made a steam engine for mining the first time. In the period between 1785 and 1790, cotton spinning mills started to use steam power. In 1790, the first rolling mill of metalworking with steam power was established in the UK.

Between 1800 and 1802, R. Trevithick and Oliver Evans, an American engineer, developed the high-pressured steam engines separately. In 1805, Arthur Woolf, a British engineer, patented the high pressure compound engine, in which high-pressure steam from the boiler first expands in a high-pressure cylinder and then enters one or more subsequent lower pressure cylinders. The complete expansion of the steam occurs across multiple cylinders. As there is less expansion in each cylinder, less heat is lost by the steam. This significantly reduces the

Table 4.1 Machine inventions during the First Industrial Revolution

Year	Country	Invention	Inventor
Transportation means			
1807	U.S.A.	Steam boat	R. Fulton
1804	UK	Steam locomotive	R. Trevithick
1814	UK		G. Stephenson
1852	U.S.A.	Safety device for lift	E. Otis
Construction and mining machines			
1800s	UK	Steam powered roller	
1805		Steam powered crane	
1806		Roller crusher	
1825		Tunneling boring Machine	M. Brunel
1835	U.S.A.	Steam powered excavator	W. Otis
1800s–1840s		Overhead crane	
1858	U.S.A.	Jaw crusher	Eli W. Blake
Thermal machines			
1816	UK	Stirling engine	R. Stirling
1854	UK	Commercial ice-making machine	J. Harrison
1860	UK	Refrigeration system with reverse sterling cycle	A. Kirk
1876	Germany	Method of liquefying gases	C. Linde
Textile and sewing machines			
1764	UK	Spinning Jenny	J. Hargreaves
1769		Water-frame	R. Arkwright
1785		Power loom	E. Cartwright
1790	UK	Earliest sewing machine	T. Saint
1804	France	Jacquard loom	J. Jacquard
1830		Chain stitch sewing machine	B. Thimonnier
1846	U.S.A.	Lockstitch sewing machine	E. Howe
1859	U.S.A.	Singer treadle sewing machine	Singer Company
Information machines			
1822	U.K.	Mechanical computer	C. Babbage
1836	France	Camera	L. Daguerre
Agricultural machines			
1784	U.K.	Grain thresher	A. Meikle
1833	U.S.A.	Reapers	O. Hussey
1834			C. McCormick
1850	U.S.A. and Europe	Steam powered tractors	
Others			
1775	U.S.A.	Submarine	D. Bushnell
1783	France	Hot air balloon	Montgolfier brothers
1860	U.S.A.	Steam powered submarine	

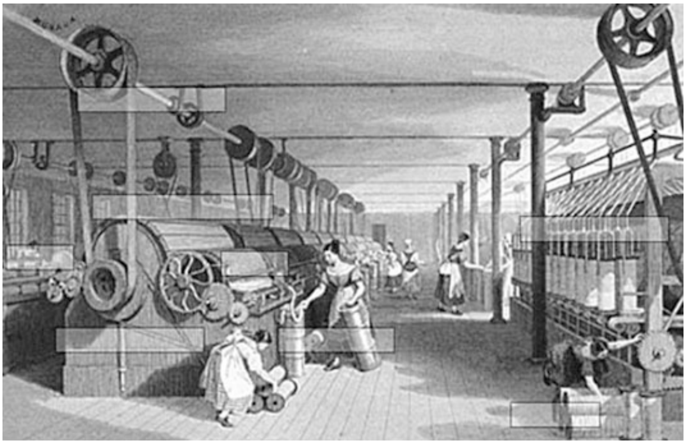


Fig. 4.11 Textile factory during English Industrial Revolution (www.whodoyouthinkyouaremagazine.com)

magnitude of cylinder heating and cooling, making higher expansion ratios practical and increasing the efficiency of the engine. These inventions made the engine smaller and more efficient, expanding the application of steam engines (Singer et al. 1958b).

As a new power, steam was used to drive cranes, rollers, excavators and tractors. In the 19th century, steam engines remained the dominant prime mover until the era of electrical motors. The appearance of motors with three-phase alternating current finally pushed the steam engines out.

One of the shortcomings of steam engines is that it is hard to be downsized. Therefore, line shaft was generally installed in workshops during the First Industrial Revolution. The line shaft, driven by a steam engine outside the workshop, delivered the power and motion to each production machine through flat-belt drives (Fig. 4.11).

In the mid. 19th century, hydro-turbines and gas motors were invented as well. Given that they were closely linked to the Second Industrial Revolution, they will be introduced in Sect. 5.3.

4.3.2 Textile and Sewing Machines

The textile industry was once the most important sector in Britain. After the invention of the spinning Jenny, development of the textile industry and invention of new textile machines took alternate to push each other forward (Rübberdt 1972; 中山秀太郎 1987; Pan and Wang 2005).

4.3.2.1 Alternating Progress of Spinners and Looms

After Hargreaves' invention of the spinning Jenny in 1764, Richard Arkwright, an inventor and a leading entrepreneur during the early Industrial Revolution, invented the spinning frame, also called water frame, in 1769. This was a big machine spinning 96 strands of yarn at once and requiring many workers to work around simultaneously. The spinning machines put an end to the home-based textile workshops, which were replaced by the more advanced, modern textile factories. A direct consequence was that many workers who used to work at the workshops lost their jobs. In response they destroyed machines and burnt factories. In spite of this, the progress for large, advanced factories to replace the traditional home-based spinning workshops was inevitable.

In 1777, Arkwright went further with steam engines to replace hydraulic power. It took about half a century for the steam engines to take over the entire spinning industry.

In 1779, Samuel Crompton, an English textile worker, invented the Spinning Mule on the basis of Hargreaves and Arkwright work. It could spin 48 strands of voile at the same time (Spinning Jenny can only spin 8 strands).

With the continuous improvement of spinners, the spinning productivity was improved dramatically, leaving weaving the bottleneck. In 1785, Edmund Cartwright, an English rural clergyman, invented the steam-powered loom. But his invention was not well accepted because the machine was heavy.

In 1830, Richard Roberts, an English engineer, invented the Roberts Loom, a power loom with cast iron frame. This loom was more viable than its predecessors, and of higher efficiency. Thus, it was soon widely accepted by the industry. Roberts was a highly productive inventor. His most famous invention was the automatic spinning machine made in 1825. In addition, he made great contribution in machine tools and measurement instruments (中山秀太郎 1979).

In 1820 Britain possessed only 2,400 spinning machines. But to the year of 1857 the number reached 250,000. In 1851, Britain had almost half of the spindles in the world. Only in Lancashire were there 50 million spindles. Britain dominated the cotton spinning industry of the world for a long time.

4.3.2.2 Wool and Linen Machine

The rapid development of the cotton industry also gave an impetus to wool and linen textile. During the last 40 years of the 18th century, hosiery machines, carding machines and fabric cutting machines were invented successively.

4.3.2.3 Sewing Machines

In 1790, an English inventor, Thomas Saint, invented the first sewing machine for shoe making, but he did not successfully advertise and market his invention. The

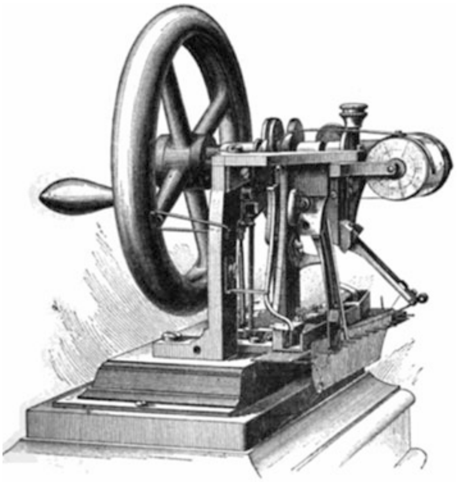


Fig. 4.12 Howe's sewing machine (en.wikipedia.org/wiki/Elias_Howe)

first practical sewing machine was invented in 1829 by Barthélemy Thimonnier, a French tailor. However, the workers at that time regarded the machine as a dangerous competitor, and were fearful of losing their jobs. On a morning in January 1831, about 200 tailors burned down the factory and destroyed the 80 Thimonnier's machines. Thimonnier ended up of dying in poverty. In fact, Thimonnier's machine was not the first sewing machine. Some other people also made inventions in sewing machines and some were even patented. But all of them were not commercialized.

Elias Howe, an American mechanic, made significant refinements to the design concepts of his predecessors. By April 1845, Howe had created a practical sewing machine using the lockstitch design (Goddard 2010; Rübberdt 1972). In a public demonstration, Howe's invention proved to be five times faster than the swiftest hand sewers, reaching up to 300 stitches per minute (Fig. 4.12). In 1846, he was granted the patent for his machine. His machine already had the three essential features which most modern machines have: a needle with the eye at the point, a shuttle operating beneath the cloth to form the lock stitch, and an automatic feed.

In 1850, Isaac Singer improved Howe's machine slightly, and established the Singer Sewing Machine Company. Most of the sewing machines at that time were hand-operated. The Singer Company invented the pedal sewing machine and the motor driven sewing machine in 1859 and in 1889 respectively, starting a new era of the sewing machine industry. The company dominated the sewing machine production in the world for a long time (Forsdyke 2008).

4.3.2.4 Jacquard Loom

In 1804, Joseph Jacquard, a French weaver, invented a programmable automatic knitting machine, the Jacquard loom. It was a device fitted to a power loom, being able to simplify the manufacturing process of textiles with complex patterns, such as brocade and damask (Goddard 2010; Rübberdt 1972; Delve 2007).

The Jacquard Loom used pasteboard cards with punched holes, each card corresponding to one row of the design. Multiple rows of holes were punched in the cards. The many cards that made up the design of the textile were strung together in order. This system could be installed in any kind of weaving machines.

Although being threatened by the weavers who were afraid of losing work to the new machine, he still launched the machine to the market in 1810, and it quickly became the best seller. Since then, silk was no longer a luxury product only for few people.

Jacquard made important contribution to the development of the earliest programmable loom, which in turn pushed the development of other programmable machines (Essinger 2004). For example, in an early version of digital compiler developed by IBM a paper tape with punched holes was used. Punched cards remained in use in modern computing until the 1980s.

4.3.3 Construction and Mining Machines

4.3.3.1 Excavator

In 1835, William Otis, a young American engineer, designed a steam-powered mechanical shovel with single bucket, and was granted the patent in 1839. This machine was made from iron and wood, and of partial swing, being mounted on a railway chassis. It was not widely used due to its poor cost effectiveness. In the 1870s, steam shovels equipped with improved steel cable were used in open ore stripping (Fig. 4.13). The first partial swing steam shovel using a tractor chassis appeared in 1880. Steam shovel showed its great power in digging the Canal Panama in 1881 (Farrell 1994, 18) and was since then widely used in mining, construction and road work (Fig. 4.13).

4.3.3.2 Tunneling Boring Machine

In 1818, Marc Brunel was granted the patent of tunneling shield. It was intended to be applied in the construction of the Thames Tunnel under the River Thames, which started in 1825. However, the concept was not really used effectively in the construction due to some reasons. The first practical tunnel boring machine (TBM) was commissioned in 1845–1846 when building the tunnel through the Alps between France and Italy (Pan and Wang 2005; Bancroft 1908).

Fig. 4.13 A derelict steam shovel in Alaska (http://tractors.wikia.com/wiki/Steam_shovel)

4.3.3.3 Crushers

The success of steam engines greatly increased the demand for coal and iron. In 1806, a roller crusher driven by a stream engine was created, which was mainly used to crush coal and coke. In 1858, a jaw crusher for crushing ore was invented (see Sect. 5.3.2).

4.3.3.4 Cranes

From ancient to modern times, cranes had never stopped improving. However, modern cranes were not built until the emergence of new sources of mighty power. In 1805, steam powered cranes were made for construction of the London dock. By the early 19th century, many modern factories appeared in Europe. The first crane company in the world was established in Germany in 1830 (Kurrer 2008), starting mass production of overhead cranes in 1840. In 1845, William Armstrong, a famous English industrialist, designed a hydraulic crane. He also established a crane manufacturing factory (Dougan 1992).

4.3.3.5 Lift

Lifts already existed in the Ancient Roman. To the first half of 19th century, hydraulic lifts were installed in many factories in Europe, in which water power was used and the cage was balanced by a counterweight. The design of counterweight was safer than cable, but slower.

To solve the safety concern of cable lifts, an American, Elisha Otis, invented a safety device in 1852. In this device, ratchet teeth were made on the guiderails of both sides, while lock hooks were installed on the lift. The ratchet teeth mesh with

Fig. 4.14 Otis free-fall safety demonstration in 1854 (99percentinvisible.org)

the hooks if the cable broken. This device prevents the lift car from falling in case the hoisting cable breaks (Fig. 4.14).

The 1854 New York World's Fair provided a great chance for Otis to demonstrate his invention to the public. He first stood on a platform, which was suspended by a rope high in the air. Then he ordered a person to cut the rope with an axe. The crowd was completely amazed to see that the platform come to a halt after falling a few inches. After the World's Fair, orders flew in continuously; doubling each year was kept for many years (Singer et al. 1958a; Rübberdt 1972; Goddard 2010).

In the early days, Otis' lifts were powered by steam.

4.3.3.6 Mining Machines

During the First Industrial Revolution, coal mining was changed from manual production relying on picks and shovel to mechanized operation for each production stage. Steam powered winch, water pumps and fans replaced windlass, bucket of water and natural ventilation.

In 1849, coal milling shearers were invented. In 1857, air compressors were used to provide energy for pneumatic drills (Rübberdt 1972).

4.3.4 Agricultural Machines

The period from the First Industrial Revolution to the end of the 19th century was the initial stage of agricultural mechanization.

4.3.4.1 Grain Thresher

In 1786, a Scottish engineer named Andrew Meikle invented the grain thresher (ANON 2015). Initially, the machines were horse powered and manual fed; later, it developed into steam powered. About half a century later, an important improvement, separating the grain and the shell in the threshing process, was made by an American, significantly increasing the efficiency and reducing the labor required.

4.3.4.2 Reapers

American farmers were nagged by the harvest every year. At that time, a farmer can only harvest half an acre of wheat every day by hand. America, being different from Europe, has vast land and fewer people, so the labor cost was very high. If someone could design a machine to increase the harvesting efficiency, he would become a national hero and certainly make a fortune. Obed Hussey and Cyrus McCormick each invented a reaper independently in 1833 and 1834 respectively, and both were granted the U.S. patent (McCormick 1931; Greeno 1912; McNeil 1996). On the first trial, McCormick's machine was a great success, demonstrating a much higher efficiency than manual by two times. The dream of mechanized harvesting came true, but animal power was still remained in use (Fig. 4.15).

Since the mid. 19th century to the end of 20th century, American agriculture provided foods and clothes for American people as well as one fifth of the world population. More than 10 million farm workers made this a reality. Without the invention of the reaper, the farm workers needed might be as high as 90 million.

4.3.4.3 The Cotton Gin

The demand for raw cotton in Britain was growing rapidly. The southern part of U. S. was an important base to supply cotton to the British. In this business, an important work was to separate seeds from cotton fiber. This work could be done only by hand then, with an extremely low efficiency. Eli Whitley, an American inventor, patented a manual de-seeding machine in 1794, known as the cotton gin (中山秀太郎 1987). This invention dramatically boomed cotton export from the U. S. increasing the amount from less than 230,000 kg in 1793 to 42 million kg in 1810 (U.S.A. Department of the Treasury 1895–1896). The cotton gin was one of the most important inventions in the First Industrial Revolution (Fig. 4.16).

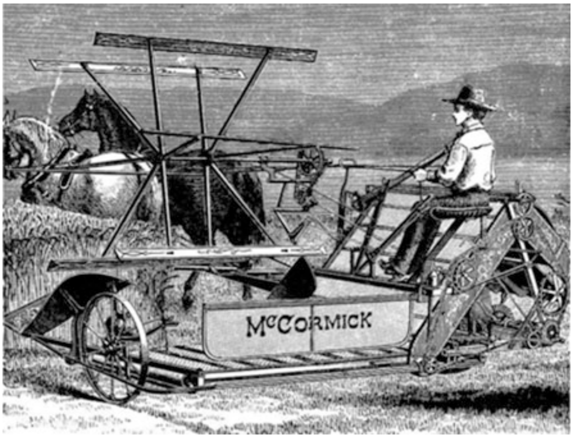


Fig. 4.15 McCormick's reaper (fineartamerica.com)

Fig. 4.16 A model of a 19th-century cotton gin on display at the Eli Whitney Museum (www.jsonline.com)

4.3.4.4 Steam Driven Tractors

In 1832, a plow with steam driven cable appeared in Britain. In 1858, a steam powered tractor was developed in the U.S., which could drive eight plows at a speed of 5 km/h in cultivating.

4.3.5 Refrigeration Machines

With the development of the food industry, the storage and transportation of food called for the development of refrigeration machines (Pan and Wang 2005).

In 1816, Robert Stirling, a Scottish priest, proposed a thermodynamic cycle (Stirling cycle) consisting of two isothermal processes and two isochoric processes. This cycle was initially used for thermodynamic engine, in which the working fluid in the system was compressed and expanded at different temperatures. The Sterling engine, although as old as the steam engine, was not widely accepted. In 1860, Alexander Kirk used the reverse sterling cycle for refrigeration purpose, and it turned out very successful (Peter 2006, 278). As a result, an unsuccessful engine became a successful refrigerating machine.

The first practical vapor compression refrigeration system was built by James Harrison, a British journalist who immigrated to Australia. He created the first commercial ice-making machine in 1854. In 1856 he was granted the U.K. patent for a vapor compression system using ether, alcohol or ammonia as the working media (Singer et al. 1958a). Harrison also introduced his refrigeration system to breweries and meat packing houses. By 1861, a dozen of his systems were in operation.

Carl von Linde, a German engineer and professor, began to study refrigeration in the 1860s and 1870s in response to the demand from brewers for a technology that would allow year-round, large-scale production of lager. He patented an improved method of liquefying gases in 1876 (Yenne and Gross 1993), representing the beginning of modern compression refrigerators. His new process was widely used until the late 1920s.

Neither the mechanism of refrigeration nor the working medium is a mechanical problem. However, the compressor, the heart of a refrigerating system, is a real machine.

4.3.6 Fluid Machines

4.3.6.1 Development of Pumps

A pump is the core in any fluid machine. It has been a long history in the development of pumps. Records about pumps could be found in literature of the Renaissance, or ever earlier. The 1st and 2nd Industrial Revolutions saw very dynamic activities in pump invention and improvements.

(1) Piston pump and plunger pump

In 1650, Otto Guericke, the German scientist who did the famous hemisphere experiment, designed a single piston air pump. Samuel Morland, an English inventor, invented and patented a plunger pump in 1675 when he was involved in projects to improve the water supply to Windsor Castle (Rosen 2010). This type of pumps later was widely used in homes, ships and factories. However, Moorland's plunger pump was still different from the modern piston pumps (Fig. 4.17).

(2) Centrifugal pump

The first machine having some features of centrifugal pumps was for mud lifting described in a treatise early in 1475 by an Italian Renaissance engineer (Reti 1963).

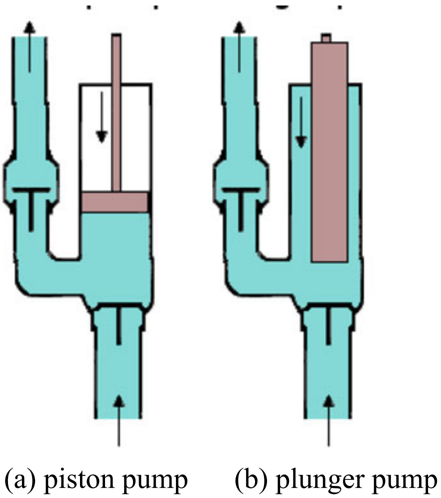


Fig. 4.17 A plunger pump compared to a piston pump (https://en.wikipedia.org/wiki/Plunger_pump)

True centrifugal pumps were not developed until the late 17th century. Denis Papin proposed the concept in 1689 and built one in 1705. In this pump, Papin used straight vanes. In 1750, L. Euler did theoretical analysis on the fluid flow in a centrifugal pump, laying the theoretical foundation for further development. In 1818, centrifugal pumps began to be made in mass production in the U.S. In 1851, a British engineer, John Appold, started to use curved vanes in centrifugal pumps (Fig. 4.18) (Ji et al. 2008).

4.3.6.2 The Hydraulic Press

The emergence of steam engines and other machines put forward a need for forged parts of large size. In 1795, a British engineer, Joseph Bramah, invented a hydraulic press (Feldman and Ford 1979), marking the beginning of industrial application of modern fluid power. By 1826, hydraulic presses had gained wide application.

4.3.6.3 Compressors

Thousands of years ago, compressed air was already used in smelting blast furnace in metal production and heating furnace in forging operation. Later blowers developed into water powered.

In 1650, O. Guericke designed the first single piston air pump in history (Heilbron 1979). In 1757, J. Wilkinson patented a hydraulic powered blowing engine for blast furnaces (Temple and Needham 1986). This machine became the origin of later mechanical air compressors. To the 1770s, mechanical compressors began to be powered by steam engines.

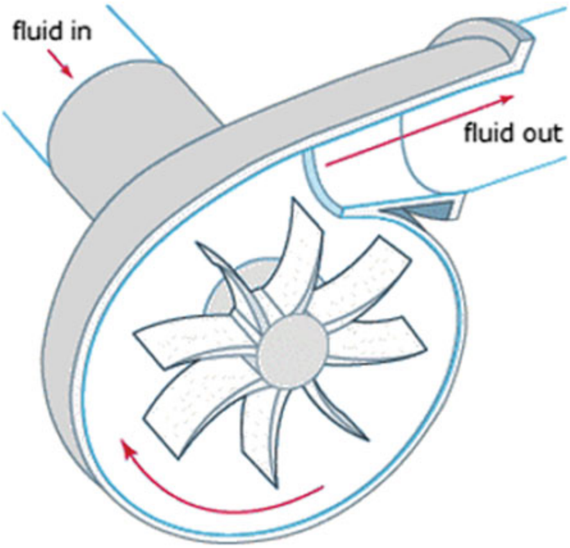


Fig. 4.18 Centrifugal pump with curved vanes (http://wermac.org/equipment/pumps_centrifugal.html)

Compressed air is safer to the operator than hot steam; therefore, it replaced steam, becoming the main power of pneumatic drills.

4.3.7 Weapons

4.3.7.1 Naval Vessel

Initially, vessels of the Royal Navy were made of wood. Being conservative, the Navy warships adopted steam engines later than merchant ships. Under the persuasion of Marc Brunel, The Navy began to adopt steam engines to its auxiliary ships in 1822 (Yang 2005). Shortly after in the Crimean War, steamships demonstrated great advantages. Thereafter, steamships became widely accepted and metal replaced wood becoming the main material to make naval vessel. Propeller armed warships and rotating turret appeared later.

4.3.7.2 Submarines

Historical records in military technology suggested that submarines were invented unimaginably early. In 1578, a British mathematician described an imagined submarine in a book. During 1620–1624, Cornelius Drebbel, a Dutch-born British engineer, invented a “diving ship”, and made a trial voyage on the Thames River (Tierie 1932). Soon the military potential of submarines was realized. They could

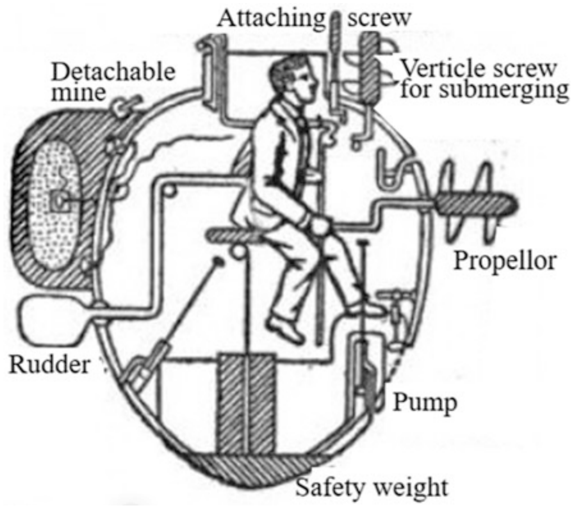


Fig. 4.19 The first submarine "Turtle" (http://ericshanfield.com/2011/09/observations-bathysphere/)

abruptly attack enemy's ships on water surface and quietly deliver supplies to friend ships due to the ability to stay and move under water in secret.

During the U.S. Independent War, David Bushnell built the first military submarine, *Turtle*, in 1775 while studying at Yale College (Goddard 2010; Swanson 1991). It accommodated only one person, and was manually operated with a screw for propulsion. The up and down was implemented through a foot valve controlling water flux into or discharge from the chamber. It could dive up to 6 m deep and remain underwater for up to 30 min (Fig. 4.19). In 1776, the U.S. Navy tried to attack the flagship of British Royal Navy with "*Turtle*", but failed.

In the 1860s, steam engines were used in submarines.

4.3.7.3 Guns

Rifles were born in Rhineland, Germany, around the beginning of the 16th century. Initially they were mainly used by hunters with little military enthusiasm (McNeil 1996). After spreading to North America in the 18th century, a German born Pennsylvania craftsman made some improvements for the use of wood cutters by making the riffle lighter and longer.

The rifling, making spiral grooves inside the gun barrel, gives a spin to the bullets. Thus, a greater range and better accuracy, compared with an original smooth bore guns, can be achieved. In 1835, an American, Samuel Colt, invented the fast loading rifle, which brought a great fortune to him in the American Civil War and the American-Spanish War (Rübberdt 1972; McNeil 1996).

In 1847, Alfred Krupp, a German entrepreneur, began to produce cannons of cast steel. At the Great exhibition in London in 1851, Krupp displayed a steel barrel with a large caliber which had never seen before, completely amazing the crowd

(Rübberdt 1972). In the middle of the 19th century, Krupp's cannons played a critical role for Germany to beat France and Austria. The Krupp's enterprises became the pillar of the later German militarism.

4.3.8 Information Machines

"Information", as a technical term, has been widely used after WWII. The term "Information machine" is used as a generic term for camera, typewriters, copying machines, etc. These machines do little mechanical work, and are mainly used for processing information. Although the term "information machine" appeared pretty late, some information machines already existed during the First and the Second Industrial Revolution.

4.3.8.1 Camera

A French artist and photographer, Louis Daguerre, patented and successfully commercialized photography in 1839 (Singer et al. 1958a). His name was one of the 72 names inscribed on the Eiffel tower. The invention of photography itself was not a mechanical problem. However, a camera was a very precise machine.

4.3.8.2 Paper-Making Machine and Printing Machine

The French Revolution at the end of the 18th century enlightened the whole Europe. Many countries established a compulsory education system, greatly reducing the number of illiteracies. Correspondingly, the demand for books and newspapers was increased dramatically. However, the printing technology progressed little during the 350 years after the invention of movable type by J. Gutenberg in the 15th century (see Sect. 3.2.3).

Before the invention of continuous paper making, paper was made in individual sheets by a series of processing operations. In 1799, Louis-Nicolas Robert, a French engineer, invented and was granted a patent for a continuous paper making machine (Hunter 1978) during working at S.-L. Didot. Robert got in quarrel with Didot, the owner of S.-L. Didot, over the ownership of the invention, and finally sold the patent to Didot. In 1801, Didot's brother-in-law, John Gamble, obtained a British patent on an improved version of this machine. In 1807, the brothers Fourdrinier, were awarded new patents. Fourdrinier machine became the well-known name later; however, its original design was made by L.-N. Robert.

In 1809, an English man, named John Dickinson, invented another continuous mechanized paper-making process and founded a few paper mills in England. His machine used a cylinder wire mesh different from that of Robert (Fig. 4.20).

Fig. 4.20 Large Fourdrinier-style paper-making machine (http://maps.thefullwiki.org/Fourdrinier_machine)

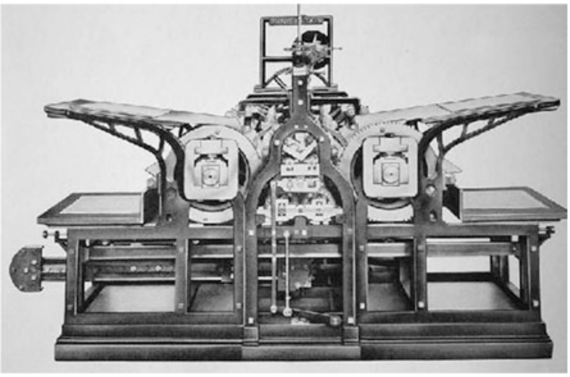


Fig. 4.21 Koenig's printing press (www.jilliankent.com/uncategorized/exploring-the-regency-with-guest-blogger-sara-king-2/)

Within a few years, the production of paper increased by 10 times. Without the improvement in paper-making, there won't be modern printing machines. The continuous production of the paper also inspired the development of continuous rolling operation of steel and other materials.

In 1810, a German inventor, Friedrich Koenig, invented a high-speed steam powered printing press, which could print on both sides of the paper at the same time (Fig. 4.21). His machine mechanized most of the printing operation, leaving only the delivery and collection of papers done manually. Its printing speed was increased 4 times higher than its predecessor, reaching 1100 sheets/h (Pan and Wang 2005).

4.3.8.3 The Mechanical Computer

In the early 19th century, mathematical tables were calculated by hand, creating very heavy workload. In addition, mistakes and errors were unavoidable in hand

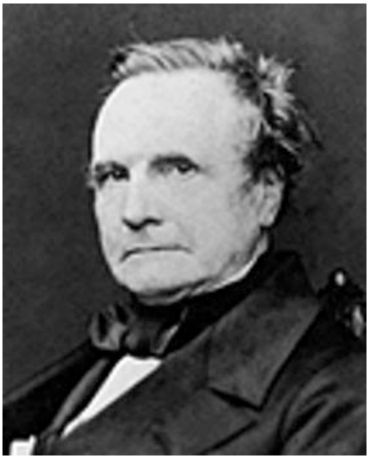


Fig. 4.22 C. Babbage

transcription and calculation. Thus, Charles Babbage (Fig. 4.22), a British mathematician and inventor, determined to create a machine to calculate tables (Goddard 2010; Williams et al. 1978). After 10 year effort, a prototype of the first mechanical computer, which he called the Difference Engine (Fig. 4.23), was built in 1822. This machine satisfied the requirement of compiling mathematical tables with an accuracy of up to 6 digits.

Motivated by the promising prototype, the British government funded him in 1823 to build a working machine of the Difference Engine with a higher precision of 20 digits. He envisioned that this machine was made of about 25,000 parts which had a manufacturing accuracy within 1/1000 in. However, this machine was never completed because he went into conflict with the chief engineer, and the British government withdrew its funding for the project.

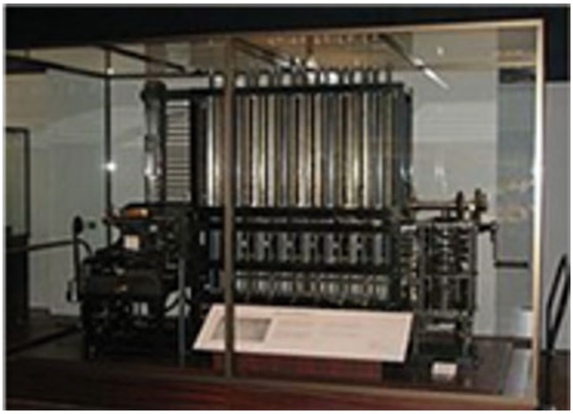


Fig. 4.23 Model of difference engine in London Science Museum (https://en.wikipedia.org/wiki/Difference_engine)

In the Difference Engine project, he realized that a much more general design was possible; thus, Babbage proposed to build a general computing machine, the Analytical Engine, which could automatically solve a problem with 100 variables. The Analytical Engine was to be programmed using punched cards, which obviously was inspired by Jacquard's idea in the automatic knitting machine. The engine was also intended to employ several features subsequently used in modern computers, including sequential control, branching and looping. Essentially the logical structure of the Analytical Engine was the same with modern programmable digital computers. Thus, he was considered by some scholars a "father of computer" (Halacy 1970).

In 1843, Ada Lovelace, a daughter of the great poet George Byron, learned Babbage's work and was fascinated with the machine. She worked with Babbage during the development of the Analytical Engine. In Lovelace annotation, a way to calculate Bernoulli numbers with the machine was included. For this achievement, she has been described as the "first computer programmer".

Babbage's Analytical Engine was a marvel of mechanical ingenuity even from nowadays viewpoint. Unfortunately, he did not complete the construction of this machine in his life. It was not easy to turn such an ingenious idea into a practical machine due to the limitations of that time. The manufacturing technology, for example, could not support him in machining accuracy. Lathes and the milling machines were invented not long ago, and grinding machines was not born yet. However, he left the computer world a precious legacy, including 30 design concepts, nearly 2100 assemble drawings and 50,000 component drawings. More importantly, the spirit of striving for success in adverse environment should be appreciated. Babbage tragically failed in building his machine, but he is still a hero.

4.4 Birth and Early Development of Modern Machine Building Industry

4.4.1 Status of Machining in 18th Century

Steam power greatly promoted the application of machines, and various new machines were invented. A new industry, the machine building industry, thus, came into being.

Before steam engines appeared, wood was the main material of engineering structures. Although lathes and other machine tools already existed then, they were made of wood for the main structures, and were for machining wooden parts as well. Metals, mainly copper and iron, were also used for apparatus, locks, clocks, pumps and small hardware on wooden structures. The accuracy of metal parts mainly depended on fine craftsmanship.

Watt’s steam engine was mainly made of two metals, cast iron and copper alloy which could be cut with hardened carbon steel tools. At that time, heat treatment had developed for several hundreds of years, tools for wood cutting could be made very well. However, for cutting metals, very low cutting speed had to be maintained to avoid quick failure of tools. For example, it took 27.5 working days to machine the holes and end surfaces of Watt’s cylinder (Trent 1991).

The steam engine required machining large metal parts, such as cylinders, with high dimensional accuracy, leading to the first leap in metal cutting technology. The manufacturing of steam engines resulted in the establishment of a real machine-building industry. The clock-making industry before was only a prelude.

4.4.2 Inventions and Improvements of Machine Tools

4.4.2.1 Modern Concept of Machines Tool

Although human powered lathes appeared already in Egypt and Europe thousands of years ago, the technologies in machine tools and cutting tools had progressed very slowly before the Middle Ages. The modern concept of machine tools were not formed until the late Middle Ages. The main points of this concept include: (1) for making metal parts, (2) guiding the cutting tool by the machine rather than by hand. With the requirement for machining large metal parts of high accuracy, metals replaced wood, becoming the main materials of lathe frames in the 18th century. Machine tools meeting the above two criteria eventually appeared in the first Industrial Revolution.

4.4.2.2 Boring Machine

The manufacturing of Watt’s engines needed innovative machine tools and presses. In 1774, John Wilkinson, an English industrialist, invented a water powered boring machine in which a boring bar holding the cutting tool and going through the cylinder was supported on both ends. This was fundamentally different from the cantilevered borer commonly in use at that time (Fig. 4.24). In the following year, he used this machine for boring Watt’s cylinder of about 50 in. in diameter, and achieved a precision of 1/16 in. Without this machine, commercialization of the Watt’s engine would be almost impossible.

The Wilkinson’s boring machine should be regarded as the first modern machine tool (Roe 1916).

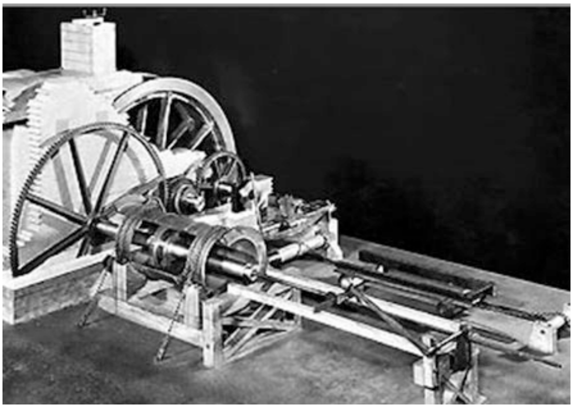


Fig. 4.24 Model of Wilkinson's boring mill (http://webarchive.nationalarchives.gov.uk)

4.4.2.3 Screw Lathe

In the days before Watt, the typical lathe was operated by a treadle and the workman held the cutting tool against the work. This led to poor machining precision, especially in cutting iron.

The history of modern lathe started from the screw machine. Thus, we will start from screw manufacturing to iterate the history of lathe. The first lathe made entirely of metals was created by a French inventor, Jacques de Vaucanson, in 1751 (ANON 1751–1766). Many parts in a screw lathe, such as the lead screw and the slide, had been developed in several centuries, containing a lot of contributions from medieval inventors whose names were not documented. L. da Vinci made drawings of a screw machine, but it is not clear if the design was put in construction. However, one thing is clear that screw machines already appeared in France in the 16th century.

To the second half of the 18th century, two types of machines, the screw lathe and the wooden screw machine, were created. The former could make screws with different pitches, and was suitable for small quantity production in tool-shops, and the latter was a special equipment for mass production of wood screws.

In 1797, A British innovator, Henry Maudslay (Fig. 4.25), created a lathe with the tool-holder driven by a leadscrew (中山秀太郎 1987; Singer et al. 1958b; McNeil 1996). The tool holder, which he designed dedicatedly to carry the cutting tool, was mounted on a carriage moving along a precisely manufactured guide rail. The carriage was driven by the leadscrew and could be positioned accurately. In 1800, he adopted changing gears; thus, the feed and the pitch of the screw machined could be adjusted. Maudslay's machine was called screw lathes at that time (Fig. 4.26). The adoption of leadscrew was a revolutionary event in the evolution of machine tools. With the leadscrew, the cutting tool was able to be guided by the machine; this, as stated before, is a key factor in the modern concept of machine tools. Since then leadscrews have been adopted to many types of machine tools.

Fig. 4.25 H. Maudslay

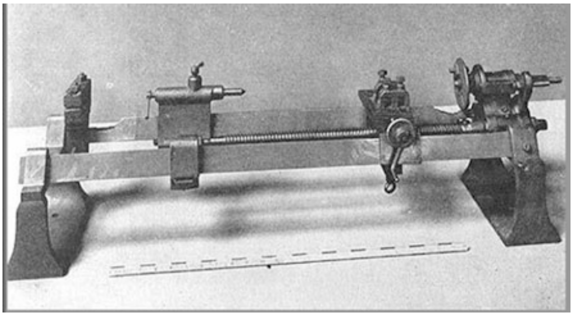


Fig. 4.26 Maudslay's screw lathe (http://saltofamerica.com/contents/displayArticle.aspx?19_266)

For many years Maudslay was considered the original inventor of the sliding carriage. However, it turned out later in the 20th century that Maudslay was neither the inventor nor the first to use it on lathe (Roe 1916). In fact, the sliding carriage on a lathe was invented by a Russian engineer, A. Nartov (Андрей Нартов) in 1718, who introduced this invention when he traveled in Britain, France and some other countries (Загорский 1960). However, Maudslay was indeed the first to combine the carriage, the leadscrew and the changing gears into a precision machine tool, which has been widely applied in almost all modern industries.

Beginning with the screw lathe, modern machine shops were formed, marking the born of a modern machine building industry. All these made Britain the first "world factory" (Sun and Zhao 2009).

The other type, the wooden screw machine, started the industry of hardware manufacturing. Later various automatic, specially-designed machine tool dedicated for screw making were developed.

As a result, screws and other threaded parts could be manufactured at very low cost, becoming affordable for frequent replacement in application.

Along with the invention of lathe, Maudslay also made outstanding contribution to the standardization of screw threads. At the beginning of the 19th century, Maudslay, along with some apprentices working in his workshop, invented the caliper which made the geometric accuracy of cylinders machine in his shop far above other companies. In 1844 the detail of Whitworth's workshop micrometer was published (ANON 1844). Because of his many contributions H. Maudslay was known as the father of the British machine tool industry.

4.4.2.4 Other Machine Tools

At the end of the 18th century, production of interchangeable parts was first achieved in the U.S., making mass production through assembly lines possible. Mass production needed a large number of unskilled workers, creating a demand, in turn, for high precision machine tools and measuring tools.

Milling machines are one of the most important machine tools. There is not a consensus on who invented the milling machine (中山秀太郎 1987; Singer et al. 1958a, b). Some credited the invention to Eli Whitney, saying he made the first milling machine in 1818. Some others tended to the opinion that several engineers were involved in developing the machine during the period 1814–1818. Thus, no single individual could be identified as the inventor. This ambiguity indicated that invention of the milling machine was one key problem encountered at that time.

In 1861, Joseph Brown, an American engineer, invented the universal milling machine for the purpose of milling spirals, such as the flutes of twist drills. It was a great success immediately after being put on the market (Brown and Sharpe 1919). This invention was another landmark in the history of machine tools after Maudslay's screw lathe.

In 1817, Richard Roberts, one of Maudslay's apprentices, invented the planning machine. In 1836, John Nasmyth, another apprentice of Maudslay, created a shaper; which had already the basic structure of modern shapers (Roe 1916; Mcneil 1996).

In 1845, an American, Stephen Fitch, invented the first turret lathe for the production of screws in a percussion lock which is a part in pistols. Fitch's machine was made by simply installing a turret head at the end of a lathe to hold cutters. This new machine greatly improved the efficiency of screw production, and reduced the requirement for operators' skill (Rolt 1965; Hounshell 1984).

By the middle of the 19th century, all general purpose machine tools, including lathe, planner and milling machines, had been existed. Table 4.2 listed the main inventions in machine tools and press machines during the First Industrial Revolution (Rübberdt 1972; Rao 1916, 2013; 中山秀太郎 1987). It is worth noting

Table 4.2 Inventions of machine tools and presses during the First Industrial Revolution

Year	Country	Invention	Inventor
1774	U.S.A.	Boring machine	J. Wilkinson
1795		Hydraulic press	J. Bramah
1797		Metal screw lathe	H. Maudslay
1817		Planer	R. Roberts
1818	UK	Horizontal milling machine	
1822		Spiritual drill	
1825	UK	Slotting machine	R. Roberts
1836		Shaper	J. Nasmyth
1839		Steam hammer	J. Nasmyth
1840		Drilling machine	
1845	U.S.A.	Turret lathe	S. Fitch
1846	Germany	Universal rolling mill	
1847	France	Radial drilling machine	
1855	U.S.A.	Universal dividing head	
1862	U.S.A.	Universal milling machine	J. Brown

that invention of a machine tool was generally a long and evolving process, involving multiple person's contribution.

The manufacturing of steam engines and other large machines created an urgent need for large forgings. Joseph Bramah, an English locksmith, invented the hydraulic press in 1795, marking the beginning of application of modern fluid transmissions to engineering (Feldman and Ford 1979).

The concept of steam hammer was already described by Watt in 1784 in his patent for the steam engine (Rowlandson 2014). In 1806 and 1827, two patents regarding steam hammers were granted; however, it was not until 1839 that the first working steam hammer was built. To produce the large paddle wheel shaft used in locomotives and steamships, a Scottish engineer, James Nasmyth, and a French engineer, François Bourdon, reinvented and built the steam hammer independently (Chomienne 1888).

In 1770, Watt invented the spiral micrometer with an accuracy of up to 1/1800 in. Richard Roberts invented the plug and the ring gauge (Rübberdt 1972).

4.4.3 Birth of Interchangeable Parts

The unique history of the early America, exploring of the neocolony, the western development and the Independent War, created a huge need for guns. The modern

Fig. 4.27 E. Whitney

production of interchangeable parts began in firearm making at the end of the 18th century. Previously, guns were made one at a time by gunsmiths, and each gun was unique. If one single component of a gun needed a replacement, the entire gun either had to be sent to an expert gunsmith for custom repairs, or discarded and replaced by another gun.

During the 18th and early 19th centuries, the idea of replacing the traditional method with a system of interchangeable manufacturing was gradually developed. The development took decades and involved many people.

Eli Whitney (Fig. 4.27) became famous in the U.S. because of his invention of the cotton gin. However, he was on the brink of bankruptcy due to a series of misfortunes by the late 1790s. In 1797, the U.S. was preparing a war with France due to the conflict caused by the French Revolution. This gave Whitney an opportunity. He sighed a contract with the U.S. government in 1798 to produce 10,000–15,000 muskets within a short time frame (中山秀太郎 1979, 1987). To implement the production, he created a large number of dedicated machine tools to do different works, such as filing, boring, grinding and etc., separately. He invented quick checking gauges to replace the less efficient calipers, and used dedicated jigs and fixtures in the production. This marked the beginning of production of interchangeable parts.

In July 1801 he built ten guns, all containing the same parts and mechanisms. He first disassembled them before the U.S. Congress and placed the parts in a mixed pile. Then he reassembled all of them right in front of the Congress by randomly picking up the mixed parts.

As mentioned before, the production of interchangeable parts, in turn, promoted the further development of dedicated machine tools. By the middle 19th century, general purpose machine tools were all invented, the conditions for producing interchangeable parts were finally all ready. At the same time, for the mass production of new mechanical products, such as weaving machines, sewing machines, bicycles and firearms, interchangeable manufacturing expanded rapidly thereafter.

The real implementation of interchangeable mass production should be attributed to Samuel Colt and Elisha Root (Singer 1958b; Hounshell 1984). S. Colt was the inventor of the revolver. During the period from 1849 to 1854, he started mass production of revolvers in his own factory, and hired E. Root to organize the production. At that time, although the concept of interchangeable production was already demonstrated by Whitney, its application to mass production of complex parts did not see a great progress yet. Root solved this problem. To make the parts interchangeable and increase the production, he built many semi-automatic machines, made dedicated gauges, and used special fixtures in the factory. Through those measures, revolver production was changed from hand-making to machine-making (Singer et al. 1958a).

The new production form, characterized with extensive use of interchangeable parts and mechanization, was first established by E. Whitney and further developed by S. Colt and S. Root. After the London World Expo in 1851, it spread all over Europe known as the "American system of manufacturing". The world center of machine tools manufacturing quietly shifted from Britain to the U.S.

4.4.4 The Beginning of Standardization

To adapt the interchangeable production, standardization became extremely important. In the 18th century, bolts and nuts were made and used in pairs, and even the bolts made by the same lathe were not interchangeable. In 1841 Joseph Whitworth advocated uniform screws in a paper. Later, some leading engineers in Britain created, based on Whitworth's method, a screw standard having a fixed thread angle of 55° and a standard pitch for a given diameter. This soon became the national standard in Britain, marking the first standard in the fields of machinery manufacturing (Roe 1916; McNeil 1996).

In 1864, an American engineer, William Sellers, proposed the standard of screw threads with a thread angle of 60°. It became later the standard of current metric screw thread (Scharf and Westcott 1884).

4.5 Perpetual Motion Machine

To discuss the history of physics and machines, the perpetual motion machine is a topic we can't get around (Angrist 1968). It may seem inappropriate to present this topic in this section, given that they were not achievement. However, it is also meaningful to briefly mention the topic in this chapter to show the zigzag path in the history. It was in the middle of the 19th century between the two Industrial Revolutions that the theory was made clear. Perpetual motion machines were impossible.

Perpetual motion machine is an old topic with a history of about 800 years (Wu 2009). It is said that its concept was originated in India and introduced to Europe in the 12th century. Once it was a hot sought-after topic and thousands of persons were involved. In 1635, the first patent in perpetual motion machine was issued by the British Patent Office. During the nearly 300 years from 1617 to 1903, about 600 applications in perpetual motion machines were filed.

Among those proponents of perpetual motion machines, there were tricksters and totally ignorant people, and superior scientists as well. To name a few, L. da Vinci drew a lot of sketches of perpetual motion machines and tried to build them; James Joule, the British physical scientist and one of the discovers of the energy conservation law, was once fascinated with the perpetual motion machine and spent all his spare time studying it; Robert Boyle also put forward a scheme of perpetual motion, with whom Denis Papin even wrote an article to discuss the concept. However, these scientists got to the correct understanding after experiments and scientific investigation. As da Vinci concluded in the last that the perpetual motion was impossible. Joule learned from this event, and contributed to the establishment of the energy conservation law.

In 1845, Joule determined the mechanical equivalence of heat through an experiment. Based on his work, Hermann von Helmholtz, a German physicist, proposed the complete expression of the energy conservation law (the first law of thermodynamics) in 1847.

Nicolas Carnot, a French scientist, established the first successful theory of the maximum efficiency of heat engines in 1824. His work, although attracting little attention during his lifetime, was further developed by Rudolf Clausius in 1850 and Lord Kelvin in 1848 into the second law of thermodynamics (Jiang 2010).

Any machine in operation would inevitably dissipate energy. Recognition of energy conservation means that no machine can have a perpetual motion.

The basic laws of thermodynamics theoretically put an end to the perpetual motion machine. The hot wave on perpetual motion machine was cooled down. Actions were taken in some countries against further exploration on perpetual motion. The French Academy of Science decided in 1775 that it would stop any publication on perpetual motion machines. The U.S. stopped accepting any patent application about perpetual motion machine in 1917 (Wu 2009).

As a Chinese physicist, Feng Duan, put as below:

> If monuments were erected for the founders of the energy conservation laws, an inscription such as “to remember the people who failed to make perpetual motion machines” should be added alongside the outstanding scientists for the unnamed heroes. Although their goal was absurd, the establishment of thermodynamics would be impossible without their failures (Wu 2009).

Some people are still peddling inventions obviously contradicting with scientific knowledge. This fact simply affirms that science and education need to be further popularized.

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Chapter 5
Second Industrial Revolution

> *The bourgeoisie, during its rule of scarce one hundred years, has created more massive and more colossal productive forces than have all preceding generations together.*
> —Carl Marx (German philosopher, economist and sociologist, 1818–1883), Friedrich Engels (German philosopher, social scientist, 1820–1895)

During the second half of the 19th century, the world entered an entirely new era. A series of unprecedented industrial achievements, such as electric power, steel, automobile and aircraft, brought tremendous changes to the industry structure, and also greatly improved the living standard of people.

The Second Industrial Revolution began from the 1860s, and finished around the dawn of the 20th century. This chapter will provide an introduction on the development of mechanical science and technology during the Revolution, but with an extension of time to the eve of WWII.

5.1 Introduction to the Second Industrial Revolution

5.1.1 Background

5.1.1.1 Background of Social Needs

After the First Industrial Revolution, steam power promoted enormously productivity. With the development of mass production and mechanization in the industry, however, the shortcomings of steam power became outstanding. To name a few, steam engines were large in size, and were difficult to be downsized; the overhead line shafts limited the mechanical efficiency and the distance of transmission; production was almost impossible to be arranged into a production line. Further industrial development required a more convenient power source; this became the breakthrough of the Second Industrial Revolution.

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https://doi.org/10.1007/978-981-15-0833-2_5

Due to the difficulty to downsize a steam engine, automobiles with steam engines were never successfully developed although many attempts were made.

During the First Industrial Revolution, cast iron displaced wood, becoming an important material for machines. However, steelmaking processes remained little progressed. Wide application of steam engines dramatically increased the operational speed of machines and the load on them, demanding for more steel production with higher quality.

5.1.1.2 The Scientific Background

In 1820, Hans Ørsted, a Danish physicist, discovered the magnetic effect of electric current. In 1831, a British scientist, Michael Faraday (Fig. 5.1), revealed the principle of electromagnetic induction. The two discoveries paved the way toward the invention of electric motors and generators. In 1824, after summarizing the materials on steam engines, Nicolas Carnot (Fig. 5.2), a French physicist, proposed a theoretical ideal thermodynamic cycle, known as the "Carnot cycle", laying the theoretical foundation for the development of heat engines. Without these scientific advances, electric motors and internal combustion engines would have never been invented.

Later in the 1860s, on the basis of Faraday's discovery, James Maxwell (Fig. 5.3), a great Scottish scientist, proposed a complete theory of electromagnetic field. Maxwell and Faraday laid the theoretical foundation for the human society to enter the age of electricity.

Fig. 5.1 M. Faraday

Fig. 5.2 N. Carnot

Fig. 5.3 J. Maxwell

5.1.1.3 The Political Background

By the 1870s, the democratic movements in the major Western countries approached completion. Slavery was prohibited in the U.S.. Serfdom in Russia was abolished. Unification was achieved in Germany and Italy. British democracy progressed further. Republic system was established in France after long term political chaos. In these countries, the feudal system was completely overthrown and the capitalist mode of production was established. The political condition of the Second Industrial Revolution was completed.

Germany in particular began the process of reform and unification from the early 19th century (Rübberdt 1972). As a result, it developed rapidly in economy, science, technology and education, becoming a rival of Britain as the primary industrial nation in Europe during the Second Industrial Revolution.

5.1.2 The Age of Electricity

Wide application of electricity was the primary symbol of the Second Industrial Revolution.

5.1.2.1 Electric Motor and Generator

Based on Faraday's discovery of electromagnetic induction, many people in France, Britain, Denmark and Germany, tried to build electric generators during the period of 1830s to 1860s. Among them the most famous was a German, Werner Siemens (Fig. 5.4), who made a self-excited DC generator in 1866, and displayed it at the Paris world Expo in 1867.

The invention of steam engines was started by D. Papin in 1690, and completed by J. Watt in 1790, covering 100 years. However, it took only 35 years from Faraday's discovery of the electromagnetic induction to Siemens' invention of the generator. The time from science to technology was greatly shortened.

In 1882, Thomas Edison (Fig. 5.5), the great American inventor, built the world's largest generator at that time, the first DC power station and the first electric lighting system in New York.

Although some people tried to build electric motors since the 1830s, almost all of them had to use voltaic batteries. Thus, no one reached the stage of practical use. For example, Moritz Hermann Jacobi (Борис Якоби), a Russian-Prussian engineer, created the first real rotating electric motor in May 1834 (Richter 2013), and constructed a 28-foot electric motor boat powered by battery cells in 1839. The boat was tested on the Neva River carrying 14 passengers, at a speed of three miles per hour.

In 1869, Zenobe Gramme, a Belgium engineer, developed a DC generator. At the Vienna World Expo in 1873, two generators were mistakenly connected. The current generated by one machine flew into the armature coil of the other, which suddenly began to rotate on its own (ANON3 2014). People came to realize incidentally a fact that a generator could be turned into a motor. Gramme became the first in history to create practical and commercial motors.

5.1.2.2 The Age of Electricity

Siemens' generator symbolized the age of electricity, marking the beginning of the Second Industrial Revolution.

Electricity began to be used for driving machines, taking the position of steam. Electricity outperforms steam in many ways. It is cheaper and can be transmitted quickly through long-distance with little loss. It is also convenient in distribution according to the need of users. Its wide application brought the human society from "the age of steam" into "the age of electricity". In the second half of the 19th century, many new electric products and technologies were invented, such as lights, electric trams, electric drills, and electric welding etc. T. Edison himself held as many as 1093 U.S. patents, and many ones in other countries, being regarded as the most productive and greatest inventor in history.

Motors considerably changed the picture of workshops during the 20 years beginning from the end of 19th century. Individual machine tools started to be powered by electric motors, eliminating the overhead line shafts and steam engines. Large scale manufacturing became possible.

With the expanding of electric power supply, some issues of DC motors were exposed, such as poor reliability and high cost. During the 1880s, effort was put into the study of alternating current (AC) electricity. In fact, an early generator built in Faraday's laboratory when investigating the electromagnetic induction was of AC.

The first large two-phase AC generator was created by an English electrical engineer, James Gordon, in 1882 (Singer et al. 1958a). Nikola Tesla (Fig. 5.6), a Serbian-American scientist, designed the first two-phase AC motor and patented it in 1891.

A sharp debate over DC and AC power took place in both the U.S. and the UK (Singer et al. 1958a). Alternating current could change the voltage through a transformer, and high voltage transmission could greatly reduce the resistive loss. Due to these reason, AC stood out becoming the winner. N. Tesla was a brilliant scientist, and made outstanding contributions in many fields. He used to work for T. Edison; however, Edison used his influence to suppress Tesla's AC power supply system.

M. Dolivo-Dobrovolsky (М. Доливо-Добровольский), A Ukraine engineer in German electric company (AEG), developed the three-phase AC generator and motor, and demonstrated the technology of long-distance transmission with three-phase alternating current in 1891 (Neidhöfer n.d.). Since then, more economical and reliable three-phase alternating current was widely accepted. At the turn of the century, motors replaced steam engines in a large scale, and the electric power industry entered a new stage.

Fig. 5.4 W. Siemen

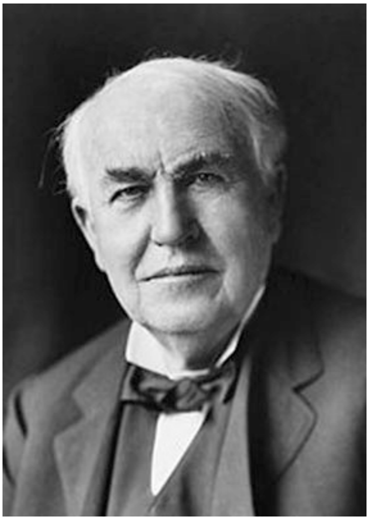


Fig. 5.5 T. Edison

In order to provide sufficient power, more power stations were built. Correspondingly, steam and hydraulic turbines, being critical equipment in power stations, were growing fast, forming a new sector of power machinery (see Sect. 5.3).

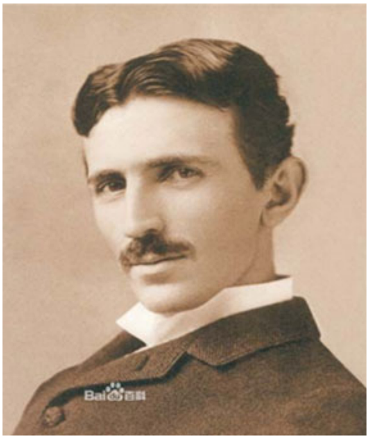


Fig. 5.6 N. Tesla

5.1.3 *Era of Steel*

During the first half of the 19th century, iron production increased rapidly due to the need of construction and railway. However, steel production still remained stationary. The UK was then the largest steel producer; its annual output was only 60,000 tons in 1850. Due to the limit of old smelting technology, the quality of steel was unsatisfactory and the price was high. Thus, steel was only used as materials of tools and instruments (Singer et al. 1958a).

In 1856, Henry Bessemer, a British engineer, invented a new steelmaking process with converter (the Bessemer process), the first industrial process for making steel directly from molten pig iron (Fig. 5.7). The Bessemer process greatly improved the quality of steel, and achieved mass production at low cost. In 1850, C. Siemens, a German, developed the regenerative furnace. In 1865, P.-É. Martin, a French engineer used the regenerative furnace for making steel. This process is known as the open hearth process, and the furnace as an "open-hearth" furnace. The new process has a series of advantages, such as low cost, large capacity of furnace (in Fig. 5.8, width of the furnace was about 11 m), high steel quality, and good adaptability to raw materials. Thus, it displaced the Bessemer process, becoming the main steelmaking technology. However, a drawback of this process is that the melting and refining a charge takes several hours of time. In 1878, C. Siemens patented the electric arc furnace. The first electric arc furnace was built by a French scientist, Paul Héroult, and the commercial production began in the U.S. in 1907. The electric arc furnace steelmaking solved the problem of making full use of scrap steel.

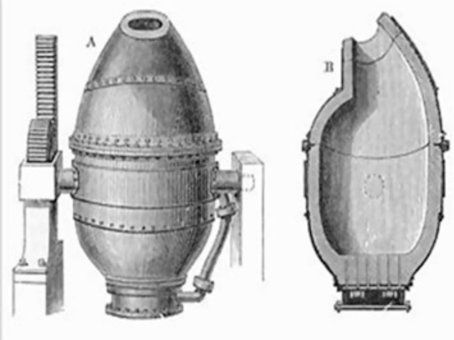


Fig. 5.7 Schematic diagram of Bessemer converter (https://en.wikipedia.org/wiki/Bessemer_process)

Steelmaking is an oxidation smelting process. At that time, metal in converter was smelting with oxygen in the air, and a lot of heat was taken away by nitrogen. At the end of the 19th century, oxygen for industrial use became available. At the early 20th century, oxygen producing process, in which air was liquefied and distilled, was successfully developed. During the 1920s and 1930s, steelmaking with oxygen began to be tested both in open hearth furnaces and in converters. After WWII, oxygen top blown converter steelmaking was developed successfully and applied widely, replacing the open hearth furnace steelmaking.

With the advance in smelting technology, steel output grew fast, and quality was improved significantly as well. Steel, due to the better toughness and strength, had longer service life, replacing gradually wrought iron and becoming the new material in machinery, railway, construction and many other fields. The flourishing of steel industry led to rapid growth of the heavy industry. This period was known as the “era of steel”. Until now, steel is still the main material for machinery despite many new materials have been developed.

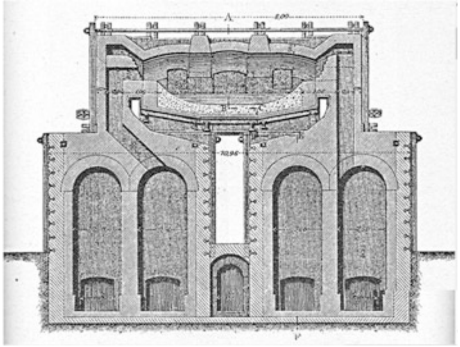


Fig. 5.8 Siemens furnace from 1895 (https://en.wikipedia.org/wiki/Open_hearth_furnace)

5.1.4 Introduction to Development of Mechanical Technology

In the Second Industrial Revolution, electrical motors and internal combustion engines replaced steam engines, becoming the dominant prime movers. In the age of electricity, steam and hydraulic turbines were rapidly developed and widely used.

Shortly after the internal combustion engine, automobiles and aircraft were invented. The automobile and aviation industries pushed forward the machine design and manufacturing technology in many aspects.

More and more new machines were invented, and applied in many fields. Machines even began to enter people's daily life. Machines tended to develop toward high speed, great power, high precision and light weight.

Great progress was made also in mechanical and hydraulic transmissions. Machine design entered a semi-theoretical and semi-empirical stage.

In this period, various precision machine tools, such as grinding machines and gear processing machines, were developed. Mass production appeared and modern management system was firstly established in machine building enterprises.

5.1.5 Features of the Second Industrial Revolution

The Second Industrial Revolution, as the first one did, greatly promoted the capitalist economy. However, it also showed some features different from the first one.

5.1.5.1 Science Ahead

In the First Industrial Revolution, technical inventions were mainly made by experienced craftsmen and technicians, such as J. Hargreaves and J. Watt. They did not have solid theoretical knowledge; therefore, science and technology were separated.

In the age of electricity, the situation was basically changed. Scientists were going ahead of engineers; theories and experiments ahead of technological innovations. Science became an important promoting factor in technology and production development. For example, M. Faraday's discovery of electromagnetics directly laid the theoretical basis for the invention of generators and motors. Internal combustion engines were invented and improved by several engineers; however, its theoretical basis was laid by a physicist, N. Carnot.

Combination of science and technology was related to the education reform in the 19th century. Paris Institute of Technology (École Polytechnique) was established during the French Revolution, which was specialized in engineering education. The concept of combination of teaching and research was firstly proposed and advocated in German universities, where the tutor system was established later in postgraduate training.

5.1.5.2 Comprehensive Industrialization

The First Industrial Revolution started the process of industrialization. However, the influence was limited to the light industries, mainly the textile industry, in which mechanized factories replaced manual workshops. While the Second Revolution expanded the industrialization to the heavy industries, such as iron and steel, and machine building etc. In addition, some new industries, including petroleum, chemical, electrical, automotive etc. emerged and developed.

5.1.5.3 Rising of Industrialized Countries in the West

The First Industrial Revolution started first in Britain. Correspondingly, almost all new machines and technologies during this period of time were invented and developed in Britain first, and then spread to the U.S. and other European countries. The revolution in these countries was much slower. The Second Industrial Revolution, however, occurred almost simultaneously in several advanced countries. Germany and the U.S. rose quickly in this period. Britain, however, slowed down mainly due to its stagnation of engineering education.

In Germany, a unified domestic market was formed after the nation reunification. The government made appropriate national development strategy, and paid great attention to education and labor force training. The Humboldt's model was developed in higher education, (see the Chap. 8) and industrialization rapidly developed. As a result, Germany surpassed Britain and France in a very short period of time, becoming the leading country in the Second Industrial Revolution.

After the war of independence and the civil war, the U.S. got on a fast track of development. The country, like no others, was full of vigor and vitality right after birth. To the eve of WWI, the total output value of the manufacturing industry of the U.S. ranked already the first in the world.

During the second half of the 19th century, the European technologies and production methods started to spread to other countries, such as Japan where the Meiji Restoration took place in 1868.

5.2 Internal Combustion Engine and New Transportation Revolution

Power remained the most important keyword in the Second Industrial Revolution as it was in the First one. However, the old steam power stepped down, while new powers rose. Electric motors and internal combustion engines replaced steam engines, becoming the dominant drivers in the industry. Internal combustion engines led to the birth of automobile and aircraft, causing a revolution in the way of transportation (Goddard 2010; Pan and Wang 2005; Williams et al. 1978a).

5.2.1 Invention and Development of Internal Combustion Engine

5.2.1.1 Background of the Invention

Despite the continuous improvement, the inherent shortcomings of steam engines were becoming realized, including large size, poor mobility, low efficiency, and the need for heavy boilers. The heat is converted to mechanical energy through steam. All these issues were related to the fact that the fuel is burning outside the cylinder, the so-called “external combustion”. Therefore, people attempted very early to change the “external combustion” to “internal combustion” by combining the boiler and the cylinder into one unit.

In 1859, a Belgian, Jean Lenoir, made the first practical internal combustion engine which burned a mixture of coal gas and air.

The first oil well of the world was drilled in the U.S. also in 1859. Since then the oil industry developed quickly. Gas and diesel became ordinary commodities, laying the material basis for internal combustion engines.

5.2.1.2 Invention of the Gasoline Engine

In 1862, a French engineer, Alphonse de Rochas (Fig. 5.9), proposed the principle of four stroke internal combustion engine.

After seeing de Rochas’s proposal in the newspaper, Nicolaus Otto (Fig. 5.10), a German engineer, put it into practice immediately. In 1876, Otto made the first four stroke internal combustion engine with gas as the fuel. This machine run at 80–150 r/min, had a thermal efficiency of 12–14%, and a mass-power ratio of 272 kg/kW. These performances would be very poor in nowadays standard; however, they were the best at that time.

Fig. 5.9 A. de Rochas

Fig. 5.10 N. Otto

In 1885, Gottlieb Daimler, a German engineer, invented the carburettor which transformed gas into mist, and increased the engine speed to 800 r/min. The next year, another German engineer, Karl Benz, invented a mixer and an electric ignition device. Inventions of Daimler and Benz improved greatly the performance of Otto's engine which was then referred to as a gas engine.

In 1889, the first twin cylinder V engine was designed by W. Maybach and built by G. Daimler.

In 1903, airplane was invented. To meet the new requirements, the main topics of internal combustion engines in the first 20 years of the 20th century were to increase the power and reduce the mass-power ratio. The engine speed reached 1500 r/min during this period. Four cylinder and 8 cylinder in-line engines and 16 cylinder V engines appeared in succession. The mass-power ratio of the multi-cylinder engines gradually reduced to 5.44 kg/kW, reaching the level to be used in aircraft.

During this period, another research topic was to install a turbocharger on the gasoline engine. Airplanes met a serious problem then that the engine could not get adequate oxygen at high altitude. A turbocharger was first applied in Britain in the 1920s, in which an air compressor was used to increase the gas pressure to the engine. With this device, the performances of an engine were significantly improved, reaching a pressure of 1.5 ATM, a mass-power ratio of 0.68 kg/kW, a power of up to 2570 kW, and a speed of up to 3400 r/min.

5.2.1.3 Diesel Engines

In 1892, Rudolf Diesel, a German engineer, designed the diesel engine. A diesel engine works differently from a gas engine. It has no ignition system, and the fuel supply system is relatively simpler. Thus, its reliability is higher than gas engines. In addition, a higher compression ratio gives higher thermal efficiency, and is of more economy than gas engines. Under the same power a diesel engine has a larger torque output, thus, a lower speed. Due to the higher work pressure, however, the parts require higher strength and stiffness. Consequently, a diesel engine is in general relatively heavier, larger and with high level of vibration and noise. Because of these features, diesel engines are mainly used in ships, construction and mining machines, agricultural machines, heavy trucks and tanks.

5.2.1.4 Significance of Internal Combustion Engine

Since the early 20th century, the application of internal combustion engines has expanded rapidly. Most mobile machines are driven with internal combustion engines. Gas engines mainly developed in the 20th century toward increasing the volume of cylinder, compression ratio, speed, and fuel efficiency.

The invention of internal combustion engine led to the appearance of automobiles and airplanes, bring revolution to transportation.

The invention of internal combustion engine also promoted development of the oil industry; thus, the petrochemical industry was established. Oil became a new energy as important as coal. In 1870, the world oil output was only 0.8 million tons. To 1900 it soared to 20 million tons.

By around 1950, steam engines were basically pushed out of industrial applications by electric motors and internal combustion engines (Williams et al. 1978b).

5.2.2 Invention and Early Development of Automobile

The invention of automobile was an important event in the Second Industrial Revolution (Pan and Wang 2005; Singer et al. 1958a; Williams et al. 1978b).

Attempts to construct a vehicle propelled by means other than internal combustion engines, such as a steam engine, or an electric motor, are traced back to 1770. This effort reached summit in the first half of the 19th century. However, no one was successful.

In 1885, K. Benz (Fig. 5.11) developed successfully a three-wheel vehicle (Fig. 5.12), and he patented it in early 1886. Also in 1885, G. Daimler (Fig. 5.13) patented a bicycle equipped with a gas engine. From nowadays viewpoint, Benz and Daimler's inventions were not more than a three-wheel and a two-wheel motorcycle. In 1886, Daimler made the world's first four-wheel automobile. G. Daimler and K. Benz were known as the "father of automobile", and the year of 1886 is regarded as the first year of the automobile era.

The speed of Benz's vehicle was only 18 km/h. After 67 years, an automobile built in the U.S. in 1953 reached a record speed of 264 km/h. Today, a super sports car runs at a speed as high as 400 km/h, and the time to accelerate from zero to 100 km/h takes only 3 s. The dramatic progress in speed since the birth of automobiles is an indicator of the development of the automotive industry, the progress of technologies, and the popularity of automobiles. The world automobile industry has a marvellous history, full of spectaculars and legends.

Fig. 5.11 K. Benz

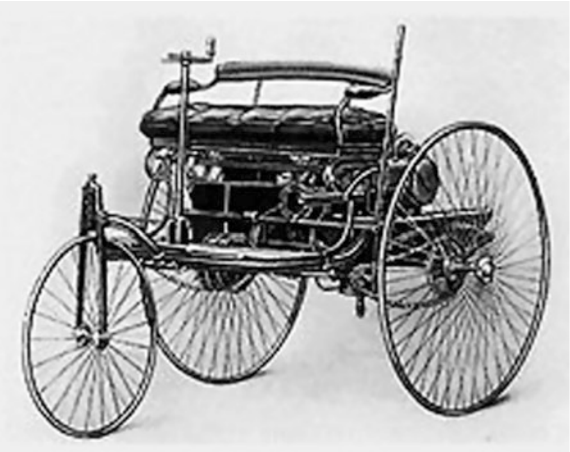


Fig. 5.12 Benz car (https://en.wikipedia.org/wiki/Karl_Benz)

In the major industrialized countries, the automotive industry had been formed before the WWI.

With an ambition to build affordable automobiles, Henry Ford (Fig. 5.14), an American entrepreneur, developed the world's first assembly line in 1913. This assembly line increased the productivity by 8 times; in every 10 s a vehicle drove off the line. This mass production method greatly reduced the cost of automobiles, changing automobiles from an expensive curiosity to an affordable commodity. To the 1924, every 7 people in the U.S. owned an automobile; the U.S. became a real "kingdom of automobiles".

The vehicles of Benz and Daimler were very much different from what we commonly see nowadays in both structure and appearance. It was neither easy nor pleasant to drive an early automobile. To start the engine, a handle must be operated hardly. Turning required big effort due to no steering assistance equipped. Steering was not agile; dangerous situations often occurred. The braking system was not effective either. As a complex system, an automobile actually is the result of many inventions. The period from 1886 to the 1930s was known as the "age of automobile inventors". Shown in Table 5.1 are some inventions related to automobiles before WWII and their applications. Some of the inventions were inspired by intuition, having no systematic mechanics analysis; however, dynamics was considered in all of them given the higher automobile speed.

French made significant contribution in forming the basic structure of modern cars (Table 5.1).

Fig. 5.13 G. Daimler

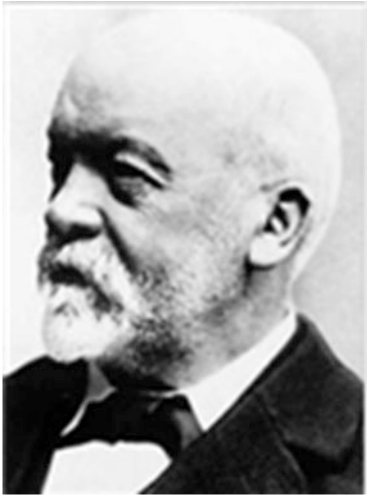
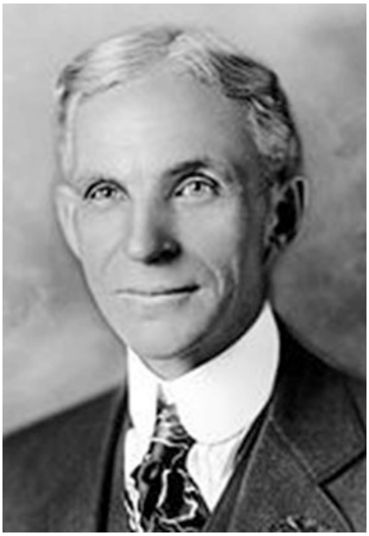


Fig. 5.14 H. Ford



At the early 20th century, the speed of internal combustion engine reached 1000–1200 r/min, doubled the number in 1886. To the 1920s it further soared to 3400 r/min. The speed of automobiles has been also in continuous increase since the birth of the automobile industry. It already exceeded 100 km/h in 1920, more than five times of that of the first Benz car.

Table 5.1 Inventions directly related to traveling and handling of cars before the WWII

Year	Country	Contents
1888	UK	Practical application of inflated tires
1889	France	Important inventions in history of vehicles: gear transmission and differential
	Germany	Twin cylinder V-type engine
1891	France	The basic transmission structure formed: front engine, rear wheel drive and special chassis
1897	UK	High pressure lubrication system
1898	France	Universal joint replaced chain drives in automobile
1900		All metal body replaced the wooden structure
1902	UK, France	Automobile brake
	UK	Friction type shock absorber
1903	UK	8 cylinders V-type engine
1904		Air brake system
1905	Germany	Turbocharger and hydraulic coupling
1906	Germany	Front wheel brake
1912	Germany	Front wheel steering mechanism
1923	Canada	Automatic transmission
1927	U.S.	Hyperbolic gear
1931		Independent suspension
1930s	Sweden	Hydraulic torque converter
1934	U.S.	Streamlined body
1940	U.S.	Using patent of Munro, General Motors produces automatic transmission, Hydra-Matic, on a large scale

5.2.3 Invention and Early Development of Aircraft

5.2.3.1 Pioneers of Aircraft Research

Flying in the sky had been a human dream since ancient times. During the Industrial Revolutions, the passion of flying was ignited again. In 1783, the first manned flight of hot air balloon was realized in France. This balloon was with no power. During the period of 1894–1900, a German, Ferdinand Zeppelin, designed and made an airship with a piston engine. It was able to take 20 passengers; with it regular flight was implemented. Either the balloon or the airship had a specific gravity less than the air; thus, they are essentially different from an aircraft. Throughout the 19th century, effort was never stopped in the UK, Germany and France in theoretical exploration, manufacturing and testing of aircraft. During the 1890s, there were pilots killed in experimental flights in both Britain and Germany.

In 1886, the invention of carburetor and electric ignition system brought gasoline engines toward technical maturity, giving a great impetus to research on aircraft.

5.2.3.2 Main Contributions of Wright Brothers

In 1903, the Wright brothers, Orville Wright and Wilbur Wright, developed an airplane and had a successful flight test in the U.S. (Goddard 2010; Singer et al. 1958a).

The Wright brothers were not the first to build and test an aircraft. However, they were undoubtedly the first to make controlled, sustained fixed-wing flight. Despite the death of Otto Lilienthal, a German aviation pioneer, in a flying glider was a hard blow to human's dream of flying, the Wright brothers still believed that human could make powered flight, and Lilienthal's tragedy was due to the lack of knowledge in controlling the airplane. With this believe, the Wright brothers started the powered flying exploration right after Lilienthal's death in 1896.

The three rotation of an aircraft around the coordinate axes fixed at the center of mass, known as the pitch, the roll and the yaw (shown in Fig. 5.15), are the critical dynamic parameters in aircraft flight. The breakthrough of the Wright's brothers was that they solved the problem to control the three parameters in flight, so the pilot could effectively keep balance of the aircraft. Three axes control became later the design criterion of all kinds of fixed-wing aircraft.

All the flight pioneers before put emphasis on the power of the engine. The Wright brothers, however, took a different route, determining from the very beginning that: (1) manipulation of the plane was a key problem to be solved; (2) to manipulate an aircraft, a mechanical device must be used to take advantage of the air dynamics effect. The first patent they filed in the U.S. was an aerodynamic control system, not a flying machine.

5.2.3.3 Outstanding Inventors

The Wright brothers (Fig. 5.16) showed keen interest in machine assembly and flight when they were teenagers. They used to repair bicycles for a living.

They paid great attention to the importance of theory. In order to read aerodynamics literatures written in German, they worked hard to learn the language. The Wright brothers did excellent in summarizing the past experience of others, and learning lesson from it. Although Lilienthal failed in flight, and lost his life, he opened up a correct approach—starting from a glider and then proceeding to powered flight after stable control was achieved with the glider. The Wright brothers exactly followed this route. During the period of 1900–1902, they built three gliders and tested them in a self-made small wind tunnel. Through the tests, they obtained more solid data, making it possible to design and construct more efficient wings and propellers. They also gained knowledge in the tests to effectively control long time gliding flight.

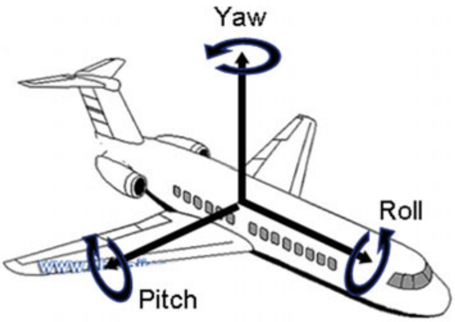


Fig. 5.15 Three key flight parameters

The Wright brothers constructed the first self-powered biplane, the Wright Flyer I, which was equipped with two propellers. On December 17, 1903, they successfully realized the first powered manned flight in history. The records they set on that day through four flights include the continuing flying time of 59 s, flight distance of 260 m, flight height of 3.8 m and flying speed of 48 km/h. During the two years following, they continued to develop the Flyer II and Flyer III.

5.2.3.4 Following Developments

In 1906, the Wright brothers patented their invention. Initially, however, their success did not attract much attention in the U.S. In 1908, France first noticed this ground breaking event, and gave the due credit to their achievements, stirring a hot wave of enthusiasm on aviation all over the world. Several years after Wright brothers' success, Europe made manned flight as well.

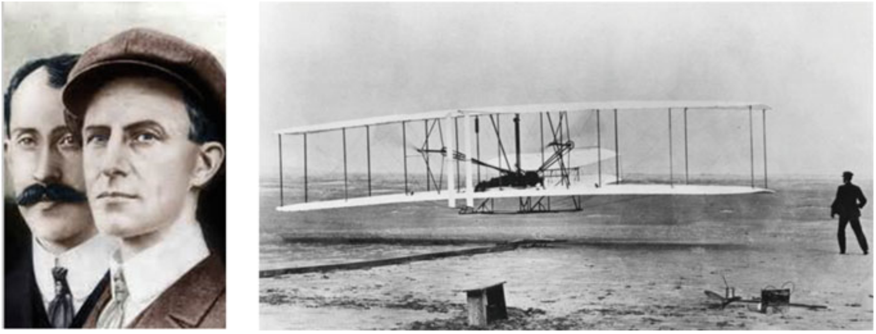


Fig. 5.16 Wright brothers and their first flight (https://www.thoughtco.com/wright-brothers-make-the-first-flight-1779633)

The aviation industry was established in the major industrialized countries thereafter.

Airplanes were firstly used for military purposes in WWI (1914–1918), initially only for reconnaissance. By the end of the war, however, the air force had become an important branch of the armed force, and many types of specialized, airplanes, including fighters, bombers and ground-attackers, were developed.

The aircraft fuselage was initially made of non-metallic materials, mainly spruce wood, bamboo and fabrics. Hundreds of thousands of such airplanes were made during WWI. In 1909, Germans accidentally discovered that aluminum could be hardened in the research on making aluminum coins (Williams et al. 1978a). In 1915, a plane with whole aluminum fuselage was made, greatly improving the strength and reducing resistance.

In 1919, international civil aviation routes were opened, marking a new era of transportation.

The success of aircraft promoted the study on the aviation technology which, in turn, improved aircraft design. Tremendous progresses have been made in improving the aerodynamics of fuselage shapes and developing huge engine power.

During the late 1920s, biplanes were gradually transited to monoplanes. In the 1930s, streamlined shapes were first adopted in Boeing 247 to increase the speed.

In around 1930, some changes happened to airplane design. Stationary landing gears were replaced by retractable ones; cockpit changed from open to closed; wing flaps begun to be used; and completely metal fuselages became widely accepted.

To the 1930s, the mass-power ratio of the piston engine was decreased to 0.68 kg/kW. The engine power was increased from 294 kW of 1919 to 2570 kW of the end of 1930s. Radial piston engines were developed and widely used in the U. S., while Britain and Germany made progress in in-line and V-type engines. At the late 1930s, radio navigation was widely used in civil aviation aircraft.

Records of flying range, ceiling and speed were continuously refreshed. A series of long-distance flights showed that reliability and safety of aircraft was greatly improved. In 1938, a ceiling record of 17,094 m was set up. In 1939, an unprecedented record of speed of 755 km/h of planes with piston engines was made by a German pursuit plane.

In 1939, helicopters were gradually improved, approaching technical maturity. Germany made a successful flight of jet planes. In the late 1930s, WWII was looming; new types of military aircraft were developed in several countries.

The development of transportation is closely related to economic and social development. Automobiles and airplanes caused revolution to transportation, connecting countries of the world unprecedentedly closely. At the same time, it also changed people's way of life and improved quality of life.

5.2.4 Other Changes in Transportation

Electric motors and internal combustion engines began to displace steam engines not only in automobiles and airplanes, but also in other traffic tools.

5.2.4.1 Electric Locomotive

In 1879, the first passenger train of the world driven by an electric locomotive appeared in Berlin. It was created by Wiener Siemens, who was also the first to build a DC generator (Singer et al. 1958a). At that time, with more and more tunnels excavated and city subway developed, smoke of steam locomotives became a real problem. The municipal authorities tended to prohibit the use of steam locomotives in city, directly leading to the development of electric locomotives.

5.2.4.2 Ships with Diesel Engines

In 1886, G. Daimler, the well-known automobile inventor, tested a gasoline engine on his self-made boat with success. Due to the very high speed, gasoline engines were widely used in torpedo boats and motor boats in WWI. However, diesel engines replaced gas ones, becoming the predominant power in ships for economic reasons. In 1902, the first marine diesel engine was installed in a French canal boat. In 1903, the Russian oil tanker "*Vandal*" was built, sailing in Caspian Sea and Volga River, symbolizing the world's first diesel ship (Yang 2005).

5.2.4.3 Locomotive Driven by Diesel Engine

During the 1880s and 1890s, some tests were carried out on driving locomotives by internal combustion engines, but no one was of success. In 1912, a success was recorded in Switzerland. In this test, a diesel engine was used to drive a generator from which an electronic motor took power and drove the locomotive. However, this concept was not widely adopted by the industry (Churella 1998). Later on, the Soviet Union, Germany and the U.S., also made effort to develop diesel engines for locomotives. In 1935, General Motors Co. made a diesel engine which could take full advantage of the horsepower at low speed, representing the most important step in the development of diesel locomotives. This technology made diesel locomotives completely replace steam ones in the U.S. (Williams et al. 1978b).

5.2.4.4 Bicycles and Motorcycles

The invention of bicycles, seemingly simple, took nearly a hundred years (Singer et al. 1958a; Jiang 2010). In 1791, a wooden bicycle was invented by a French craftsman, Comte Mede de Sivrac, in which there was no driving and steering devices. It was moved forward by pedaling both feet on the ground. Due to the lack of steering mechanism, to change its direction one had to get off the bicycle first, and then turn it by hand. In 1816, a German, Karl Drais, added a handlebar to control the direction of the bicycle. In 1869, a Scotsman, Thomas McCall, installed a crank on the rear axle, and a coupler to connect the rear crank and the front pedal. Obviously the bicycles mentioned above were greatly different from what we see today (Fig. 5.17).

In 1874, a British man, H. Lawson, connected the pedal and rear axle by chain, replacing the originally used four-bar linkage. In 1886, John Starley, a British engineer, installed a front fork and brakes. Besides, he made several other important changes, including using the same size of front and rear wheels for keeping balance, using a diamond shaped frame made of steel pipes, and using rubber wheels for the first time. After those changes, Starley's bicycle looked pretty much the same with today's bicycles. In addition to the improvements on bicycles, he also reconstructed the machine tools for making bicycles, laying the foundation for mass production. Due to the many contributions he made on bicycles and bicycle production, Starley was later known as the "father of bicycles".

In 1888, John Dunlop, a Scottish inventor, inflated a watering rubber pipe and mounted it on bicycle wheels in a bicycle race, it turned out this greatly helped him stand out from other competitors. Pneumatic tires was a great step in the history of vehicles. They increase flexibility, reduce vibration and increase the traction between wheels and the road. Consequently, the speed of vehicles were greatly increased. When Dunlop went to register his invention, he was told that, Robert Thomson, another Scottish, had registered the invention of pneumatic tire already in 1845 (ANON2 n.d.). Despite of this, it was Dunlop who first established the tire making factory.

Fig. 5.17 Models in bicycle's history **a** C. Sivrac, 1791 **b** K. Drais, 1816 **c** J. Starley, 1886

Motorcycles driven by steam first appeared during the late 1860s. However, this was not regarded as a real motorcycle; generally only vehicles with two or three wheels driven by a gasoline engine are considered motorcycle. By this definition G. Daimler was the first to invent a motorcycle; he filed a patent in 1885. Later on improvements were made in Germany, France and the U.S. and mass production started in the 20th century (Jiang 2010).

5.2.4.5 Elevators

The initial development of elevators was mainly driven by the need in moving raw materials such as coals and lumbers. In the mid-19th century, elevators were operated on steam power. In 1867, a hydraulic passenger elevator was displayed at the Paris World Expo. In 1870, Anton Freissler, an Austrian engineer, built a hydraulic elevator for transporting people the first time in history. At that time the municipal water supply system was directly used to operate the elevator. Water-pipes were often burst due to the water hammer phenomenon. Later, it was switched to use independent pumps for the supply of pressured water (Lu 2001).

In 1880, the German inventor Weiner Siemens invented the electric elevator. It was coincident with the time when the U.S. entered a booming era of high-rise buildings. An American inventor, Frank Sprague, made many contributions to improve the speed and safety of elevators by using the elevator floor control, acceleration control and safety control. Compared with the hydraulic and steam driven elevators, Sprague's elevator had a much larger load capacity and higher operation speed (Greller 2014).

Table 5.2 listed inventions of transportation means during the Second Industrial Revolution.

Table 5.2 Inventions of transportation means in the Second Industrial Revolution

Time	Country	Contents	Inventor
1879	Germany	Electric locomotive	W. Siemens
1885		Gasoline engine car with 3 wheels	K. Benz
1886		Gasoline engine car with 4 wheels	G. Daimler
1886	UK	Perfection of bicycle	J. Starley
1888		Pneumatic tire	J. Dunlop
1897		Steam turbine driven ship	C. Parsons
1897	U.S.	Gasoline engine driven submarine	
1900	Germany	Rigid airship	F. Zeppelin
1903	U.S.	Airplane	Wright brothers
1904	Russia	Diesel ships	
1915	UK	Aircraft carrier	
1933	U.S.	Boeing 247	Boeing Co.
1939	Germany	Jet aircraft	

5.3 Machine Inventions in Second Industrial Revolution

Electricity, oil fuel and steel were the three cornerstones to the invention of machines in the Second Industrial Revolution, which influenced the human society much deeper and broader than in the First Industrial Revolution.

(1) After entering the era of electricity, the demand for electric power rose sharply. Thermal and hydraulic power generations led to the invention and development of steam and hydraulic turbines, respectively. Manufacturing of these power machines further inspired the invention of new machine tools.
(2) Internal combustion engines made automobiles, airplanes and jet aircraft invented in series, also promoted the development of many other machines for which electric power was not convenient to be used (such as tractors, oil extraction machines). Manufacturing of automobiles and aircrafts demanded for the invention of many precision and special machine tools.
(3) After entering the era of steel, the need for iron and steel was driven high by the manufacturing of machines and construction needs. This further pushed the development of various mining machines, such as drilling machines, crushing machines, processing machines, hoisting and conveying machines and so forth.

5.3.1 Power Machinery

During the Second Industrial Revolution power machinery developed vigorously (Table 5.3). In addition to motors and internal combustion engines, the invention of several other power machines were also very important.

In the 1890s, the electric power industry was established. At the early stage, steam engines were the prime mover in thermal power stations. High efficiency, high speed and high capacity were the needs for prime movers in power stations. These requirements constituted the original motivation for developing steam turbines which appeared in 1884. Hydraulic turbines were also invented later for hydraulic power resources.

5.3.1.1 Steam Turbine

A steam turbine is a rotary machine which transforms the thermal energy of steam into the kinetic energy of a rotating shaft. According to the working principle, steam turbines can be divided into two categories, impulse and reaction turbines.

Table 5.3 Inventions of power machines in the Second Industrial Revolution

Time	Country	Contents	Inventor
1850	UK	Inward-flow reaction hydraulic turbine	J. Francis
1860	France	Practical gas engine	J. Lenoir
1876	Germany	Four-stroke internal combustion engine	N. Otto
1884	UK	Multi-stage reaction steam turbine	C. Parsons
1889	U.S.	Impulse hydraulic turbine	L. Pelton
1893	Germany	Diesel engine	R. Diesel
1896	U.S.	Impulse steam turbine	C. Curtis
1913	Austria	Propeller-type hydraulic turbine	V. Kaplan
1930	Germany	Jet engine	H. von Ohain
1939	Switzerland	Practical gas turbine	

In 1629, an Italian, Giovanni Branca, described a wheel with flat vanes like a paddlewheel which was rotated by steam produced in a closed vessel and directed at the vanes through a pipe. This was the initial form of impulse turbines (Lardner 1850). In 1883, Gustaf de Laval, a Swedish engineer, created a single stage impulse turbine with only a power capacity of 3.7 kW. Due to the limited power capacity, single stage turbines are rarely used nowadays.

The device described by Hero of Alexandria in the 1st century (see Chap. 2) could be regarded as the rudiment of modern reaction turbines. In 1884, Charles Parsons, a British engineer, made the first multistage reaction turbine with a power capacity of 10 hp. The multistage design greatly improved efficiency and increased the turbine's capacity.

Parsons publicized his engine in a very special way. He built a yacht equipped with 3 turbines. In June of 1897, at the naval parade to celebrate the diamond anniversary of the Queen of Victoria, he drove his yacht shuttling around the parade of fleet. It was ordered to expel him, but no one of the boats could catch up with his yacht (Yang 2005).

Steam turbines have a continuous steam flow of high speed, being more powerful than the reciprocating engines. Thus, they developed fast, and approached maturity technically soon in almost all aspects. Steam turbines have been continuously developed toward increasing power capacity, requiring higher pressure and temperature of steam, which, in turn, gives higher thermal efficiency (Fig. 5.18).

The invention of Parsons made it possible to produce a large amount of cheap electricity. It also brought revolutionary changes to shipping and naval vessels.

In 1896, Charles Curtis, an U.S. engineer, built a multistage impulse turbine (Goddard 2010). Now, this kind of turbines are only used in limited applications, such as driving a pump or a blower, due to its relatively lower power capacity. In 1901, a Frenchman, C.-E. Rateau, invented an improved impulse turbine. Rateau's and Parsons' machines have been developed in parallel, and were combined in some cases (Williams et al. 1978b; GSHCAS 1985).

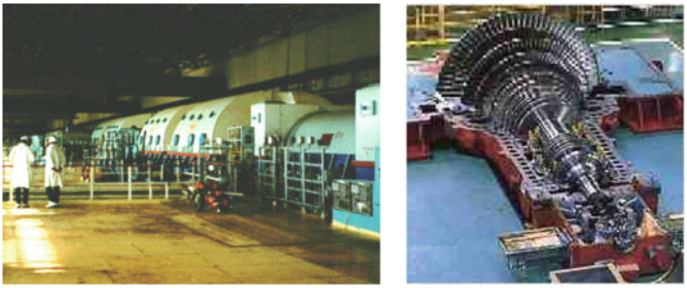


Fig. 5.18 Steam turbine generator unit

In the early 20th century, steam turbines were the first option for powerful prime movers. Its thermal efficiency was increased from 18% in 1907 to 38% in 1940.

5.3.1.2 Hydraulic Turbines

In Europe, water power had been used in driving mills, textile machines and machine tools after the Middle Ages. Later, steam power basically replaced water in many applications. However, steam engines are huge in size. In places where coal transportation is not convenient, steam power is not feasible; thus, hydraulic power was still used. With the arrival of the era of electricity, hydropower stations needed powerful hydraulic machines of high efficiency. Hydraulic turbine became a hot topic of research.

Three kinds of hydraulic turbines are dominant in application (Singer et al. 1958a; Williams et al. 1978a).

In 1850, James Francis, an English-American, designed an inward-flow reaction turbine, in which the working fluid came to the turbine under immense pressure and the energy was extracted by the turbine blades from the working fluid. Turbines of Francis type are still in use today, mainly for cases with water head ranging from 40 to 600 m.

In 1889, an American, Lester Pelton, made a new type of impulse turbines. In this machine, a series of buckets were arranged along the circumference of the water wheel. The water from a nozzle impacted the buckets along the tangential direction and made the wheel rotate. The turbine is suitable for places with small flow rate, but large height drop. It is still in use today.

In 1913, Viktor Kaplan, an Austrian professor, invented the axial-flow propeller turbine (Fig. 5.19). The water flow 5 gives an axial impact to the propeller 4 which rotates the generator rotor 2 at the top. The angle of the propeller could be adjusted according to the change of the flow rate. It is suitable for the cases with large flow rate but small drop. Now, it is also applied to situation with a drop ranging between 70 and 80 m.

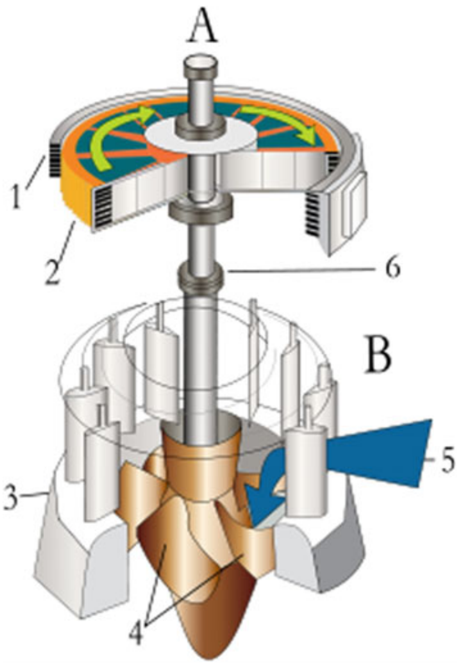


Fig. 5.19 Kaplan's hydraulic turbine (https://en.wikipedia.org/wiki/Water_turbine)

Steam turbines and hydraulic turbines greatly promoted the development of the electric power industry. The world's annual output of electricity in 1940 tripled that in 1900.

5.3.1.3 Gas Turbines

The speed of reciprocating internal combustion engine is limited by the inertial loads. Thus, gas turbine, a rotary engine with higher speed and efficiency, became a suitable option for power stations and aircraft (Williams et al. 1978b).

Early in 1791, John Barber, an English mine owner, firstly described the working process of a gas turbine. From the 1870s to the first half of 20th century, engineers in Britain, Germany, France, Russia and other countries proposed various concepts, and developed different types of gas turbines. But all failed due to some reasons, such as low efficiency, and failure to disengage the starter.

At that time, the theory of thermodynamic cycle for gas turbines was already established. The unsuccess of gas turbines was mainly due to, (1) the low efficiency of compressors, (2) no alloys available to withstand the high temperature of 700–800 °C. With the rapid development of air dynamics, the gas flow between blades of the compressor was gradually understood. Axial flow compressors with efficiency as high as 85% appeared in the mid-1930s. At the same time, progress was also made in materials; chromium nickel alloy steel was invented which could withstand a temperature above 600 °C. Thus, a higher initial gas temperature could be used and the gas turbines with the isobaric heating cycle was successfully applied.

In 1939, a Swiss company, BBC (Brown, Boveri & Cie), made successfully a 4 MW gas turbine for power generation. Its efficiency reached 31.5%. Hereafter, gas turbines were starting to grow rapidly. In 1941, a gas turbine locomotive was made in Switzerland. In 1947, a naval ships equipped with a gas turbine was built in Britain. Since then, gas turbines have been utilized in more and more applications.

5.3.1.4 Jet Engines

Since the 17th century, people tried to make jet engines with steam power, but all ended up with failure (Williams et al. 1978b).

In 1921, a Frenchman, Maxime Guillaume, was granted the first jet engine patent. In 1923, a report issued by American National Standards Institute (ANSI) claiming that jet engines were of no economic value for low altitude flight.

In 1928, Frank Whittle, a British air force engineer, designed a new jet engine, and obtained a patent in 1932. In 1937, experiments of the engine failed due to a fuel leakage. Then the British government had no more interest in the engine.

The theoretical and experimental research was mainly done by the British, but the practical work was left to the German. Hans von Ohain, a German engineer, designed a jet engine independently. Then he joined Heinkel Co., which was working on the design of jet engines. In August 1939, the first jet airplane in the world was created in Germany, and successfully tested in flight (Fig. 5.20).

WWII provided a test field for various aircrafts. Aircrafts entered the jet age after the war.

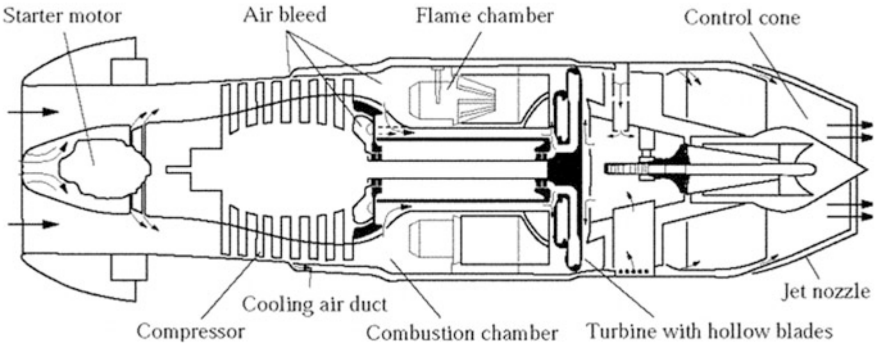


Fig. 5.20 Jumo 004B turbojet engines in Me 262 jet fighter, the first jet aircraft (http://www.aircraftenginedesign.com/custom.html3.html)

5.3.2 Mining Machinery

Inventions of various machines, excluding power machines and machine tools, during the Second Industrial Revolution are shown in Table 5.4.

After entering the era of steel, the fast growth of the machine industry dramatically increased the demand for steels, and further promoted the development of mining machinery.

5.3.2.1 Machines for Excavating Marching

In 1863, a British, Thomas Harrison, made the first practical coal cutter (Singer et al. 1958b). Over the next 20 years, the development of coal cutters was slow. The coal cutter then was powered by compressed air. The pipeline was generally very long, leading to large power loss. At the end of the century, the application of electric power in mining turned the tide, greatly promoting the use of coal cutters. Belt conveyors also appeared in the same period.

During the 1880s, hundreds of oil wells were drilled successfully in the U.S. with steam powered impact drills. Beginning from 1907, oil and gas wells were drilled with rotary drilling rigs.

Drills were used since ancient times. With the progress of technology, the power for drills include steam, pneumatic, hydraulic, oil fuel and electric power. Pneumatic rock drills are the most widely used.

Production needs promoted the progress of coal mining technology. From the beginning of the 20th century to the late 1940s, a series of mining machineries were invented, including pneumatic picks, electric drills, drilling machines, chain conveyors, pneumatic and electric rock loading machines, large power electric winches, fans and so forth. However, blasting and drills remained the dominant operation and machine at the coal mining faces.

In strip mining, the bucket capacity of power shovels reached 3–4 m^3 in the 1870s. Hybrid equipment combining mining, loading and railway transporting also appeared. The continuous mining technology, featured with large power and high efficiency, for soft rock strip mines was developed in the 1930s. This technology was widely accepted in the 1950s.

Tunnel heading machines break rocks through axial pressure and a rotating force. They are used for excavation of lanes and wells. The first patent of tunnel heading machine was obtained by a Hungarian, Z. Ajtay in 1949 (Murrow 2017).

5.3.2.2 Crushers

From the end of the 19th century to the 1920s, the rapid development of industry demanded for more minerals. In this period, the processing of minerals was transforming from relying on mainly manual work to modern technologies. Most

Table 5.4 Inventions of other machines in the Second Industrial Revolution

Time	Country	Contents	Inventor
Mining machinery and engineering machinery			
1848		Washbox with mechanical transmission	
1858	U.S.	Jaw crusher	E. Blake
1860	France	Multi-bucket excavator	
1863	UK	Coal cutter	T. Harrison
Since 1868	UK, U.S.	Belt conveyer, helical conveyer	
Since 1870s	Steam powered brick machine, gigantic shovel, movable tower crane, road roller, charging machine, caterpillar bulldozer, belt conveyer, etc.		
1874	Canada	Frue vanner	W. Frue
1881	U.S.	Cone crusher	P. Gates
1896	U.S.	Wilfley table	A. Wilfley
1900		Tower crane	
1890s and 1900s		Ball milling, classifier, processing equipment	
First half of 20th century		Pneumatic pick, electrodrill, pneumatic hammer drill,chain conveyer, electric rock-loading machine, etc.	
1949	Hungary	Heading machine	Z. Ajtay
Elevator and escalator			
1880	Germany	Electric elevator	W. Siemens
1892	U.S.	Escalator	J. Reno
Centrifugal machines and compressors			
1877	Sweden	Centrifugal machine	C. Laval
1878		Screw compressor	A. Lysholm
1879		Centrifugal separator	
1900	France	Centrifugal compressor	
Information machines			
1845	U.S.	Rotary printing press	R. Hoe
1868	U.S.	Typewriter	C. Sholes
1880s–1890s	U.S.	Movie camera and movie projector	T. Edison
	France		Lumière brothers
1938	U.S.	Electrostatic copying machine, xerographic printer	C. Carlson
Agricultural machinery			
1892	U.S.	Diesel engine driven tractor	
Weapons			
19th century	Diversified artillery		
1862	U.S.	Machine gun	R. Gatling
1883	UK		H. Maxim
1916	UK, France	Tank	
1918	UK	Aircraft carrier	
1926	U.S.	Liquid fuel rocket	R. Goddard
1939	Germany	Jet airplane	

modern process and equipment of mineral processing appeared in this period (Singer et al. 1957).

Ore dressing is a process separating useful minerals from gangue. Before dressing, the ore must be crushed and ground to very fine particles. Modern crushing machines were not created until steam engines were widely applied. In 1858, an American, Eli Whitney Blake, designed and built the first jaw crusher in the world (Wilson and Fiske 1900), called Blake jaw crusher. Later, the Dodge jaw crusher was created (Fig. 5.21). Now, the latter is more widely used. Jaw crushers are considered one of the most important inventions during the industrialization of the U.S..

In 1881, a gyratory crusher (Fig. 5.22) was invented and built by an American, Philters Gates (Lynch and Rowland 2005). A gyratory crusher (cone crusher) applies continuous crushing action, therefore is more productive than jaw crushers which have intermittent crushing action. In addition, gyratory crushers can crush ore of larger size.

Grinding ore with hard balls was one of the oldest techniques. Ball mills, however, were not built until the wide application of steam power. The first ball mill appeared in 1876 in Germany.

In the second half of the 19th century and the first half of 20th century, various grinding mills, such as vibrating mills, were invented (Zhang 2005).

5.3.2.3 Processing Machinery

The most commonly used ore dressing technique includes gravity separation, floating separation and electromagnetic separation. The equipment of floatation and magnetic separation is very simple. Gravity separation equipment, such as jigs and shakers, is relatively more complicated, thus, is to be discussed with some detail in this section.

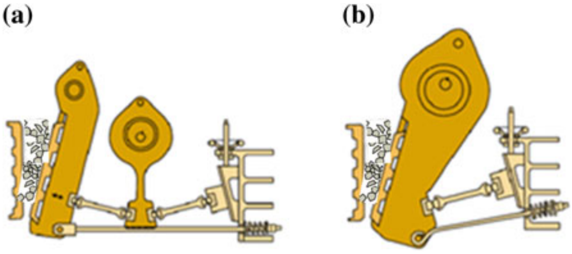


Fig. 5.21 Jaw crushers
a Blake type jaw crusher
b Dodge type jaw crusher
(http://www.sigmaplantfinder.com/blog/how-do-jaw-crushers-work/)

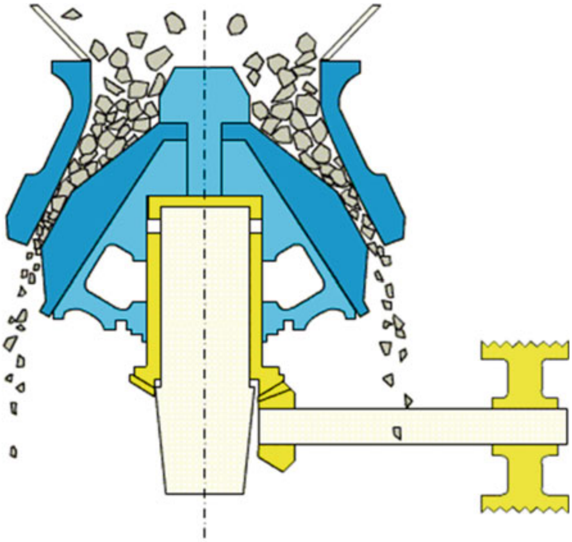


Fig. 5.22 Cone crusher (http://www.engineeringintro.com/all-about-construction-equipments/crusher-crusher-types/)

Historically, jigs were firstly used for coal dressing. Manual jigging machines were emerged in 1830 (Fig. 5.23), and jiggers with fixed sieve in 1840. In 1848, continuous operation jiggers were invented in which a slider-crank mechanism drove a piston forcing the water to flow up and down. The piston chamber and the jigger chamber are connected at the bottom. The sieve in jigger chamber is made of perforated plates or knitted with iron wire. Water flows into the jigger chamber through the sieve. The bed layer rises up slightly and then is loosened. Particles with high density are, therefore, settled to the bottom and the ones with less density are transferred to the top. After stratification of minerals and gangue, they are discharged in different routes.

In 1896, Arthur Wilfley, an America Engineer, invented the Wilfley table. The bed of the machine makes reciprocating motion longitudinally. In the lateral direction, the bed is tilted slightly. The slime is supplied at the upper-left corner as shown in Fig. 5.24. At the same time water is poured in across the bed, covering the whole surface of the bed with a thin and uniform film flow. Under the combined action of gravity, water flow and the longitudinal inertia force, mineral particles with different specific gravity move in different paths, and are separated. The device greatly increased the recovery rate of gold, silver and other metals and was soon accepted world-wide.

Electrostatic and magnetic separators were invented in 1880 and 1890 respectively. Successful dressing of iron ore promoted significantly the development of the steelmaking industry.

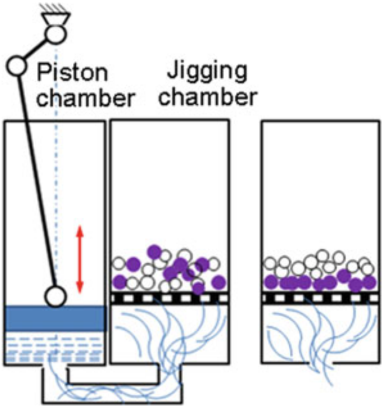


Fig. 5.23 Jigging machine

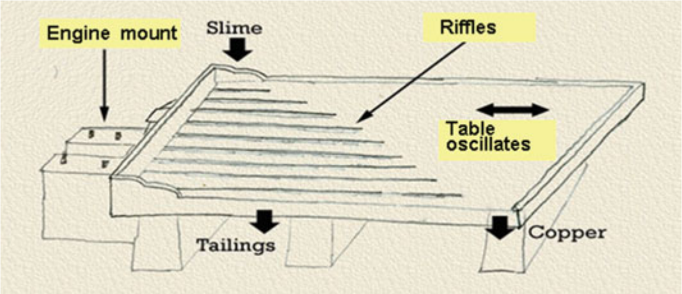


Fig. 5.24 Wilfley table

5.3.3 Construction Machinery

After the invention of steam engines, construction machines got on fast track of development. At the early 19th century, steam driven excavators, road rollers and cranes appeared in Europe.

From the early 20th century to the end of the 1940s, single bucket excavators with different power, such as electric motors, gasoline engines and diesel engines, were developed. In 1910, crawler moving device was added to make it mobile. Wheeled moving device was also widely used in mini excavators. In the 1930s, foot type walking device appeared.

In 1860, excavators with multi-bucket was firstly produced in France for the excavation of Suez Canal. At the end of the 19th century, bucket wheeled excavators were widely used in coal mining in Germany.

In the 1880s, the taking-off of the U.S. economy resulted in soaring land price at big cities; thus, high-rise buildings began to be constructed (Rübberdt 1972). In 1888, the world's first skyscraper was built in Chicago (Singer et al. 1958a). This trend in construction of buildings was heavily relying on the progress in construction machines since the 1870s. Steam driven press, heavy excavator, movable tower crane, loader, road roller, bulldozer, belt conveyer and so on were all invented in this period.

In 1867, Joseph Monier, a French gardener, invented the reinforced concrete. Monier's story was a representative case of associative innovative thinking frequently cited in textbooks of creative design. In 1872, the world's first reinforced concrete building was built in New York City. Concrete mixers invented in 1900 facilitated the large-scale application of reinforced concrete.

The invention of internal combustion engines and electric motors sped up the forming of the construction machine industry in the early 20th century, and made enormous contribution to its fast development (Haycraft 2011).

5.3.4 Pumps and Compressors

5.3.4.1 Hydraulic Pump

A pump was an ancient machine. In history, there have been more types of pumps than that of gears and of rolling bearings. However, only a few types stand the test of time, being still in use. Hydraulic systems mainly use positive displacement pumps (see Sect. 7.5.2), and water pumps are mainly centrifugal type.

At the beginning of the 20th century, batch production of high pressure multistage centrifugal pumps began, mainly for the need of supplying water to boilers. The following several decades saw a continuous increase in pump power and expansion of application. Centrifugal pumps became one of the most widely used machines in the world. In the first half of the 20th century, the pipe diameters for the cooling water pumps in power plants and large irrigation pumps reached 3 m; and the motors driving the large water pumps for storage power stations reached 75,000 kW (Williams et al. 1978b).

5.3.4.2 Compressors

In the 19th century, the only available compressor was the piston type which used slider-crank mechanisms. Later, internal combustion engines were widely used for driving the piston type air compressor.

Piston compressors have some inherent shortcomings, such as small capacity, large weight and with many vulnerable parts. Thus, centrifugal compressors and screw compressors were developed later.

In 1900, a centrifugal compressor was firstly built in France for a blast furnace blower. A few years later, batch production was achieved in both Europe and the U. S. Centrifugal compressors soon became dominant because of their relatively larger capacity, lighter weight and simpler structure.

In 1878, Alf Lysholm, a Swedish professor, invented a screw compressor, which could provide compressed air with high pressure, large flow rate and low noise. However, real development did not come until the 1930s. Since the 1940s, it has been widely used for gas turbines of aerospace and power generation.

5.3.5 Information Machinery

5.3.5.1 Typewriter

As early as in 1714, a British inventor, Henry Mill, obtained the first patent of typewriter. However, his typewriter was not widely accepted then, and no further information was retained. In 1868, An American, Christopher Sholes, and his coworkers invented the first practical typewriter (Williams et al. 1978b).

5.3.5.2 Printing Machines

Printing and paper-making are closely associated technologically. During the First Industrial Revolution, mechanization was already realized in the paper-making process. A paper-making machine then could produce paper as continuous tape, creating a new opportunity to improve the paper feeder of a printing machine. The cumbersome discrete supplying of paper (sheet by sheet) became redundant. In 1845, an American inventor, Richard Hoe, was granted the patent of rotary printing machines (Singer et al. 1958a) (Fig. 5.25).

The rotary machine was first used for printing newspapers. In 1866, The Times of London began to be printed with the machine. The paper roll installed in the machine was up to 8 km long, and the paper was fed with a speed of 240 m/min. This new machine was able to print 25,000 copies of the newspaper every hour.

In 1870, printing on both sides of the paper simultaneously was achieved. In 1900, 6-color rotary press was produced. To the time before WWII, printing process was completed with mechanization in the main industrialized countries of the world.

5.3.5.3 Film Camera and Projector

Movie takes advantage of the principle of persistence of vision of human eyes. The invention of the movie involved three important parts: (1) the moving of an object was broken down into many short time intervals, and pictures at the discrete time

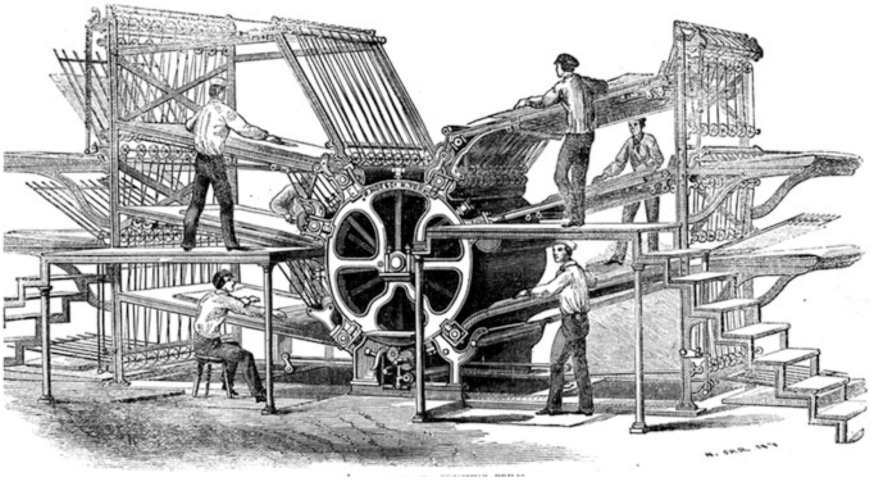


Fig. 5.25 Hoe's six-cylinder rotary press from the 1860s (https://en.wikipedia.org/wiki/Rotary_printing_press)

instants were recorded; (2) the invention of film long enough for continuous shooting; (3) the film was projected onto a screen picture by picture. The former two parts represent the film making, and the third is the movie showing.

In 1881, a British photographer, Eadweard Muybridge, recorded a running horse, making the first experiment of continuous photography. In 1885, the celluloid film was invented and produced by the Eastman plant. T. Edison, the most famous American inventor, immediately used the Eastman film in movie camera. In 1889, William Dickson, commissioned by Edison, built the first motion-picture camera and named it the Kinetograph.

In 1893, W. Dickson went further to develop a film projector which was able to move the film continuously, and project the pictures one by one in sequence to the same position of a screen. A light with on and off synchronized with the film speed was used; consequently, continuous motion could be seen due to the persistence of vision. Later, it was further improved with a series of small holes punched on both sides, through which a Geneva mechanism was used to drive the film in intermittent motion (see Fig. 7.13).

In 1894, Auguste Lumière and Louis Lumière, the brothers in France, developed independently the Cinématograph, which combined a film camera and a projector. In 1895, they showed a movie in Paris publicly for the first time.

In 1912, T. Edison invented sound film. Later on wide screen film and color film appeared in 1927 and 1940 respectively (Jiang 2010; Pan and Wang 2005).

5.3.5.4 Electrostatic Copying Machines

In 1938, Chester Carlson, an America engineer, invented and patented an electrostatic copying machine (Owen 2004). In the following 10 years, Carlson approached about 20 companies to produce his machine, but no one showed interest. However, the Xerox Company determined in 1949 to produce his machine, which was put on market in 1950. The initial machine was of very low efficiency, making a copy in 4 min. Later with continuous improvement the speed was increased to 150 copies per minute. The Xerox Company earned an enormous fame by this product so that Xerography, which came from the company's name, became an English word of copying.

5.3.6 Weapons

5.3.6.1 Machine Gun

Since the 14th century, multi-barrel guns and magazine guns have been used.

In 1862, Richard Gatling, an American agricultural machinist, patented a machine gun. In his gun a hand crank was used to rotate 6 rifle barrels to launch position. A machine gun with 5 barrels used in the Civil War was already able to lunch 700 rounds per minute. However, the gun was so heavy that it, like a field gun, had to be mounted on a massive shaft. This limited its practical use.

In 1883, an American-born British, Hiram Maxim, obtained the patent of Maxim gun. In this gun, the shell was thrown out by bullet recoil, and the bullets in a canvas belt entered the barrels continuously. The barrels were cooled down by a water jacket. This type of guns demonstrated its power in the Russo-Japanese War and WWI.

Later, light machine guns, submachine guns and other firearms appeared (Jiang 2010).

5.3.6.2 Tanks

The use of machine guns and bunkers broke the balance between the offensive and defensive strength, calling for a new weapon which could be used in combat situations both offensively and defensively. Tanks were developed exactly for this purpose in France and Britain simultaneously during WWI. In 1916, tanks were first put in use by the British Amy during the Battle of Flers–Courcelette in France. The name "tank" was used deliberately in the developing process as a security measure to keep the secret (Pan and Wang 2005). This name since then has been used in both office documents and common parlance. Later, Germany and the Soviet Union also started to develop tanks. From the mechanical point of view, the track, the most noticeable feature of a tank, actually was conceptually borrowed from crawler tractors which were invented in 1907.

5.3.6.3 Warships

Steam power and steel laid the material foundation for modern warships (Yang 2005; Pan and Wang 2005).

After being invented in 1903, airplanes began to be used for military purpose. Then people went further to propose combining airplanes and warship so that they could play a greater role, leading to the birth of aircraft carriers.

Seaplanes, which were capable of taking-off and landing on water, were invented in 1910. One year after in 1911, the French Navy built the first seaplane carrier, *Foudre*, which carried seaplanes on the main desk, and lowered them to the sea by cranes. In 1913, the Royal Navy also tested a seaplane carrier which was transformed from a cruiser, HMS Hermes. The U.S. Navy tested its seaplane carrier in the same year. In 1914 during WWI, the Imperial Japanese Navy conducted the first successful naval raid with its seaplane carrier, *Wakamiya*, on German forces.

During WWI, the Royal Navy already started to test the HMS Hermes for the use of wheeled aircraft by adding a flight deck. The first ship having a full length flat deck, named HMS Argus, was built by the Royal Navy in 1918 (Fig. 5.26). In 1920 the U.S. Navy constructed its first aircraft carrier, *USS Lanley*. Japan completed the *Hosho* in 1922.

Aircraft carriers played a significant role in WWII. The aircraft carrier fleets of Japan and the U.S. came into clash in the Pacific Ocean.

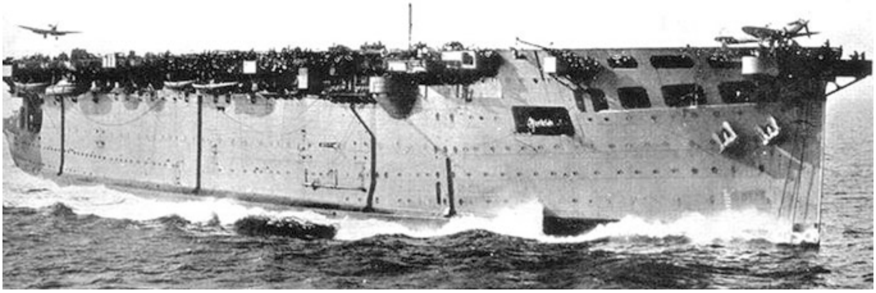


Fig. 5.26 HMS Argus (I49), conventionally-powered aircraft carrier (https://www.militaryfactory.com/ships/detail.asp?ship_id=HMS-Argus-I49)

5.3.6.4 Artillery

In the 17th century, mortars and howitzers were widely used in English and French troops. Since the 19th century, artillery was gradually diversified. At the beginning of the century, cannons were developed, which have longer barrel, and thus, longer ranges. Besides, they could be shot horizontally. Initially the artillery was mounted in a rigid carriage to which a very large force was exerted when shooting. Thus, the targeting accuracy in launching was limited. At the end of the 19th century, elastic carriages emerged. An elastic carriage could absorb the recoil at launching and resume the barrel back in place after launching; therefore, the launching speed and accuracy are effectively improved. During WWI, military aircraft demonstrated its great power. In response, after the war anti-aircraft artillery was invented.

Torpedo was also developed during this period. To the first half of the 20th century, various weapons had been developed quite maturely. On the eve of WWII, arms race among the main powers became increasingly intensive; a unprecedentedly bloody and brutal combat in human history was looming ahead.

5.3.7 Other Machines

5.3.7.1 Mechanization in Agriculture

In 1892 practical tractors powered by internal combustion engines were built. In 1907 caterpillar tractors appeared. Subsequently, various suspension devices for farm tools, including hydraulic suspension device, were developed, which greatly improved the performance of tractors.

The period from the First Industrial Revolution to the end of the 19th century was regarded as the initial stage of agricultural mechanization. During the first half of 20th century, agricultural mechanization experienced fast growth. During the 1910s and 1920s, steam engines and internal combustion engines competed severely for the power of tractors (GSHCAS 1985). In the 1920s and 1930s, several important improvements were made, including pneumatic tires, diesel power, and hydraulic three-point suspension. These improvements made the diesel engine tractors stand out, and become the winner in the competition.

The concept of hydraulic three-point hitch suspension was first proposed by an Irish, Harry Ferguson, who obtained a British patent in 1926. The first tractor made in the U.S. in 1939 adopted the Ferguson's system, which is still in use on most modern tractors today (Ertel 2001).

In 1924, combine-harvesters driven by a tractor appeared (Pan and Wang 2005).

In the 19th century, machines were also used in animal husbandry; mowing machines, shearing machines and feed crushing machines were invented in this period.

5.3.7.2 Packaging Machines

Packaging includes mainly filling, wrapping and sealing, along with cleaning, stacking, disassembly, measurement etc. Generally, a packaging machine has very complicated motions and complex structures. Packaging machines can improve productivity, reduce labor intensity, meet high hygiene standard, and is suitable for mass production. In ancient China, mulberry skin after treatment was used for packaging foods, which may be the origin of modern packaging paper.

Commercial paper bags were first manufactured in England, in 1844. In 1850, world paper price tumbled and paper packaging began to be used. An American, Francis Wolle, patented a machine for automated bag-making in 1852 (Hook and Heimlich n.d.). In 1861, the world's first packaging machine factory was established in Germany. In 1911, the factory produced an automatic machine which could complete forming, filling, and sealing simultaneously. In 1898, an American, Michael Owens, invented a machine that could make glass bottles automatically at a rate of 240 per minute (ANON1 n.d.). It was reported that labor costs could be cut by 80%.

In the first half of the 20th century, mechanization of packing was implemented in many industries, such as the food, medicine, cigarette and household chemical products.

5.3.7.3 Washing Machine

Manual washing machines first appeared in England in 1782, then also in the U.S. in the second half of the 19th century. In 1906, the first electric washing machine was born (Pan and Wang 2005).

5.4 Machine Manufacturing in 2nd Industrial Revolution

In the 2nd Industrial Revolution, machine speed kept continuous increasing; automobiles and airplanes appeared. Improving productivity and accuracy of machining became the central topic of manufacturing. Great progress was made in cutting-tool materials; a variety of general and special machine tools formed a large family. Mass production was developed; standardization and serialization were gradually improved. The machine manufacturing industry was getting out of infancy, and headed step by step towards modernization.

5.4.1 Development of Machine Tools

From the 1870s to the turn of the centuries, electric motors gradually replaced steam engines and overhead line shafts. At first, the motor was installed outside the machine tool at a certain distance, and later directly installed inside the machine.

From the 1890s to the early 20th century, the operational and transmission systems of machine tools experienced rapid development.

In this period, the automotive and aviation industries became the main market of machine-tools; correspondingly, their needs strongly influenced the design of machine tools. Many new machine tools were invented, such as grinding machines, gear hobbing machines, gear shaping machines, automatic machine tools, combined machine tools, and precision machine tools, forming a large machine tool family. The machine-tool industry, the core of machine manufacturing industry, began to take shape. The main inventions on machine tools and cutting tools of this period are listed in (Table 5.5).

5.4.1.1 Progress of Lathe

Maudslay's lathe (see Sect. 4.4.2) was designed for machining of screws with different pitch, in which 3 or 4 change gears generally hang between the output shaft of the headstock and the input shaft of the feeding box. The shortcomings of this design were obvious. In 1892, an American engineer, Wendell Norton, invented a new mechanism, known as the Norton Mechanism (Norton 1892), which is installed in the feed box of a lathe (Fig. 5.27). With the Norton mechanism, machining of screws is no longer dependent on the replacement of the change gears. However, the rigidity of this mechanism was unsatisfactory. In 1962, a Chinese scholar, Zhao Shengbin, put forward a new device, called the three-shaft sliding gear mechanism (Zhao 1962). In some Chinese factories, this new mechanism has been adopted to replace the Norton mechanism, which has already been used for half a century.

In 1896, an American, Oakley Walker, invented the electromagnetic clutch. At the beginning of 20th century, lathes with gear transmission and driven by a single motor appeared.

5.4.1.2 Automatic Lathes

From Maudsley's screw lathe to Fitch's turret lathe (see Sect. 4.4), the development of lathes was closely related to the mass production of threaded fasteners. The continuous needs for manufacturing cheaper screws further drove the development of automatic lathes.

Although as early as in 1792, Maudsley made already taps and dies for making screws. However, die heads did not replace single point cutting tools until the first half of the 19th century in batch production of threaded parts. In the 1870s, the

Table 5.5 Inventions of machine tools and cutting tools in the 2nd Industrial Revolution

Time	Country	Contents	Inventor
1864	U.S.	Cylindrical grinder	
1868	UK	Alloy tool steel	R. Mushet
1873	U.S.	Automatic lathe	C. Spencer
1874		Bevel gear cutting machine	W. Gleason
1875		Universal cylindrical grinder	B & S Co.
1877		Surface grinder	
1890		Vertical boring machine	
1897		Gear shaping machine	E. Fellows
	Germany	Gear hobbing machine	R. Pfauter
1898	U.S.	Electromagnetic clutch	O. Walker
		High speed steel tools	F. Taylor
1900		High precision grinder	C. Norton
1890s and 1900s	Rapid development of electric powered mechanical press and air hammer. Emergence of various special-purpose grinding machines		
1902	U.S.	Hydraulic transmissions used in machine tools	Brown and Sharpe Co.
		Broaching machine	Lapointe Co.
Early 20th century		Milling cutter with multi spiral blades	F. Holz and A. de Leeuw
1910		Milling machine improved and perfected	
1911		Combined machine tool	
1905–1920	Swiss, U.S.	Jig borer	
1913	Special-purpose milling machines for machining complex parts		
	Swiss	Gear grinding machine	Maag Co.
	U.S.	Spiral bevel gear cutting machine	W. Gleason
1922	U.S.	Centerless grinder	Cincinnati Co.
1923	Germany	Carbide	K. Schroter
Early 20th century	UK,Soviet Union	Ceramic tool	

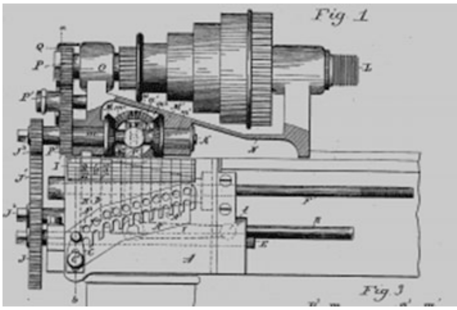


Fig. 5.27 Norton mechanism (https://www.datamp.org/patents/displayPatent.php?id=26257)

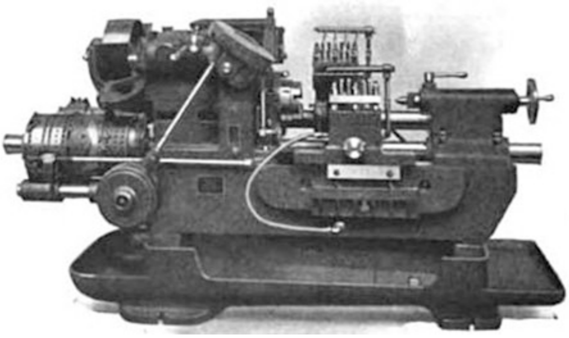


Fig. 5.28 Automatic lathe in 1921 (https://en.wikipedia.org/wiki/Automatic_lathe)

cutting cycle of turret lathes was partially achieved automation with the cam control technology. A fully automatic turret lathe was developed and patented first by a U. S. inventor, Christopher Spencer, in 1873. However, the cam drum, which was the key part of the patent and was called "the brain of the machine" by Spencer himself, was not well protected due to mistakes of his patent agent. Many people soon figured out his idea, and successfully developed fully automatic lathes as well (Singer et al. 1958a). Soon after, Spencer made another step inventing a three spindle automatic lathe.

The automation of lathes in this period was realized mechanically with cams, thus known as mechanical automation which was the first stage of automation in machine building. To the time of WWI, various efficient automatic and specialized lathes based on the cam control were developed because of the needs for weapons and vehicles (Fig. 5.28).

5.4.1.3 Grinding Machines

During the 1830s, to meet the need for machining hardened parts in watches, clocks, sewing machines and firearms, grinding machines with natural abrasive wheels were developed in Britain, Germany and the U.S. These early grinders were simply made by adding grinding wheels to lathes or planers, having the issues of low rigidity, and severe vibration. Thus highly skillful workers were needed to operate the machine to achieve the required precision of workpiece.

In 1875, Brown and Sharpe Co. in the U.S. created a universal cylindrical grinder, which was the first machine ever built in history having the basic features of modern grinding machine. In 1877, the company made a plane grinder, in which the grinding head was installed on a column and the worktable moved in reciprocation (中山秀太郎 1975).

In the 1890s, silicon carbide was synthesized and the value of aluminum oxide in grinding was discovered. The use of these two abrasive materials brought a revolution to the grinding technology (Singer et al. 1958a). In order to take full advantage of the new grinding materials, an American, Charles Norton, invented a new grinding machine in 1900, which was able to machine large work-pieces with high precision and efficiency. Norton's grinder was considered the third most important invention in machine tools, following Maudslay's lathe and Brown's universal milling machine (Williams et al. 1978b).

In 1902, Brown and Sharpe Co. in America first applied hydraulic transmission and its control technology to grinding machines, greatly promoting the development of grinders. With the development of automobile industry, crankshaft grinders, cam shaft grinders, planetary internal grinders and piston ring grinders with an electromagnetic sucker were developed in succession. Automatic measuring devices began to be used in grinding machines in 1908. In around 1920, centerless grinders, sliding guide grinders, honing and superfinishing machines were invented (Williams et al. 1978b). The development of grinding machines, along with the invention of coordinate boring machines in 1912, brought the machining technology into a new stage of preciseness.

5.4.1.4 Milling and Boring Machines

At the early 20th century, the automobile, aircraft and engine manufacturing industries created the requirement on high precision of parts, which inspired the further development of milling machines. Milling machines are more precise, but more convenient in operation compared with grinders. During a long period of time in the early stage, milling cutters with single tooth were used. Vibration and low quality of surface finish were the two factors greatly hindering the application of milling machines. Later, Frederick Holz and Adolph de Leeuw at Cincinnati Milling Machine Co. invented a milling cutter with multi spiral teeth. This invention overcame the shortcomings of the single tooth cutter, and made milling machines indispensable for manufacturing complex parts. In 1910, horizontal milling machines and universal milling machines were almost matured technically. In 1913, special milling machines designed for machining complex parts in cars and airplanes appeared. Eventually milling machines replaced shapers and planers in many applications (Williams et al. 1978b; GSHCAS 1985).

At the early 20th century, the clock and instrument industry brought forward a need for machining multiple holes. The precision requirement on the distance between the holes were very high. In 1905, a small desktop coordinates centering machine was made in Switzerland. At the end of WWI, Switzerland and the U.S. independently developed coordinate boring machines, which could quickly and accurately determine the position of the center line of the hole.

5.4.1.5 Gear Cutting Machine Tools

In the ancient times, gears were formed by manual filing. To the late Middle Age, watch and clock making became an important industry in Europe; thus, methods of making gears with cutting tools began to be studied. From the second half of 18th century to the middle 19th century, many patents in gear manufacturing were granted. All these gear cutting methods fall in the category of form-cutting as we call it today.

At the end of 19th century, both the machine tools and the automotive industry required to improve the productivity and machining precision of gear manufacturing. The form-cutting methods, thus, were no longer able to meet these requirement, and new methods had to be developed. This led to a golden age of innovative gear cutting technologies (Litvin n.d.). In 1897, a German engineer, Robert Pfauter, invented the hobbing processing of spur and helical gears, and the required machine tool, the hobber with a differential gear device. In hobbing, gear teeth were cut out through continuous relative motion between the cutting tool and the work piece. The generated surface of the gear tooth is the envelope of the tool surface family. This is the so called "generation method". R. Pfauter is the pioneer in gear manufacturing with the generation method.

Also in 1897, an American engineer, Edwin Fellows, invented the gear shaping method and the gear shaping machine. Maag Co. in Swiss invented the gear grinding method in 1913. These two methods belong to the generation method as well.

In 1874, an American Engineer, William Gleason, invented a bevel gear shaper. In 1895, an American John Buck invented the bevel gear shaper for simultaneously processing two sides of a gear tooth (Singer et al. 1958a). The most famous invention by Gleason was a cutting method of spiral bevel gears (see Sect. 12.4.2).

5.4.1.6 Broaching Machine

The history of broaching could be traced back to the early 1850s. At that time it was used only to cut the keyway in gears and pulleys. In 1902, an American company, Lapointe, produced the broaching machine (Williams et al. 1978b). After WWI, broaching was used for machining rifle barrels. During the 1920s and 1930s, the machining precision was significantly increased along with a reduction of machining cost, mainly due to the progress in broaching and grinding technology.

Following the invention of electric motor, mechanical presses driven by electric power and air hammers appeared at the end of the 19th century.

In the first half of 20th century, the manufacturing technologies were mainly a continuation of the traditional technologies developed in the 19th century. However, continuous improvement and expansion of application never stopped. The advance in machine tool design, new cutting tool materials, and the automation technology combined pushed the manufacturing industry forward.

5.4.2 Tool Materials and Cutting Speed

Since the Industrial Revolution, it has been a main stream to improve manufacturing productivity through increasing the cutting speed.

Metal cutting tools, such as milling cutters, taps and dies, were developed in the late 18th century mainly for the need of manufacturing steam engines and other machines. The invention of twist drill is traced back to 1822, but commercial production did not start until 1864. At that time all cutting tools were made of high carbon tool steel, and the cutting speed was only between 6–12 m/min.

In the 1860s, the appearance of the converter and open hearth furnace made the output of steel far exceed that of cast iron. Steel is much harder to be machined than iron. To keep an acceptable tool life, the cutting speed had to be decreased. By the end of the 19th century, the cost of machining became a significant part in the total cost of manufacturing, requiring improvement of the cutting tool materials.

In 1868, a British, Robert Mushet, created successfully an alloy tool steel containing tungsten, increasing cutting speed to 18 m/min.

Two American engineers, Frederick Taylor and Maunsel White, made a cutter from an alloy tool steel containing 18% tungsten, and heat treated it with a new method. The cutter was displayed at the Paris Expo in 1900. In the demonstration, the cutter was still working smoothly even having the nose turned cherry red because of the cutting heat. It caused a great sensation, and the alloy steel of the cutter has been known as "high speed steel" since then. Its cutting speed reached 36.5 m/min (Trent 1991).

In 1893, a French chemist, Henri Moissan, discovered tungsten carbide when studying artificial diamond. This material is close to natural diamond in hardness, but very brittle. In 1923, a German, Karl Schröter, invented WC-Co which contains cobalt binder. Then he put it into commercial production in 1926. This material performs excellent in machining cast iron, non-ferrous metals and non-metallic materials, but unsatisfactorily in machining of steel. Later, titanium carbide and the tantalum carbide were developed, which could be used for cutting steel at high speed. Compared with high speed steel, the cutting speed of the carbides increased by 2–4 times, reaching more than 100 m/min. Surface quality and dimensional accuracy were also greatly improved.

Because the high-speed steel and carbides were expensive, tools were generally designed with only inserts made from the expensive cutting material and attached to a toolholder made from cheaper materials through mechanical clamp or welding. During 1949–1950, indexable blades started to be used as turning cutters in the U. S., soon accepted as milling cutters and other tools.

At the early 20th century, the UK and the Soviet Union began to use ceramic cutters (Williams et al. 1978b), which, however, were not widely used until the 1950s.

From the 1920s to 1950s, cutting speed was doubled almost every 10 years, as shown in Fig. 5.29 (Weck 1979). The progress in cutting materials caused the machine tool to be operated at higher speed. As a result, vibration became severe,

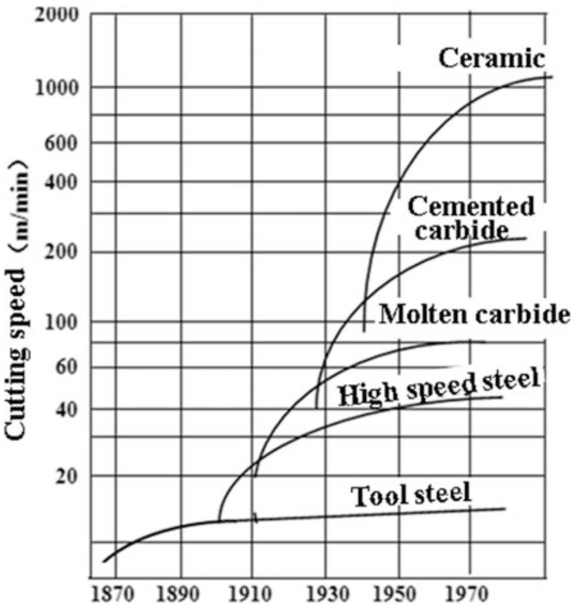


Fig. 5.29 Increasing of cutting speed for steel

and more heat was produced during machining. To tackle the problems, on the one hand, machine tools tended to be designed stronger; on the other, the effect of hot deformation on the machining accuracy was taken into account in analysis.

In 1931, Carl Salomon, a German expert, put forward the concept of high speed cutting for the first time. His concept was far ahead of its time. Further development of the cutting mechanism and feasibility of the high speed cutting concept started only after WWII, and continued to the 1990s.

After significant increase of cutting speed, parameters of the cutting process need to be chosen carefully. To guide this process, the first handbook of cutting was published in the U.S. in 1932.

5.4.3 Progress in Metrology

The emergence of modern machine tools required proper measuring technologies. After the concept of interchangeability was applied to production in particular, the requirement on measurement technologies became even higher. J. Watt and H. Maudsley made great contributions toward the improvement of measuring techniques.

In the period of 1851–1852, a British engineer, Joseph Whitworth, demonstrated a plug gauge and a screw micrometer at the Paris Expo, preluding to the era of precision measuring tools. An American engineer, Joseph R. Brown, invented a vernier caliper in 1851 and a micrometer in 1867, which reached an accuracy of 0.025 mm, and was produced commercially (Williams et al. 1978b).

To the end of the 19th century, these two tools had been widely used in Britain, the U.S. and some other countries. However, there was still lack of calibrating tools, which were supposed to have higher precision level, after repairmen was made to these measuring tools. To this end, a Swedish inventor, Carl Johansson, made the first block gauge by hand grinding in 1898. This was a major milestone in the history of metrological technology (Williams et al. 1978b).

Visual inspection used to be the only way to check surface roughness. However, with the further development, visual inspection no longer met the real requirement. In 1930, the first mechanical comparator with the accuracy of 0.001 mm was invented. Since then several instruments with high precision, such as autocollimators, profile projectors, optical planes, sine bars and micrometers, have been applied normatively in machining workshops (Williams et al. 1978b).

Further development of the machine industry put forward higher requirements for measurement. Many more quantities, far beyond only dimensional, required measurement, such as displacements, velocities, accelerations, forces, torques, strains, pressures, flow etc. For some non-electrical quantities, various electric measurement technologies were often used due to a series of advantages. The most widely used electric measurement technique is with resistance strain gauges, which were developed in the U.S. during WWII (Williams et al. 1978b).

5.4.4 Taylor's Scientific Management

F. Taylor (Fig. 5.30), who invented the high-speed steel, laid the foundation of scientific management. Starting from an apprentice in Midvale Steel of the U.S., Taylor gradually climbed up the ladder to a foreman, and finally the chief engineer. From his many year practice, he recognized that the lack of effective management means was a serious obstacle to improve productivity. Beginning from the operation of a lathe worker, Taylor systematically investigated the detailed work components in the business, and the time needed for each component. Then, he tried to find ways to improve the efficiencies in each working component, and tested in the factory. Gradually he formed the framework for the theory of scientific management (Williams et al. 1978b).

Taylor believed that the principal purpose of management was to seek the highest productivity, which was the common basis of the employer prosperity and the employee's prosperity. To achieve this goal, scientific and standardized management methods should be adopted to replace the traditional management based on experience.

Taylor achieved great successes. His influence, at least in the following aspects, is still being felt today. (1) He first studied management through experiments, (2) he first analyzed individual work components and the work flow, (3) he first proposed that empirical management should be replaced by scientific management, (4) he

Fig. 5.30 F. Taylor

first proposed the idea of standardization of work, (5) he allocated work between managers and employees, making management a scientific subject. He laid the foundation for the modern management theory.

Taylor was the founder of scientific management, from which a new discipline, industrial engineering, grew out gradually. As such, Taylor is also regarded as the father of industrial engineering.

5.4.5 *Ford's Mass Production*

In 1913, Ford Motor Company developed the world's first assembly line (Fig. 5.31), on which a total of 15 millions of Model T (Fig. 5.32) were produced by 1927. This set a world record, until 45 years later surpassed by the Volkswagen Beetle (Brinkley 2004; Lewis 1987).

Henry Ford showed strong interest in machinery when he was still a kid. At the age of 12 he established a small mechanical workshop of his own; at the age of 15 he built an internal combustion engine; and at the age of 16 he left home for Detroit becoming a mechanical apprentice.

In 1896, Ford made his first car. In 1908, the famous Ford Model T was launched ("T" represents one type of the cars developed in Ford Motor). In 1918, half of the cars traveling in the U.S. were Model T.

In 1913, Ford developed a new assembly line, which reduced the assembly time for each Model T's chassis from 12.5 to 2.66 h, greatly improving the production efficiency (Lewis 1987).

Fig. 5.31 Ford's assembly line of cars (http://www.pbs.org/wgbh/aso/databank/entries/dt13as.html)

Fig. 5.32 Model T car (https://en.wikipedia.org/wiki/Ford_Model_T)

The dramatic increase of productivity helped lower the price of the Model T from $850 to $360. In 1914, Ford pioneered the worker daily wage of $5, which was almost double the rate for general factory workers at that time. Besides, Ford reduced the workday from 9 to 8 h, which allowed the factory to run 3 shifts a day instead of 2. Model T was seen then all over the world, and Ford was known as the "person who put the world on wheels" (Brinkley 2004).

In summary, the Ford assembly line had the following technical characteristics.

(1) The machining and assembly process were analyzed and decomposed into a series of single step operation.
(2) Machine tools on the line were arranged based on the order of operation; this greatly shortened the material handling distance.
(3) General purpose machine tools were replaced by special ones dedicated to specific work, such as the multi-head drilling machine, which could simultaneously complete drilling of all holes on both sides of a cylinder.
(4) The concept of interchangeable parts was adopted in production; and gauges and fixtures were integrated to machines in order to reduce personal errors.
(5) Conveyor belts were used between machine tools and on the assembly line.

Although mass production was already achieved in manufacturing of guns in the early 19th century, H. Ford started to make large-size products in mass production. Ford's mass production mode was based on the so-called "rigid automation" meaning that product, process and equipment were fixed without changing in a long period of time.

H. Ford had a strong sense of equality and fraternity. People came to Detroit to work for Ford, not only because of the high wages. He also helped to settle immigrants, and was willing to hire disabled who were not considered by other enterprises (Williams et al. 1978b).

H. Ford transformed the automobile from the rich's toy to a necessity of general people. In 1999, the magazine *Fortune* voted him as "Businessman of the Century", in recognition of his outstanding contribution to human society.

The development of society and economy created higher demand for mechanical products. The mass production rapidly spread to the manufacturing of other products.

Beginning from the early 20th century, the scientific management system by F. Taylor and the mass production by H. Ford were widely spread in some countries. This not only promoted the development of machinery industry, but also greatly impacted the social structure, specialization of labor and the overall economy.

The mass production created speed and efficiency. The two World Wars further strengthened the pursuit of speed and efficiency. The mass production of weapons with high efficiency in the U.S. was an important factor to the victory of the anti-fascist war.

5.4.6 Standardization and Serialization

During the First Industrial Revolution, screw threads were standardized. This was the first standard in machine manufacturing.

Unified international standards of metrology were the necessary condition of standardization. The French Revolution promoted the establishment of the centimeter-gram-second system and the decimal system as the basic standard of measurement system. In 1799 the meter prototype and kilogram prototype were made. The French system was finally accepted as the international measurement standard (GSHCAS 1985) at an international conference in 1872, almost 100 years since it was established. The main reason for this lagging behind was that Europe was split politically at that time.

In the 1870s, Charles Renard, a French military engineer, put forward the concept of series of preferred numbers (GSHCAS 1985) which was the basis of serialization. In the 1920s and 1930s, the preferred numbers were adopted as a standard first by some countries, and then by the international organizations. Since then, standardization and serialization were widely adopted in dimensioning practice first by individual companies, and later by countries and international organizations.

At the beginning of the 20th century, the modern industrial production mode, represented by the automobile industry, was rapidly formed. The large quantities of production and variation of individual parts required not only specialized production, but also broad cooperation. Industrial standards were the basis for both specialized production and cooperation. In 1901, the UK established the world's first organization for standardization, Engineering Standards Committee (later, the British Standards Institution, BSI). In 1902, Newall Co. compiled and published the first standard to standardize limits and fits, which was the world's first tolerance standard (Li 1987).

Between the two world wars, standardization was realized in material properties, size and shape, tolerances and fits, machine parts and components, spindle speed and feed of machine tools. All these greatly reduced the workload of design and planning, and manufacturing cost (Williams et al. 1978b).

The international activities of standardization started in the field of electronics. In 1906, the International Electrotechnical Commission (IEC) was established; this was the world's first international standardization organization. Work in other technical fields was implemented through the International Federation of the National Standardizing Associations (ISA) founded in1926, whose main working field was mechanical engineering. ISA's work ended in 1942 because of WWII.

In 1946, delegates from 25 countries met in London, and decided to create a new organization to promote international cooperation and unify industry standards. In February 1947, the International Organization for Standardization (ISO) officially began its operations. ISO's headquarter was located in Geneva, Switzerland.

5.5 Trends of Development of Machinery

Since the Industrial Revolutions, machines have been developed toward high speed, high power, light weight, automation and high precision. These trends are still continuing. The machine design, manufacturing, and other relevant theories have been developed all around these trends.

5.5.1 High Speed and Large Capacity

Changes of power, progresses in material and in manufacturing technologies greatly promoted the machine manufacturing industry, making it possible to manufacture high speed and high power machines. For the purpose of productivity, machines have always been designed operating at higher and higher speed and power. These two factors have significantly influenced the development of all mechanical theories, of the machine dynamics in particular.

In the times of steam engines, an overhead line shaft was typically used to drive multi-machines. The load to the engine was large; thus, the speed was pretty low. In addition, many transmission belts were used in the workshop to deliver power to individual machines. High speed was unfavorable for security consideration. After electric motors appeared, each machine could be driven independently by a motor. The restriction on speed was largely removed. Therefore, after the Second Industrial Revolution, both the speed and power of machines have been going upward all the time.

5.5.1.1 Locomotives

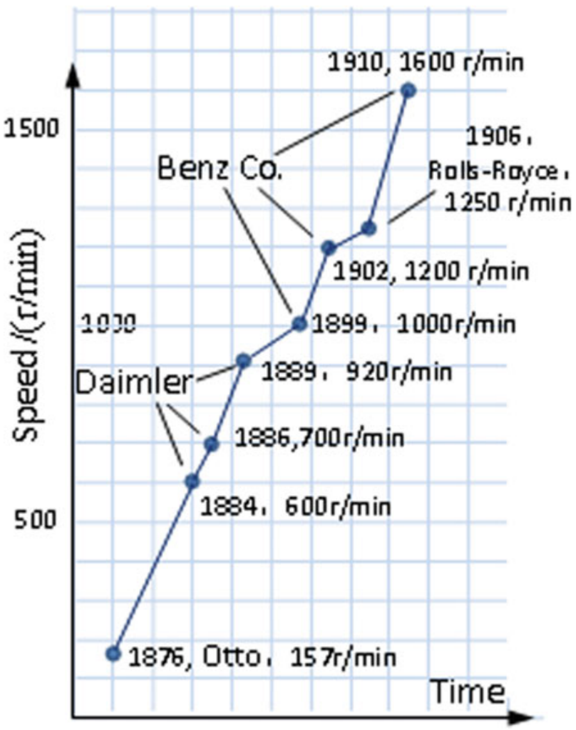
In 1804, the speed of Trevithick's first steam locomotive was only 8 km/h. In 1825, the average speed of Stephenson's train was more than doubled, reaching 15 km/h. In 1885, the average speed on the Trans-Canada Railway, which was of 4600 km long, reached nearly 40 km/h. By WWI, steam trains with speed of 161 km/h appeared. In 1972 and 1995 the speed for steam locomotives hit the records of 180 and 230 km/h respectively, more than 10 times of the Stephenson's.

As early as in 1879, the German Siemens company built the first electrified railway. At that time, the speed of electric train was only 13 km/h. To the year of 1948, the power of the first American gas turbine electric locomotive reached 3520 kW, and the speed was 104 km/h. Since the 1970s, several countries, including France, Germany, Japan and China, started to developed high speed trains traveling at 320–550 km/h.

5.5.1.2 Internal Combustion Engines

In 1876, the speed of Otto's internal combustion engine was only 157 r/min. The speed of Daimler's engine jumped to 600–920 r/min. In the first 20 years of the 20th century, the transportation industry demanded for high power internal combustion engines. The main routes taken for uplifting the power included increasing the speed (Fig. 5.33), increasing the number of cylinders, adding and improving auxiliary devices. In the period of 1899–1902, the speed of the engine by Benz company reached 1000–1200 r/min.

Fig. 5.33 Speed of gasoline engines



In the 1970s, the gasoline engine speed reached 8000 r/min. Now it is above 10,000 r/min (such as in race cars). The maximum speed of diesel engine also achieved up to 5000 r/min.

5.5.1.3 Steam Turbine Generator Units

The wide application of electric power created a demand to increase the capacity of steam turbines. At the beginning of the 20th century, the unit capacity in coal power stations reached 10 MW. In the 1920s, the peak load of power need in some big cities of the U.S., such as New York, was close to 1000 MW. More than 100 units would be needed if each unit capacity was kept 10 MW. Thus, there was a real need to increase the unit capacity. To the 1920s and 1930s, the unit capacity, actually, already reached 60 MW, and 208 MW, respectively. After 1930, lower speed units with 6 and more poles gradually expelled out of the market; and higher speed ones with 3 and 4 poles became the main stream (Wang and Li 2012).

Another driving force to larger unit capacity is the need to improve the thermal economy of turbines.

5.5.2 *Precision*

Precision of machines is an important criterion of quality. The higher operational speed requires higher level of precision of machining which is achieved through machine tools of higher precision. Various machine tools, such as grinding machines, hole broaching machines, precision lathes, precision boring machines, and gear cutting machines, were invented under such a technical motivation.

Figure 5.34 shows schematically the development of cutting tools, measuring methods, materials, representative machine components and machines in the past two hundred years (Wu and Duan 1992). In the time of steam engine, low carbon steel and cast iron were the representative materials. Boring machines were the representative machine tool, which was used in machining the cylinder of Watt's engine requiring an accuracy of 1 mm. All these combined made the commercial production of Watt's engine possible. At the age of the internal combustion engines, machining precision reached the order of magnitude of 0.01 mm, and the converter steelmaking provided better quality steel. After entering the 20th century, manufacturing precision reached micron level. Micrometers were invented for measurement. During a hundred years before the end of WWII, machining accuracy was improved by two or three orders of magnitude at least. The progress after the war was even faster.

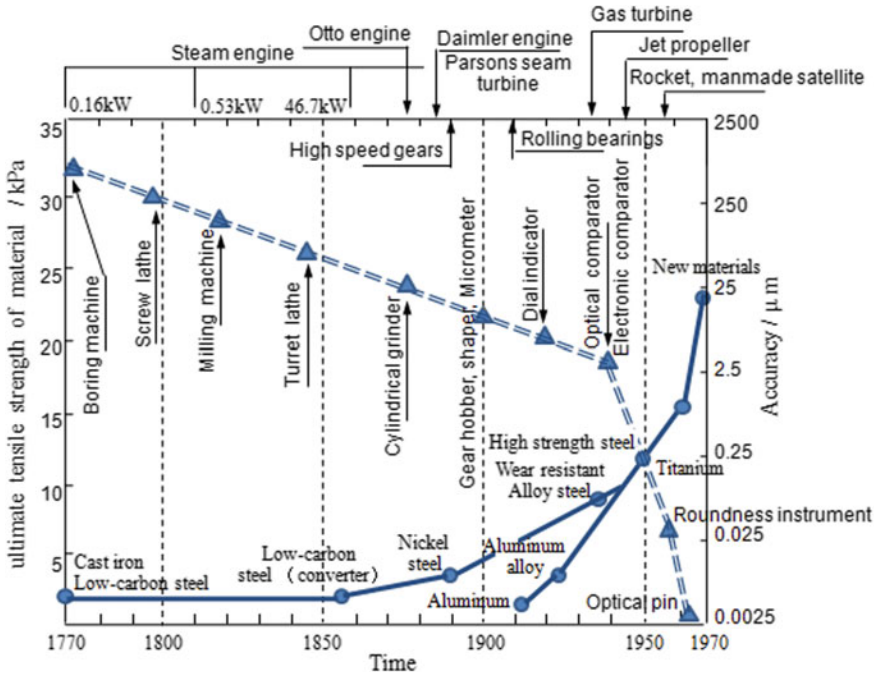


Fig. 5.34 Evolution of materials, machine tools, measurement and accuracy

High precision requires techniques to suppress vibration, which sparked the development of vibration theory, vibration suppression and balancing technology of machines.

5.5.3 Light Weight

Reduction of machine weight can save material and energy. This is especially important for vehicles and airplanes. In fact, light weight has been a constant theme in machine design. Progress in materials makes lightweight design possible. During the several decades after Otto's invention, one main goal in engine design was to reduce the mass-power ratio, which continuously decreased from 272 kg/kW of Otto's engine in 1876 to 0.68 kg/kW of the aero-engine in the 1920s. Great progress was made in terms of lightweight.

Figure 5.35 illustrates the change of size of worm gear reducers made by the famous British Radicon during the last 80 years. The trend in size reduction is obviously seen.

Lightweight requirement inspired the metallurgic industry to produce materials of high strength. As can be seen from Fig. 5.34, the material properties were increased by several times during about one hundred years before the end of WWII.

Market competition has been the driving force for saving material and energy, and thus for lightweight, in machine design. To the 1960s, the world came to a realization that the resources available on the earth was limited. Since then light weight design has become a conscious consideration in most design engineers.

Lightweight and high speed are two main factors calling for research of vibration and elastic dynamics.

5.5.4 Semi-automation

Modern automation of machines has two aspects: self-regulation and process control.

Fig. 5.35 Volume change of Radicon worm-gear reducers in 80 years

In the ancient times, people already imagined to do some hard and difficult work using an automatic device. The south pointing chariot in ancient China and watches in Europe in the late Middle Age were two examples of such automatic devices. These simple and early devices led to the formation of the modern automation technology.

In 1788, Watt invented the centrifugal governor used in the steam engine, which actually was a closed loop automatic control system for the engine speed. This invention opened a new era of modern automatic regulators, significantly influencing the subsequent development of control theory. Thereafter automatic regulators were used to many control problems in production. These regulators trace the physical quantities under control, and keep them around pre-designated given values.

In order to manufacture standard screws efficiently, the automatic screw machine was created in the U.S. in 1870. In 1895, a multi-axis automatic machine tool was built. In the automatic machine tool, the motions of longitudinal and lateral carriages and other components were controlled by cams installed on the so-called "distribution shaft" (see Fig. 7.10). This essentially is the process control through a pure mechanical way.

The manufacturing industry of hydraulic elements was developed between 1890 and 1910. However, wide application of hydraulic power did not start until after WWI. The control technology of hydraulic transmission was first applied to the manipulation of aircraft landing gears, flaps and ailerons. This success promoted the application of hydraulic transmissions in machine tools.

In the 1920s and 1930s, the relay control technology appeared.

The development of electric and hydraulic elements brought the manufacturing to the so-called semi-automation stage in the 1920s. Relays played a leading role in automatic control of machine tools, due to their simple structure, low cost and easy maintenance. Hydraulic systems were mainly utilized in grinding machines. In 1924, the first automatic machining line appeared in Britain. In 1935, an automatic machining line for automobile engine cylinder blocks was put into operation in the Soviet Union.

Thereafter, pure mechanical process control and relay control were widely used in various light industrial machinery.

After the 20th century, various automatic regulators have been applied in industrial production. Although feedback control was already used in automatic regulators, theories on feedback control were not established until the 1920s.

The mechanical automation before WWII was called rigid automation, which was suitable to the mass production then. The methods of classical control through pure mechanical ways were no longer used now; however, their historical significance should not be neglected. They promoted the study of cams and intermittent motion mechanisms. The relay control was the predecessor of modern computer control.

In around 1940, the world's earliest professional research institutions of system and control were established, which made theoretical preparation and talent training for the formation of classical control theory and the development of local automation in the 1940s.

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Chapter 6
Progress of Mathematics and Mechanics During Industrial Revolutions

The laws of nature are written by the hand of God in the language of mathematics.
—Galileo Galilei (an Italian polymath, 1564–1642)

In Chaps. 4 and 5, the two industrial revolutions were introduced, including inventions of many machines and birth and development of machine building industry, without involving the discipline of mechanical engineering, which will be introduced in Chap. 7. This chapter introduces the progress in the field of mathematics and mechanics after the establishment of Newtonian mechanics and calculus; and briefly summarizes the influence of the progress on mechanical engineering.

6.1 Progress of Mathematics Related to Mechanical Engineering

The theories of calculus and differential equations were created almost at the same time with the Newtonian mechanics. The next 200 years following saw a great progress in mathematics, especially the calculus of variations, differential geometry, linear algebra, probability theory and graph theory, which are related closely to mechanical engineering (Katz 1998; Boyer and Merzbach 1989).

6.1.1 Calculus of Variations

In 1696, Johann Bernoulli put forward a problem to challenge all European mathematicians (Fig. 6.1), which stated "to find the curve connecting two points, at different heights and not on the same vertical line, along which a body acted upon only by gravity will fall in the shortest time". This is the famous "Brachistochrone problem". This challenge falls in the extreme problem, but the independents are

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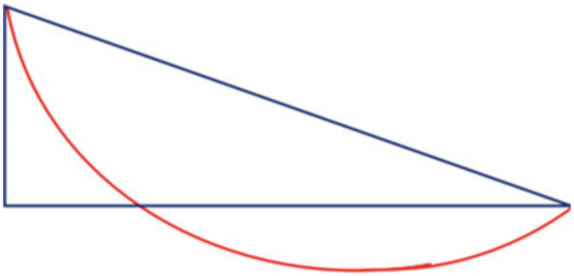

Fig. 6.1 Brachistochrone problem

functions, not just a variable or several variables. Several mathematicians showed interest in the problem. Leonhard Euler and Joseph-Louis Lagrange gave the general method for solving this kind of problem, opening a new branch of Mathematics, the calculus of variations, or variational method.

The variational method deals with the functional which is often described as "function of function". Its counterpart in calculus is function of variables. Many phenomena in reality can be expressed as a functional minimization problem, called the variational problem, which seeks the extremal function making the functional to get the maximum or minimum.

Lagrange introduced the variational method into dynamics. His principle of least action is actually that the real motion corresponds to the minimum of the Lagrange function. Therefore, the variational method and analytical mechanics were established simultaneously and inseparably.

In the second half of the 20th century, variational method became the mathematical foundation of the finite element method, which is a powerful tool for solving boundary value problems. The optimum control theory is also an application of the variational method.

6.1.2 Differential Geometry

The creation and development of differential geometry is closely connected to the mathematical analysis. Curvature of general surfaces was first studied by L. Euler. He proved a formula for the curvature of a plane section of a surface and studied surfaces represented in a parametric form in 1760 and 1771, respectively. At the early 19th century, Gaspard Monge, a French mathematician, first applied calculus to the study of curves and surfaces. In 1807, he published the *Application of Analysis to Geometry,* the earliest work in the field of differential geometry.

The local differential geometry studies properties at the neighborhood of a point on a curve or a surface in the 3-dimensional Euclidean space. In 1827, Johann Gauss, the great German mathematician (Fig. 6.2), published *General Investigations of Curved Surfaces,* which is the first milepost of local differential geometry. He pioneered the study of intrinsic geometry of curved surfaces and

Fig. 6.2 J. Gauss

made differential geometry an independent subject. In 1854, Bernhard Riemann extended Gauss's theory to the high dimensional space and created the Riemann geometry, which laid the mathematical foundation for Einstein's theory of general relativity.

In 1872, Christian Felix Klein, a German mathematician, worked on the so-called Erlangen program at Erlangen University, which characterizes geometries based on their underlying groups of transformation. In the half a century following, it became the guiding principle of geometry, and led to the creation of different branches of differential geometry.

Global differential geometry was developed in 1930s and 1940s. One of its most important parts concerns the influence of curvature of a manifold to topological and metric properties of the manifold.

In differential geometry, the high order infinitesimal can be negligible, due to the use of mathematical analysis, over an infinitely small range. Thus the complex dependency can be linearized and an inhomogeneous process becomes uniform. All of these are the particular characteristics in the research of differential geometry. Due to the study in modern times on the high-dimensional differential geometry and the overall nature of curves and surfaces, the differential geometry is closely related to Riemann geometry, topology, calculus of variations, and Lee algebra. The interaction between these mathematical branches has become one of the central problems in modern mathematics.

Differential geometry is widely applied in mechanics and engineering, such as elastic shell structures, gear and worm gear theory, robot analysis, etc.

6.1.3 Linear Algebra

Linear algebra is a subject dealing with matrices, finite dimensional vector space and its linear transformation. Its foundation, the solution of linear algebraic equations with 2 or 3 unknowns, was described already in the famous Chinese work, A*rithmetic in Nine Chapters,* which appeared in as early as the 1st century.

Theory of modern linear algebra appeared in the 17th century. However, studies were limited to 2 or 3 dimensional spaces until the end of the 18th century. It was extended to n-dimensional vector space in the first half of 19th century. During 1855–1858, Arthur Cayley, a British mathematician, established the systematic theory of matrices.

Most of multi-variable problems encountered in practice can be simplified into linear algebraic equations. Linear algebra is exactly a powerful tool to solve these types of problems, with wide application in mathematics, physics and engineering. In the computer era nowadays, it has become an important foundation of theory and algorithm in computer graphics, computer-aided design and virtual reality etc.

Eigenvalue is an important problem in linear algebra. But it was historically proposed in the study of the quadratic form and differential equations. Eigenvalue has important application in vibration analysis, involving natural frequencies and vibration modes of a system.

In the middle 18th century, Jean D'alembert became aware of the eigenvalue problem in study of the vibration of a string with a few attached lumped masses, which was represented by linear differential equations. However, he did not summarize mathematically, nor did he investigate further with this important problem.

Augustin-Louis Cauchy found and used the eigenvalue. He transformed the quadratic form into a quadratic sum. Karl Weierstrass, a German mathematician, discussed the problem of quadratic form and clarified the stability theory of the eigenvalue in 1858 with a small-amplitude vibration problem. He generalized the method to simultaneously transform two quadratic forms into quadratic sums. However, the eigenvalue problem was not expressed in matrix form until Cayley established the matrix theory.

When deriving the vibration equation of n-dimensional linear systems with Lagrange's equation, the kinetic and potential energies, are expressed as quadratic forms of n-dimensional variables. The linear differential equations are decoupled through simultaneous diagonalization of the mass matrix and stiffness matrix of the system. This is exactly transforming simultaneously the quadratic form kinetic and potential energies into the standard quadratic forms. As such, contributions of Cauchy and Weierstrass obviously advanced the vibration analysis of linear systems.

The solution of eigenvalues, in essence, is a polynomial root finding problem. Finding the roots of a polynomial of degree higher than 4 is generally achieved through iterative methods. Eigenvalue problems of high dimensional matrices can only be obtained by numerical algorithm due to considerations in computation intensity, accuracy and stability. The first numerical algorithm, the so-called power method, for eigenvalues was published in 1929 by Richard von Mises, an Austrian mathematician. Later, more numerical methods were developed after the WWII.

6.1.4 Probability Theory

Probability and stochastic process are the mathematical basis of a few important fields in mechanical engineering, such as random vibration, manufacturing accuracy and stochastic control.

In 1654, two French mathematicians, Blaise Pascal and Pierre de Fermat, discussed some mathematical problems raised in gambling, which is regarded as the beginning of study on probability theory.

In 1657, Christiaan Huygens first put forward the concept of mathematical expectation clearly. Although terms of gambling were used in his definition, it is not difficult to extend to general cases. Huygens already realized the value of this research as he put in a letter: "*I believe that a careful study of this issue, you will find it not only game-related, but also contains an interesting and profound principle of reasoning*".

In 1713, Jacob Bernoulli's posthumous, *Ars Conjectandi,* was published, which was the first monograph in the field of probability theory. His greatest contribution is the famous "law of large numbers", also known as "Bernoulli law",a landmark for the probability theory becoming a mathematical branch.

Pierre-Simon Laplace (Fig. 6.3) was a famous French mathematician, known as "Newton of France". Summarizing up his researches on probability theory in decades, He published *Analytic theory of probabilities* in 1812. This book was an

Fig. 6.3 P. Laplace

agglomeration of classical probability theories, in which he demonstrated basic definitions and theorems of probability, established observation error theory and the least square method, and studied broad statistical problems. Laplace made probability theory a part of mathematical analysis with the methodological change, before which it was regarded as a part of combination mathematics.

From Pascal, Fermat to Laplace, the establishment of classical probability theory lasted for 150 years.

P. Chebyshev (Пафнутий Чебышев), a Russian mathematician, and his student A. Markov (Андрей Марков), were pioneers of modern theory of probability. Chebyshev gave the law of large numbers for independent random variable sequence (in 1846) and the central limit theorem (in 1887). In 1907, Markov proposed the initial form of theory of stochastic process.

R. von Mises proposed the concept of sample space in 1919, and the Russian mathematician A. Kolmogorov (Андрей Колмогоров) introduced the axiomatic method in 1933, marking the start on the modern theory of probability. The development of probability in the 20th century was driven by strong needs of practical problems, such as guidance control and communication. The most noticeable contribution to the maturity of stochastic process theory is from mathematicians of the Soviet Union and the U.S. In 1940s, the noise theory in communication was proposed by using the stochastic process theory; later, the noise theory was transplanted to the field of random vibrations.

6.1.5 Graph Theory

After the WWII, the graph theory, a new mathematical tool, was introduced into mechanism and multibody dynamics (see Sects. 13.1 and 9.5.3). Graph theory is a part of topology. The so-called "graph" is composed of a number of given points and lines linking two points, representing the specific relationship between the points connected. The graph theory attracted the attention of several famous mathematicians.

The graph theory originated from the famous "seven bridge problem". In Königsberg there were seven bridges on the river as shown in Fig. 6.4a, in which A, B, C and D represent the lands. The question is: beginning from a piece of land, going through each bridge once and only once, and then returning to the starting point. L. Euler represented this problem in 1736 with a graph as shown in Fig. 6.4b; the points and the lines connecting the points in the graph represent the land and the bridges respectively. Euler proved no solution for this problem and he is considered the founder of the graph theory.

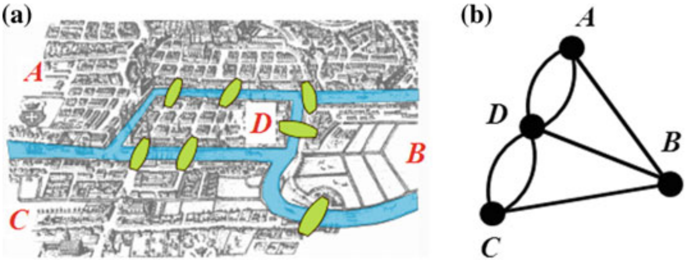

Fig. 6.4 Problem of seven bridges of Königsberg. **a** Seven bridges of Königsberg, **b** the graph

In 1857, William Hamilton, an Irish physicist and mathematician, proposed a game. The game's object is to find path along the edges of such that every vertex, representing one famous city of the world, is visited a single time, and the ending point is the same as the starting point. The problem was later called "Hamiltonian cycle problem". It attracted broad attention and extensively studied because a lot of problems in operational research, computer science and coding theory could be transformed into the Hamiltonian problem.

Another famous and stimulating problem in graph theory is the four color problem which states that any map drawn in a plane may have its regions colored with four colors in such a way that any two regions having a common border have different colors. In 1872, this problem was brought up to a mathematical conference held in London and many then leading mathematicians were involved in proving this theorem. This seemingly simple problem was not solved until in 1976 a proof was given with a computer working as long as 1200 h.

6.2 Further Progress of Mechanics

During the 250 years from establishment of Newtonian mechanics in 1687 to the end of the industrial revolutions, mechanics continued to develop mainly focusing on analytical mechanics and continuum mechanics (Wu 2000).

Continuum mechanics includes solid mechanics and fluid mechanics. Solid mechanics includes elastic mechanics, plastic mechanics, material mechanics and vibration theory etc.

Mechanics is the most important basis for mechanical engineering. Development of mechanics laid a solid theoretical foundation for the progress of machine design and manufacturing.

6.2.1 Analytical Mechanics

Newtonian mechanics, dealing with unrestricted free particles, was created with a main driving force from the development of astronomy. With rapid development of machines by the 18th century, an urgent requirement came up in the analysis of motion and forces of constrained mechanical systems. When studying dynamics of a complex system with Newton's second law and Euler formula, equations for each object in the system have to be established. This would bring in all unknown constraint reactions, some of which are not necessarily to be solved; thus, the number of unknown variables in the equations becomes unnecessarily high, making the solution of equations troublesome. This issue led to the establishment of analytical mechanics.

J.-L. Lagrange (Fig. 6.5), an outstanding French scientist, is attributed making the greatest contribution to further development of classical mechanics (Wu 2000). In 1788, Lagrange published *Analytical Mechanics,* in which he combined mechanics theory and mathematical analysis and established an analytical method with a rigorous mathematical structure. In the book's preface He wrote proudly "*One will not find figures in this work. The methods that I expound require neither constructions, nor geometrical or mechanical arguments, but only algebraic operations, subject to a regular and uniform course*" (Lagrange 1997).

He derived the Lagrange equation, with which dynamic equations could be established extremely concisely from the viewpoint of energy. The relationship between kinetic energy, potential energy and work is presented in scalar form. Dynamics analysis with the Lagrange equation has systematic procedures and unified steps. It became a universal and effective mathematical tool for dynamics of constrained systems, being a milepost in the development of classical mechanics.

Fig. 6.5 J.-L. Lagrange

In 1834, William Hamilton, an Irish physicist, derived a dynamic equation based on generalized coordinate and generalized momentum, called the canonical equation. In the Hamiltonian system, dynamics of a complete system in a multidimensional space could be studied with the variational principle.

After further development by a number of scientists, the theory of analytical mechanics approached mature.

In the 20th century, broad studies on nonlinear systems, time varying systems, systems with variable mass, and stability of motion were carried out.

As an important branch of classical mechanics, analytical mechanics not only extends the scope of classical mechanics, but also reformulates the expression form.

At its early stage, analytical mechanics was already successfully applied in celestial mechanics, rigid body dynamics and analysis of small amplitude vibration. By the 20th century, its application extended to quantum mechanics, solid mechanics and fluid mechanics. However, as a new branch of mechanics, it was not widely accepted in engineering until WWII, after which engineering and technology were boomed, and many new subjects grew up across two or more traditional disciplines. This put forward a requirement for more theoretical support,and analytical mechanics gradually gained application in aerospace technology, modern control theory, nonlinear mechanics and computational mechanics. Now, Lagrange equation has been widely used in dynamic analysis of complex mechanical systems.

6.2.2 Elastic Mechanics

Solid mechanics studies performance of the solid medium under action of external factors, such as load, temperature and humidity etc.

Long-term practical experience and the establishment of classical mechanics paved the way for solid mechanics. In addition, the need for building large-scale machines, bridges and factories in the 18th century drove forward greatly the development of solid mechanics.

Solid mechanics has progressed along two parallel paths: elasticity and plasticity, while the study of elasticity started earlier.

Elastic mechanics, also called elasticity theory, is the most important part of solid mechanics. It deals with the stress, strain and displacement of a elastic object under the action of external factors, such as forces or temperature etc. It lays a theoretical foundation for solving problems of strength and stiffness encountered in structure design and mechanical design.

Elastic mechanics differs from material mechanics in the complexity of the objects. Material mechanics basically studies only rod-shaped objects; while elastic mechanics treats elastic objects of various shapes.

In the ancient time, humans already knew how to make use of the elasticity of objects (e.g. the arrow). However, the systematic and quantitative study of elasticity began from the 17th century. Since then, the development of elastic mechanics has undergone four stages (Timoshenko and Goodier 1951; Love 1944; Wu 2001).

The first stage was before Newton. Robert Hooke, an English natural philosopher, realized that the elastic deformation of an object was proportional to the applied force, and proposed Hooke's Law in 1678. This was the initial exploration of the basic law of elastic deformations (Timoshenko 1953). In China, in the 2nd century, this law was discovered by Zheng Xuan, but had all faded from the scene (EBDM 1990; Lao 1993).

In 1807, Thomas Young, an English scientist, proposed the concept of modulus of elasticity.

The second stage began from 1820s. In this stage the basic theory of elasticity was established. The major contributions are credited to three scholars of French School of Bridges and Roads, C.-L. Navier, A.-L. Cauchy and B. Saint-Venant.

In 1821, Claude-Louis Navier derived the equilibrium equation of an isotropic elastic object, with displacements as unknowns. But he included only one elastic constant, without giving the accurate concept of stress and strain.

In 1822–1828, Augustin-Louis Cauchy published a series of articles on elastic problems (Fig. 6.6). He introduced the concept of strain, established the relationship between strain and displacement, introduced the concept of stress tensor and principal stress, discussed the relationship between strain tensor and stress tensor, established the generalized Hooke's Law (for both isotropic and anisotropic materials); derived the equilibrium equation and boundary conditions in terms of displacement. These contents constitute the foundation of the linear elastic mechanics. Therefore, Cauchy is credited as the main founder of elastic mechanics.

Fig. 6.6 A.-L. Cauchy

The fast development and establishment of the basic equations of elastic mechanics in the second stage are closely related to the development in the theories of calculus and differential equations, which are mainly attributed to Newton and Leibniz. In fact, the main contents of elasticity are represented by several sets of partial differential equations.

The third stage is the fast development of linear isotropic elasticity, symbolized by application of theory in solving engineering problems. In 1855–1858, Barre de Saint-Venant published an article on the twisting and bending of a column body, which is considered the beginning of the third stage. In his paper, theoretical and experimental results were closely agreed, proving a strong evidence of the correctness of elastic mechanics.

In 1882, Heinrich Hertz, a German scholar, derived the contact stress between two elastic bodies with a curved surface, symbolizing the establishment of classical theory of contact mechanics. In 1898, another German scholar, Gustav Kirsch, discovered the phenomenon of stress concentration in calculation of the stress distribution in the vicinity of a circular hole. These achievements explained experimental phenomena which could not be explained in the past, and played an important role in improving design level of machines and structures. As such, elastic mechanics drew the attention of the engineering circle.

During this period, the general theory of elasticity also had a great development. On the one hand, a variety of theorem about energy was established; on the other hand, many effective approximate methods of calculation, numerical algorithm were developed. These promoted a vigorous development of approximate calculations in mechanics, physics and engineering.

Beginning from 1920s, elastic mechanics entered the fourth stage, in which many complicated problems were explored and several branches of subject were formed, such as the theory of anisotropic and inhomogeneous bodies, nonlinear shell theory and nonlinear elastic mechanics, thermal elastic mechanics considering the influence of temperature, aeroelasticity and hydro-elasticity studying interaction between solid bodies and gas/water, and viscoelastic theory. These new areas enriched the content of elastic mechanics, and promoted the development of related engineering technologies.

The classical theory of elasticity successfully solved a number of stress and deformation analysis problems of bars, beams and plate-shaped engineering parts. Although the theory is elegant and almost perfect, there is a serious limitation that analytical solution is only available for parts of simple shapes, no solutions in analytic form for parts with complex shape. Thus, it is difficult for the classical theory of elasticity to be directly applied to practical engineering problems. This situation was not changed until the appearance of finite element method after the WWII. It took 135 years from the creation of Newtonian mechanics to the establishment of elasticity theory by Cauchy, and another 135 years to the appearance of finite element method.

6.2.3 Plastic Mechanics

Study on plastic mechanics could be traced back to the second half of the 18th century (Martin 1975). The phenomenon of plastic deformation was found earlier; however, research on it from the mechanics viewpoint did not appear until 1773 when C.-A. de Coulomb proposed the yield condition of soil.

In the second industrial revolution, steel was widely used. At the same time forging hammers and hydraulic presses were used in metal forming processes involving large plastic deformations. This put forward a requirement to understand the plastic deformation in theory.

Under multi-axial stress state, the criterion of yielding is called the yield condition, which should combine all stress components. For metal materials, two most commonly used yield condition are Tresca condition and Mises condition.

In 1864, Henri Tresca, a French engineer, put forward a yield criterion for metal materials in terms of maximum shear stress. In 1870, Saint-Venant proposed the stress-strain relationship in plane stress state. In 1871, the plastic stress-strain relationship was extended to 3-dimensional case by Maurice Lévy, a French engineer.

In the 20 years following, a variety of yield criterion were proposed. Among them, the most significant one was the criterion based on the maximum distortion strain energy proposed by R. Mises (Fig. 6.7) in 1913. Mises also independently proposed the plastic stress-strain relationship, later known as Lévy-Mises constitutive relationship.

R. Mises made outstanding contribution in several fields of mathematics and mechanics. In this chapter alone, his name was mentioned three times (see Sect. 6.1). He was a Jew, born in Austria, and after the Nazis came to power, he left to Turkey and finally to the U.S.

Fig. 6.7 R. Mises

In mechanical engineering, plastic mechanics is the theoretical basis of plastic limit analysis of parts, the forming analysis in metal forging, rolling and other press workings.

6.2.4 Mechanics of Materials

Mechanics of materials was developed for solving practical engineering problems, with slender rods as the object of concern. Beams and trusses in civil construction, shafts and linkage bars in machines could be simplified as a rod. Due to the simplifications made in mechanics of material, the methods of analysis and calculation are relatively simple.

Mechanics of materials was the earliest developed branch of solid mechanics. In 1638, Galileo Galilei, the great Italian scientist, put forward firstly a formula for calculation of beam strength on the basis of experiments. This is considered the beginning of mechanics of materials (Timoshenko 1953; Wu 2000).

Beams are widely used in civil engineering; therefore, beams became the first important topic in mechanics of materials. Around in 1750, L. Euler and Daniel Bernoulli proposed a theory on stress and deformation of a beam, in which shear deformation was ignored. This beam, called Euler-Bernoulli beam, is still the basic model now in analysis of strength, deformation and vibration of beams. Euler also proposed the stability of elastic bodies, and solved the stability calculation of bar's buckling. D. Zhuravsky (Дмитрий Журавский), a Russian scholar, in construction of railway bridges, solved many problems in strength of beams, such as the shear stress in beams and calculation of composite beams.

As early as in 1784, the French scholar C.-A. Coulomb studied the torsion problem, putting forward the concept of shearing.

Strength theory was another important topic in mechanics of materials. Historically, four strength theories were proposed (Wu 2000).

The first strength theory, based on maximum tensile stress, was first proposed by William Rankine, a famous British engineer.

The second strength theory, taking the maximum elongation as a criterion, was first proposed by Jean-Viktor Poncelet, a French scholar.

The third strength theory is based on the maximum shear stress, and was developed by Henri Tresca during 1867–1878 on the basis of Coulomb's friction law.

In 1904, Maksymilian Huber, a Polish scholar, proposed a criterion based on the total strain energy theory, which was later improved by R. Mises in 1913 with a criterion based on the maximum unit distortion energy, forming the fourth strength theory.

The four strength theories, being the basis of structural design, enable engineers to design various structural and mechanical objects, such as cars, high-speed railways, submarines, airplanes, gas turbines, satellites, nuclear power stations, space shuttles and other large machines and constructions.

Fatigue strength is another important topic in material mechanics, relating closely to mechanical engineering. The fatigue concept is completely a result of the first industrial revolution. Then with the increase of running speed of steam-powered locomotives, accidents caused by fracture of locomotive axles occurred very often, inspiring studies on fatigue failure. In 1870, August Wöhler, a German engineer, showed his results obtained in rotating bending tests of axle fatigue, connecting fatigue and stress together. Based on the experimental data he put forward the concept of fatigue limit, which laid the foundation for the conventional fatigue design (see Sects. 7.6.4 and 13.5).

During a period of more than a century after the creation of classical mechanics, mechanics and mathematics was of great prosperity. Several fundamental problems in mechanics of materials, including strength, stiffness and stability, were successfully solved.

Theory of elasticity is more rigorous, yet more complicated. For real world problems of strength and stiffness in mechanical and civil engineering, simplified theories and methods are favored. Therefore, mechanics of materials was still gradually enriching and remained used in solving practical engineering problems despite the existence of theory of elasticity.

At the beginning of 19th century, large engineering structures began to be built. Based on mechanics of materials, structural mechanics was developed and became an independent applied subject. In the second half of 19th century, in order to solve practical mechanical design problems, design of machine elements separated itself from the applied mechanics, becoming an independent applied subject.

One of the most important characters of modern engineering mechanics was S. Timoshenko (Степан Тимошенко) (Fig. 6.8). He was a Ukrainian in the Russian Empire, and moved to the U.S. after the civil war in Soviet Union. He was called “the father of modern engineering mechanics”. During 1925–1972, he published more than 10 books in fields of elastic mechanics, mechanics of materials and vibration theory. Some textbooks were published in 36 languages. In recognition of his great contribution to engineering mechanics, ASME established the Timoshenko award in 1957 granted to scholars who made outstanding contributions in the field of applied mechanics (Wu 2000; Mansfield and Young 1973).

6.2.5 Theory of Vibration

6.2.5.1 Birth of Theory of Vibration

Research on theory of vibration was already started far before the first industrial revolution, mainly on pendulums and music instruments (Wu 2000). At that time, machines in manual workshops were only driven by manpower and water power, and operated at very low speed; vibration was not a serious problem.

Fig. 6.8 S. Timoshenko

Early in 1602, G. Galilei, a pioneer in research on vibration, found the isochronism of single pendulum and calculated its oscillation period. C. Huygens invented a pendulum clock, and pointed out the deviation from isochronism at a large amplitude oscillation. This is the earliest observation and record on nonlinear oscillation.

Vibrating strings are the vocal elements in the violin family and the piano invented at the end of 17th century, in which a resonance chamber is generally made of wooden plates. All research on vibration of strings or plates at that time by L. Euler, Bernoulli and D'alembert is related to instruments. In the next two centuries, string, beam and plate became hot research fields of mechanics.

6.2.5.2 Development of Linear Theory of Vibration

The linear theory of vibration applies to linear systems, in which the masses are constant and the elastic forces and damping forces are proportional to the displacements and velocities respectively. It is an approximate description of vibration phenomenon under the small-amplitude condition.

During 1743–1758, in studying on vibration of strings, D'alembert decoupled a set of differential equations of the vibration system with several degrees of freedom. At that time the concept of matrix and eigenvalues had not existed; he did not summarize into general theory (Katz 1998).

After the creation of analytical mechanics in 1788, analysis of small-amplitude vibration systems became one of the main applications of analytical mechanics.

In 1839, Jean-Marie Duhamel, a French mathematician, presented a solution method, later known as the Duhamel integral, for the response of a single degree of freedom system under arbitrary excitation.

During 1820s–1850s, A.-L. Cauchy and other mathematicians solved the eigenvalue problem, laying the foundation for vibration analysis of discrete systems with multi-degree of freedom.

John Rayleigh (Fig. 6.9), a famous British physicist, made the most important contribution to classical vibration theory. At the age of 31, he was elected as a member of the Royal Society. In 1877, Rayleigh published *The Theory of Sound* (Rayleigh 1894), which was a comprehensive collection of previous researches. This book presented the vibration of elastic bodies, including plates, pipes and strings, and gas in detail, covering the main contents of today's linear vibration theory. It is regarded a classical work on acoustics and elastic dynamics, with great influence even nowadays (Wu 2000). Rayleigh put forward an approximate method to calculate the fundamental frequency (Rayleigh quotient) through simplifying and transforming a complex problem into a single degree of freedom problem. Later, in 1909, the Swiss physicist Walther Ritz improved it, forming the widely used method to approximate low order eigenvalues and eigenvectors of structures (Rayleigh-Ritz method), which is now still covered in many vibration textbooks. Also, Rayleigh first explained theoretically the parametric resonance phenomenon.

Fig. 6.9 J. Rayleigh

6.2.5.3 Nonlinear Theory of Vibration

Vibrations of most actual systems are nonlinear in essence. The nonlinear factors may come from different sources, such as nonlinear forces (electromagnetic force, elastic force and damping force), motion nonlinearity, material nonlinearity and geometric nonlinearity. In automotive vehicles springs with nonlinear stiffness are used widely. Composite material may also have a nonlinear constitutive relation.

At the end of 1939, Theodore von Kármán, a famous Hungarian-American scientist, gave a speech entitled *The engineer grapples with nonlinear problems*, fully demonstrating the important influence that nonlinear mechanics would have on the world.

It seemed to provide a convincing example to von Kármán's speech, the Tacoma Narrows Bridge, a suspension bridge near Seattle, of the U.S., vibrated severely and collapsed on November 7, 1940 (Billah and Scanlan 1991) (Fig. 6.10). The cause of accident was widely thought the nonlinear effect of wind load, which was not considered in design stage of this bridge. Until 1990s, there were publications to discuss the accident.

Nonlinear vibration is expressed mathematically as a set of nonlinear differential equations for which general closed form solution is not available. In contrast, the theory of linear ordinary differential equation has been mature. Therefore, linearizing a nonlinear system into a linear one becomes common practice in engineering. However, the linearization has to be used with its limit and risk in mind

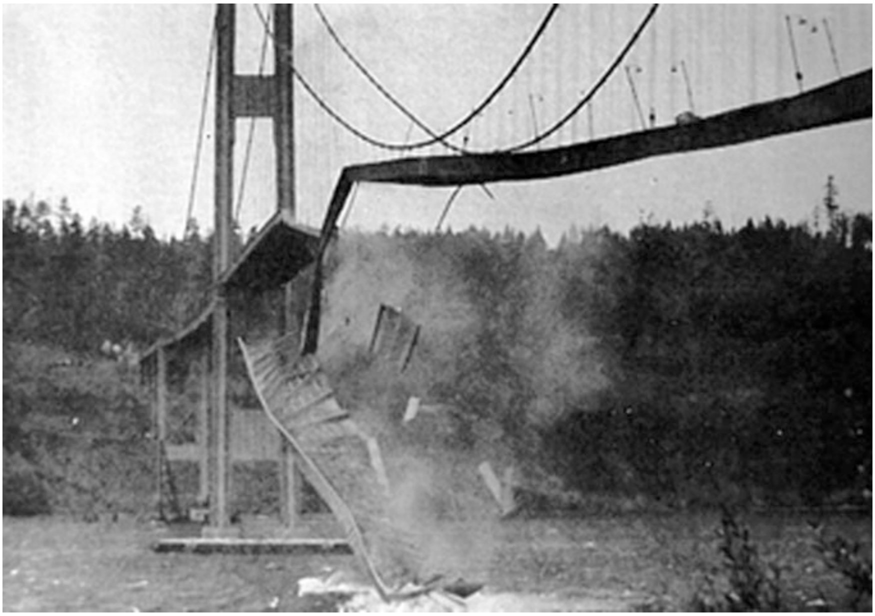

Fig. 6.10 Collapse of Tacoma bridge

that overlarge calculation error and losses of peculiar phenomena to nonlinear may happen. In the case of strong nonlinearity, special caution should be applied.

The vibration phenomena peculiar to nonlinear systems include:

Vibration may not isochronous.
Superposition principle does not apply to nonlinear systems.
For vibration systems with nonlinear restoring force, the natural frequency is related to the amplitude of vibration.
Jump and more complicated resonance exist.
chaos and bifurcation, which were revealed after 1960s, exist.

In addition, self-excited vibration and parametric vibration are generally covered in nonlinear vibration.

Research on nonlinear vibration has gone through the following three stages (Zhang et al. 2002).

(1) The first stage: qualitative theory of motion equations

For nonlinear equations, exact solution is usually not available; thus, approximate methods have to be sought. However, before obtaining an approximate solution, it is necessary to have a qualitative understanding of the problems. This led to the qualitative theory of equation of motion at the end of the 19th century. H. Poincaré (Fig. 6.11), a French mathematician, and A. Lyapunov (Fig. 6.12), a Russian mathematician, made the most outstanding contributions toward this theory.

Jules Henri Poincaré once served as the president of the French Academy of Sciences. He put forward the concept of dynamic system based on the differential equations formed in mechanics. He studied the nature of a curve near the singular points determined by differential equations, and gave the criterion of singularity classification.

Fig. 6.11 H. Poincaré

Fig. 6.12 A. Lyapunov

An important contribution made by Poincaré is the geometrical study of dynamics. He proposed the concepts of phase space and phase diagrams, visualizing dynamics by means of geometric graphics. These concepts and methods remain important tools used for qualitative research on dynamics today.

A. Lyapunov (Александр Ляпунов) completed his doctoral dissertation, *General Problem of the Stability of Motion*, in 1892, becoming a fellow of St. Petersburg Academy of Sciences at the age of 44.

The problem of equilibrium and stability of motion was concerned since ancient times. Watt installed a centrifugal governor on a steam engine. Initially, the governor worked normally. However, with the increase of engine speed, the operation of the governor became unstable. This engineering problem caused a major discussion on basic characteristics of a dynamic system (Wu 2009).

Lyapunov is the founder of stability theory of motion. He gave the rigorous definition of stability of motion along with two methods to determine the stability. Today, it is still the main content about motion stability in all textbooks.

(2) The second stages: quantitative method for nonlinear vibration

The second stage started from the late 19th century, to the 1960s.

The time history of response of a particular nonlinear system could be calculated with Runge-Kutta method proposed in about 1900. Numerical methods, however, are not convenient in analysis of the dependence of motion characteristics upon system parameters.

Therefore, approximate analytical methods, often called perturbation methods, were proposed in succession. These methods, based on the mature linear vibration theory, treat the nonlinear term as a perturbation to a linear system, computing an approximate solution in analytical form (Nayfeh and Mook 1995; Wu 2000). In 1830, Simeon Poisson, a French scholar, first put forward the idea of perturbation method in studying a simple pendulum vibration, and intensive study on various perturbation methods has been carried out since the end of the 19th century. In 1892, Poincaré established the mathematical basis for perturbation methods. Later, many scientists put forward a variety of approximate analytical methods. However, these methods are generally applicable to low dimensional problems with weak nonlinearity. For high dimensional problems, there remain difficulties to directly apply perturbation methods.

The discovery of chaos after 1960s injected new momentum to the study of nonlinear dynamics. Chaos analysis became the theme in the third stage of study on nonlinear vibrations (see Sect. 9.1.3).

6.2.6 Fluid Mechanics

Since ancient times people have used windmills, water tankers, pumps and ships. Some phenomena, such as flow resistance, shape of fans and blades, caused people's attention very early. The foundation of fluid statics was laid by Archimedes as early as in ancient Greece, but fluid dynamics began to develop at the turning of 17th and 18th century (Wu 2000; Zhou et al. 2000).

In 1687, I. Newton examined the resistance on an object moving in viscous fluid, and proposed the internal friction law, laying a preliminary theoretical basis for viscous fluid dynamics.

From the viewpoint of energy conservation, the Swiss scientist D. Bernoulli studied water flow in pipelines. In 1738, he published *Fluid Dynamics*, establishing the famous Bernoulli equation representing the relationship between potential energy, kinetic energy and pressure energy of the fluid.

L. Euler is the founder of the classical fluid mechanics. He proposed the concept of fluid continuum in 1755, and derived the differential equation, namely Euler equations, governing the fluid continuity and the motion of ideal fluid. Euler equation correctly describes the motion of non-viscous fluid.

Bernoulli equation and Euler equation are signs of the establishment of fluid dynamics as a branch in fluid mechanics, opening a new era of quantitative study on fluid motion using a combination of differential equations and measurements.

In 1827, the French scientist, C.-L. Navier, first proposed a set of differential equations for motion of in-compressible fluid on the hypothesis of fluid continuity. In 1846, the British scientist, George Stokes, derived the same set of equations with a more rigorous approach. The set of equations have been called Navier-Stokes equation, being the theoretical basis of fluid dynamics.

In 1883, the British scientist, Osborne Reynolds, proved by experiments that two kinds of flow states, namely, laminar flow and turbulent flow, existed for viscous fluid. He defined a similarity criterion, the Reynolds number, for experimental study of viscous fluid flow. He also determined the critical Reynolds number within which transition between laminar flow and turbulent flow happened, and established the fundamental equation of the turbulent flow, Reynolds equation.

The development of fluid dynamics laid a theoretical foundation for airplanes, ships, and modern fluid machines.

6.2.7 Relationship Between Mathematics and Mechanics

Apparently, the establishment and development of classical mechanics have been closely related with mathematics historically. They have been going hand in hand in almost every step of development.

At the age of Galilei, Huygens, Newton and D'alembert, astronomy was the main driving force to the development of mechanics. Mechanics at that time mainly focused on studying motion of free particles, such as celestial bodies, especially the particle's motion under gravity. The main mathematical tool used was analytical geometry, conic curves in particular. The concept of a variable was introduced and calculus was created.

At the age of Lagrange and Hamilton, the mechanical industry gained fast development; consequently constrained systems, especially mechanical systems, became the main object of research in mechanics. The concept of n-dimensional spaces and functional analysis was introduced, and the variational method was proposed.

At the end of the 19th century, Poincare and Lyapunov put forward the qualitative theory of dynamic systems, which is of universal significance in all systems described by nonlinear differential equations. The geometric tool was topology and the calculation tool was homotopy method.

History shows that every milestone in the development of mechanics always requires new mathematical knowledge or tools. Rather than throwing the mathematical problems encountered to mathematicians, the scientists of mechanics at that time, such as Newton and Lagrange, generally chose to solve the mathematical problems by themselves, or working in collaboration with mathematicians, and to create the mathematical tools needed. Therefore, outstanding scientists in mechanics, such as Newton, Euler, Lagrange, Poincare and Lyapunov, were also mathematicians. This is a prominent feature of the development of the classical mechanics at the early stage. However, this feature has been decayed since the 20th century due to the fact that knowledge in each discipline exploded; therefore, specialization became a trend.

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Chapter 7
Birth and Development of Modern Mechanical Engineering Discipline

> *If society has a technical need, that helps science forward more than ten universities.*
> —Friedrich Engels (German philosopher, social scientist, 1820–1895)

Inventions of machines and establishment of the machine industry were the backbone of the First Industrial Revolution. Electric power was the center of the Second Industrial Revolution; however, even more machines were invented in this period. Mechanical technology remained one of the cornerstones of this Industrial Revolution.

With more machines invented, more activities in machine design and manufacturing followed. Mechanical engineering, as a discipline, was born in the first half of the 19th century. To the first half of the 20th century, the discipline developed gradually into two main branches, machine design and machine manufacturing.

7.1 Birth of Mechanical Engineering Discipline

Before the 18th century, a machinist built a machine relying on experiences, intuition and skills, rather than science. During the 18th–19th century, the emergence of the capitalist economy brought two changes. First, scientists began to pay attention to real production; at the same time some ambitious craftsmen began to learn scientific knowledge. This two-way communication between scientists and craftsmen benefited the technological progress; J. Watt was a representative example in this regard.

Classical mechanics laid a theoretical foundation for mechanical science and technology. Moreover, widely application of various machines and continuous invention of new machines posted many theoretical challenges to the scientific circle. In this process, mechanical engineering knowledge gradually built up, and a set of basic theories related to mechanical engineering came into existence naturally.

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7.1.1 Birth of Mechanism Theory

7.1.1.1 The Emergence of Mechanism Subject

After the steam engine, many machines were invented. At that time, power and control were not yet a main part of a machine. The key of invention of new machines was either to select a mechanism from known mechanisms or to devise a new mechanism. For this reason, the subject of mechanism came into existence, becoming the first mechanical subject.

The use of mechanisms has a long history. However, for the thousands of years until the age of Watt, mechanisms were devised by craftsmen relying on their intuition and inspiration without the guidance of general and systematic theory. J. Watt was a typical example of this case. The experience of people in practical work was the root of mechanism theory.

After the Renaissance, a few scholars already worked on mechanisms. For example, Leonardo da Vinci designed many mechanisms, and Leonhard Euler, a great mathematician, proposed the involute as the gear tooth profile.

The study on machines and mechanisms was a part of applied mechanics after the establishment of Newtonian mechanics. This situation did not change until after the beginning of the First Industrial Revolution.

Beginning from the industrial revolution, the power and speed of machines were greatly increased. Careful and refined motion and force analysis were required. These analyses could not be done relying only on intuitions and experiences; rather systematic theories were needed. This fact motivated the establishment of mechanism theory as a subject. Initially, the mechanism theory consisted of two branches, namely theory of structure and kinematics of mechanism.

7.1.1.2 The First College Course on Machine

The Enlightenment in France laid an ideological foundation for the rising of science. Napoléon Bonaparte (1769–1821) government in the French Revolution paid great attention to science. In the second half of the 18th century, France made great progress in science, quickly replacing Britain becoming the world center of science.

Driven by the English Industrial Revolution and for the needs of war, the first dedicated engineering school in the world—Paris Institute of Technology (École Polytechnique) was established in 1794 during the French Revolution. In 1806, Gaspard Monge (Fig. 7.1), the administrator of the school and a mathematician, decided to open a course on machine. Jean Hachette was assigned to prepare the lecture notes. Thus, literally Jean Hachette was the world's first teacher on theory of machines and mechanisms. In 1806 when the course was first delivered, it contained only 6 lectures. To the year of 1850, it expanded to 30 lectures (Rubio et al. 2000; Ceccarelli 2007). In addition, Hachette started publishing papers on machine structure since 1808, and his first textbook was published in 1811.

Fig. 7.1 G. Monge

7.1.1.3 Mechanism: An Independent Subject

Early in the 1860s, Giulio Mozzi and Leonhard Euler carried out scattered research on mechanism kinematics. During the 1820s and 1830s, Michel Chasles created the French school of theoretical kinematics.

The delivery of the course at École Polytechnique greatly promoted the mechanism becoming an independent subject.

In 1834, A-M Ampère, the famous French physicist, classified in an article the branch studying mechanisms and their motion as "*cinematique*" which was a new French word he created according to "*κίνημα*" in Greek. It became "*kinematics*" in English in 1840. In this classification, he defined that kinematics studied the motion occurred in mechanisms, regardless of the forces producing the motion. Ampere was then a member of advisory council of the French Academy of Sciences; thus, his opinion was very influential. Since then, kinematics (of mechanism) was formally recognized as an independent subject (Angeles 1997; Koetsier 2000).

The subject of mechanism, as the oldest branch in mechanical engineering, is one of the cornerstones of mechanical design.

After J. Hachette's book, several textbooks in mechanism were published in Britain and Russia. These books mainly discussed composition and kinematics of mechanism, focusing on linkages and gearing. For example, Robert Willis, a professor at the University of Cambridge, published the *Principles of mechanism* in 1841 (Willis 2010). In this book, composition of mechanisms and analysis of relative motion were discussed. Another important contribution of this book is that it pointed out the applicability of involute as general tooth profile. In 1854, A. Yershov (Александр Ершов) at Moscow State University published the first Russian textbook on theory of machines and mechanisms (Артоболевский 1953; Ceccarelli 2007).

7.1.2 Theoretical Kinematics in France

After Napoleonic Wars in the first half of 19th century, there appeared a trend to apply engineering science into analysis and design of machines. Theoretical kinematics became the first subject of development under this trend (Angeles 1997). French scholars, being good at theoretical thinking and mathematics traditionally, made the most outstanding contribution in theoretical kinematics, and École Polytechnique became a research center of the world.

In 1829, the mathematician Michel Chasles (Fig. 7.2) gave a geometrical proof of the existence of instantaneous center of rotation. He also proved that an arbitrary planar motion could be generated by means of the two centrodes rolling upon each other without slipping (Koetsier 2000). Chasles was known as the father of theoretical kinematics.

In 1830, a mathematician, Étienne Bobillier, studied graphical methods to find the center of curvature of a trajectory on which an arbitrary point moves in a plane (O'Connor and Robertson n.d.).

As early as in 1765, L. Euler proposed to use involute as gear tooth profile. With the wide application of gear transmissions, gearing theory became an urgent need. Basically gearing theory is a geometric problem: A curve rolls along another curve without sliding (pure rolling), and a point fixed on the first curve describes a third curve. What is the relation between the curvatures of the three curves? Further, if two of the three curves are given, how to find the third one? Euler was known the first scholar to study these problems. Based on Euler's work, Felix Savary at the École Polytechnique derived the famous Euler-Savary equation in 1836 (Koetsier 2000). This equation is not only the basis of gearing theory, but also the theoretical foundation of higher pair mechanisms. It was also applied in the analysis of linkage mechanisms.

Fig. 7.2 M. Chasles

Theodore Olivier was one of the founders of the gearing theory. In 1842, he introduced the idea of generating conjugate surfaces through enveloping process, and applied the concept of an auxiliary surface as the intermediate generating surface. In modern terms, the intermediate surface is the cutting-tool surface. He also discovered the way to provide the conditions for line contact and point contact of the generated surfaces of gears. However, Olivier thought that the theory of gearing was no more than a subject of projective geometry (Litvin n.d.).

The screw theory, a widely used research tool in robotics today, actually has a pretty long history of application in theoretical kinematics. In 1763, a Italian scholar, Giulio Mozzi, proposed for the first time the existence of the instantaneous screw axis (Angeles 1997; Ceccarelli 2000). Chasles gave rigorous mathematical proof in 1840. However, the first monograph on the screw theory was written by an Irish scholar, R. Ball, and published in 1900 (Ball 1900). However, the theory did not catch much attention thereafter, and the interest on it was not resumed until the 1950s, mainly because of its application in analysis of modern spatial mechanisms.

French scholars, with a tradition of excellence in mathematics, made great contribution in creation of the subject of mechanism and development of the theoretical kinematics. However, the situation changed during the Second Industrial Revolution. With the rise of Germany, its research on mechanical engineering, including the subject of mechanism, gradually came to the forefront of the world.

7.1.3 Foundation of Institution of Mechanical Engineers

The wide application of machines in the First Industrial Revolution led to the establishment of the machine building industry in Britain.

In 1847, a group of engineers in Britain separated out from the Institution of Civil Engineers and established the Institution of Mechanical Engineers (IMechE) (Pullin 1997), which was the world's first academic organization of mechanical engineering. Its first president was G. Stephenson, the inventor of steam locomotive. The establishment of the Institution of Mechanical Engineers marked the recognition of mechanical engineering as an independent discipline. According to the provisions of British law, it has the right to review performance of engineers, and award the title of chartered engineer.

For a long time, the people working in building, operating and repairing of machines, were called "machinist", whose social status was not high. The emergence of academic and professional organizations of mechanical engineering, such as the IMechE, reflected strong aspiration of the mechanical profession for free academic exchanges, safeguard of common interests and improvement of their social status.

Following the establishment of IMechE, the Association of German Engineers (VDI, Verein Deutscher Ingenieure) was founded in 1856, and American Society of Mechanical Engineers (ASME) in 1880. Japan Society of Mechanical Engineers (JSME) started in 1897. India and China also established their society of mechanical engineers in 1920 and 1936, respectively.

These professional organizations of mechanical engineering played an important role in promoting the discipline development, such as organizing academic conferences and seminars, coordinating research and educating the public. More importantly, they formulated guiding technical documents and relevant industrial standards and codes.

Under the umbrellas of the societies of mechanical engineering, specialized committees and regional branches were also founded responsible for activities within branch subjects and in individual regions. With mechanization extended to almost all industrial sectors, the society of mechanical engineering in most countries became one of the oldest, the largest, and the most active academic organization.

7.2 Development of Modern Mechanism Subject

Several important landmarks existed in the establishment of mechanism subject and its first wave of development. These include (1) the delivery of the course on machines at Paris Institute of technology, (2) the definition of the subject name "kinematics" by Ampere, and (3) the research activities of French school of theoretical kinematics.

The second half of the 19th century saw the first golden age in mechanism research. Ideas from skilled craftsmen were abstracted into scientific theory; the link between theory and engineering practice became closer. The evolution and innovation of mechanisms were greatly accelerated.

7.2.1 German School and Russian School in Mechanism

Study on mechanisms developed into three famous schools, including the German school and Russian school in the second half of the 19th century; and the American school after WWII.

7.2.1.1 German School

The Second Industrial Revolution saw the rise of Germany.

Before the German school, two problems existed in development of mechanism.

Firstly, theory and practice developed independently with little interaction. On one hand, new mechanisms were mainly invented by craftmen. J. Watt, the inventor of steam engines, speed governors and the Watt linkages, for example, was an instrument maker. He had no intention to establish mechanism theory. On the other hand, the scientists, such as L. Euler and those of the French School of theoretical kinematics, had little contact with the practice.

Secondly, in terms of theory, nobody, including J. Hachette and R. Willis, had a clear picture of concept and composition of mechanisms.

Different from the Paris Institute of Technology, which was a military technical college fully funded by French government, German universities were founded following the philosophy of academic freedom, and emphasis on both teaching and research, which was promoted by Wilhelm von Humboldt, the great education reformer (see Sect. 8.1.3). This German philosophy facilitated the link and interaction between academic circle and the industry.

The founder of the German school of mechanism theory is Franz Reuleaux (Fig. 7.3), who was initially a lecturer, and later the president of the Berlin Royal Technical Academy. Reuleaux published the famous book, *Kinematics of machine* in 1875 (Reuleaux 1875). In this book, he introduced the concepts of kinematic pair and kinematic chain, and stated that the motion of a mechanism was determined by its geometric form. This was the simplest and the initial form of theory of mechanism structure. He proposed a concise notation to describe the topological

Fig. 7.3 F. Reuleaux

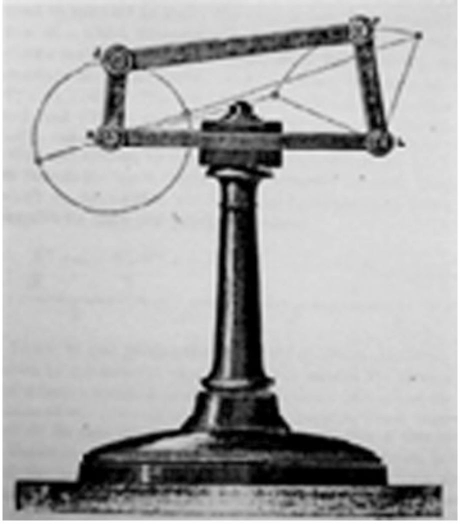


Fig. 7.4 Reuleaux's model (Reuleaux 1875)

Fig. 7.5 L. Burmester

structure of various types of mechanisms, which could be used for classification and even invention of mechanisms. He demonstrated that 54 mechanisms, which were grouped into 12 categories, could be generated from a simple four-bar linkage through transposing and changing of relative length of bars. His work laid the foundation of the modern mechanism theory. Based his work, R. Franke et al. introduced a symbolic notation to represent planar linkages (Davies and Crossley 1966), with which all possible solutions could be generated exhaustedly for a design ideas; this was the early form of linkage mechanism type synthesis.

Under the leadership of Reuleaux, physical models of more than 300 kinds of mechanisms were designed and built for use in teaching (Fig. 7.4). This greatly influenced the teaching of mechanism theory in the Western world. The influence is even felt today in the form that physical models remain an important teaching means. Besides, Reuleaux also studied the structure of the mouth of bird and fish, and drew their schematic diagrams of mechanism. He is the first documented scholar viewing mechanisms from bionics viewpoint.

Another representative figure of the German school is Ludwig Burmester (Fig. 7.5), the pioneer dealing with kinematics with geometrical theory (see Sect. 7.2.2).

Different from L. Euler and the French school scholars who were basically mathematicians, Reuleaux and Burmester had good knowledge base of both mechanics and mathematics, and, thus, could focus their effort on developing theory and creating new mechanisms to meet the industrial needs.

Siegfried Aronhold put forward the theorem of three centers for instantaneous velocity centers in 1872. The British scholar, Alexander Kennedy, also independently proposed this theory in 1886 (Norton 2003).

Beyer (1953) summarized the research achievements of the German school since the second half of the 19th century.

7.2.1.2 Russian-Soviet School

After abolishing of serfdom in 1861, Russia embarked on the route of development to a modern industrialized country.

The founder of the Russian school of mechanism is P. Chebyshev (Пафну́тий Чебышев) (Fig. 7.6), a member of St. Petersburg Academy of Sciences. Chebyshev, mainly as a mathematician, had achievements named after him in many fields, such as in polynomials, and inequalities. He received the doctorate in mathematics at the age of 28, and became a distinguished professor at St. Petersburg University at the age of 29.

Beginning from the early 1840s, Chebyshev was committed to the research of linkage mechanism for more than 30 years (Артоболевский 1953; Артоболевский et al. 1959). He started mechanism study earlier than the German school. Actually, Reuleaux translated his work into Germany.

Another famous figure of the Russian school is L. Assur (Леонид Ассур) (Fig. 7.7), who proposed the representative theory of mechanism structure of the Russian School (see Sect. 7.2.2).

In 1887, C. Gochman (Хаим Гохман) published his work on theory of gearing. Different from Olivier who dealt the theory of gearing with projective geometry, Gochman developed analytical methods, transferring the gearing theory to analytical and differential geometry. This theory released the theory of gearing from the

Fig. 7.6 P. Chebyshev

Fig. 7.7 L. Assur

constraints of projective geometry (Litvin n.d.; Артоболевский 1953). His work opened a door for the following-up study by the Russian-Soviet school, and established a rigorous mathematical theory closely related to the generation methods of cutting gears appeared at the end of the 19th century. The Soviet scholars, such as N. Kolchin (Николай Колчин) and F. Litvin (Файдор Литвин) were successors to Gochman (Litvin n.d.). Kolchin developed the geometry of bevel gears, the cylindrical worm and the double enveloping worm.

Soviet scholars made unique contribution to various aspects of mechanism theory, including analysis of complex mechanisms, theory of spatial linkages, theory of gearing, theory of mechanism precision and theory of automatic machines. In addition, they also did excellent work in machine dynamics (see Sect. 7.4). The works by I. Artobolevsky and other scholars (Артоболевский 1953; Артоболевский et al. 1959) are representative in the Soviet school.

7.2.2 Applications and Theory of Linkages

Linkages are the most basic mechanisms. With only a few links, complex motion can be realized. Although linkages were already used in ancient times, systematic theoretical research, devising of more variations and application to real machines were not begun until the First Industrial Revolution.

The golden age of linkages is the 19th century when progress in mathematics and manufacturing technology provided the capacity to create new linkages. However, the design theory of linkages became matured only after Reuleaux and Burmester. A linkage, seemingly very simple today, needed the most brilliant mind of that time to create it.

7.2.2.1 Path Generation

J. Watt was an early user of linkage mechanisms. Initially, Watt empirically designed the Watt's linkage shown in Fig. 7.8 to guide the piston moving in a straight line. Although he abandoned this mechanism later, and turned to a slider-crank mechanism for this task (Gibson 1998), it stirred the interest to systematically analyze the characteristics of linkages in theory.

The Watt linkage started the work to realize specific paths using coupler curves. Machining a plane is very easy today. However, in the second half of the 18th century, milling machines were not invented yet. It was not an easy job to make a prismatic pair of high quality with small clearance at that time. Alternatively, a linkage containing only revolute pairs was often used to generate a coupler curve to approximate a needed straight line. Besides Watt, a Russian scholar, Chebyshev, also put forward a linkage which could generate an approximately straight line (Артоболевский 1953).

In addition to straight lines, linkages could also realize approximately circular curves and other shaped curves. Before CNC machine tools appeared, specially designed coupler curves were used to machine parts with irregular shapes. This situation called for the establishment of a theory. As shown in Fig. 7.9, a coupler curve generated by the point P could be attached in three different four-bar linkages $O_1A_1A_2O_2$, $O_1C_1C_2O_3$, and $O_2B_1B_2O_3$. This conclusion was proved independently by a British scholar, Samuel Roberts, in 1875, and a Russian mathematician, P. Chebyshev, in 1878, thus, known as Roberts-Chebyshev theorem (Verstraten 2012).

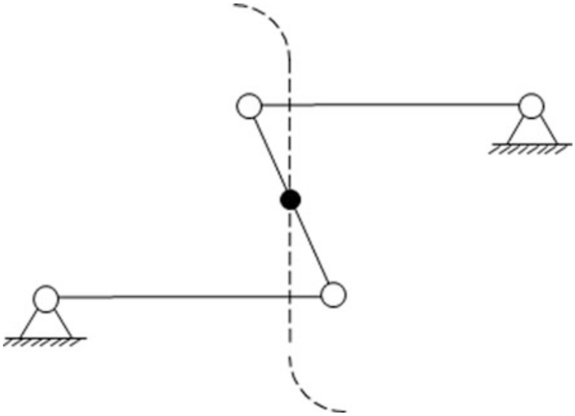


Fig. 7.8 Watt's linkage

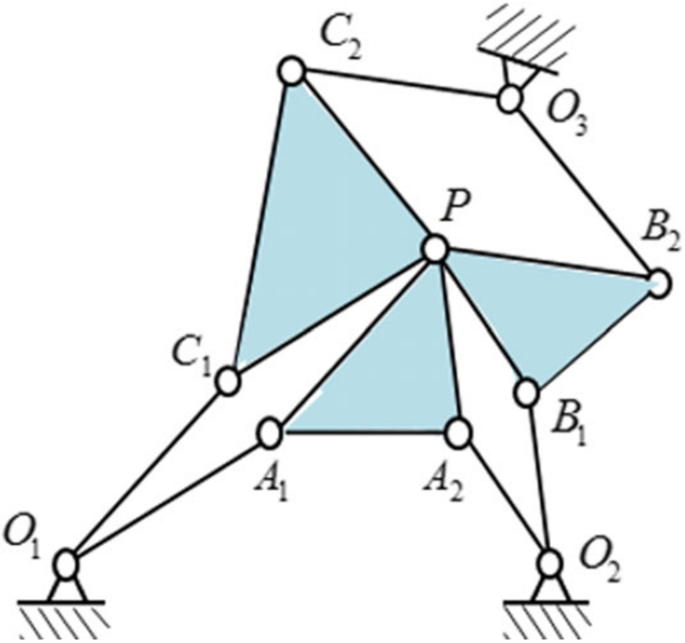


Fig. 7.9 Roberts-Chebyshev theorem

7.2.2.2 Wide Applications

Linkages were widely applied in many machines during the two industrial revolutions. An incomplete list includes shapers, sewing machines, press machines, jaw crushers, automatic machine tools, calculation machines, steel rolling auxiliary equipment, hydraulic machines, textile machines, printing machines, engineering machines and agricultural machines, etc. These were well documented in various textbooks and monographs on theory of machines and mechanisms. In addition to the most common four-bar linkage, mechanisms with six, eight and even more bars were also applied in some cases. Linkage speed generally was not very high before WWII, after which, however, high-speed linkages appeared.

Today, electronic technology has replaced linkages in many applications. However, in some special cases, especially when rapid and accurate motions are needed, mechanisms, often linkages or cams, are still needed.

7.2.2.3 Theoretical Research

Chebyshev, the founder of Russian school, proposed a formula calculating the degree of freedom for planar mechanisms early in 1869. Two German scholars, M. Grübler and K. Kutzbach, also independently put forward similar formula in 1917 and 1929 respectively; this formula was generally called Chebyshev-Grübler-Kutzbach criterion. However, this formula is not applicable in some special cases. Controversy remains; further research and development are still ongoing (Huang and Zeng 2016).

In 1883, a German scholar, Franz Grashof, put forward the conditions for existence of a crank in a four-bar linkage, known as Grashof condition (Sander and Holman 1972).

On the one hand, linkages gained more and more application. On the other, results of theoretical kinematics were not applied in the design of mechanisms; a clear framework of mechanism kinematics was not formed yet. In this case, the German school and the Russian school developed their own theories of kinematic analysis and synthesis of linkages in the second half of the 19th century.

Since 1872, L. Burmester began to study kinematics of mechanisms. He summarized three representative problems of linkages synthesis, namely generation of a specific path, generation of a specific continuous function and position guidance of a rigid body. The continuous function problem came from instruments and computational mechanisms. Some scholars attempted to make calculation of square, inverse-proportional and logarithmic function with linkages; however, the wide application of electronics technology has made this type of research out-of-date.

Burmester introduced geometric techniques into synthesis of linkages. His approach was to compute the geometric constraints of a linkage directly from the inventor's desired movement for a floating link. In his view a four-bar linkage is a floating link having two points constrained to lie on two circles. In 1886, he published the *Lehrbuch der Kinematik* (Burmester 1886), marking the establishment of a school of kinematic geometry, and making kinematics become a mature subject in the second half of 19th century.

Chebyshev established the algebraic method of mechanism synthesis. He also developed a theory on errors of a mechanism.

7.2.2.4 Assur Structure Theory

In 1916, a Russian scholar, L. Assur, put forward a theory on composition of mechanisms (Артоболевский 1953). He proved that a mechanism could be formed by connecting kinematic chains having zero degrees of freedom, which was later known as the Assur group, to the driving member and the frame in sequence. He also proposed a classification method of mechanisms based on its structure. Soviet scholars later continued Assur's work. With the Assur theory, many kinematic and force analysis problems of mechanisms were successfully solved. This theory had an important position in the history of theory of mechanisms, and is still covered in some textbooks nowadays. Following the basic idea of Assur, some Soviet scholars, W. Dobrovolsky (Владимир Добровольский) and I. Artobolevsky (Ива́н Артоболевский), proposed the unified system of classification of mechanisms.

7.2.3 Evolution and Design of Cam Mechanism

7.2.3.1 Evolution

Although cams were already used in ancient times in China and west Asia (see Sect. 2.2), theoretical research on it did not started until 1829, when A. Schubert, a German researcher, put forward the concept of pressure angle (Angeles 1997).

After automatic machine tools were invented at the end of the 19th century, a lot of automated machines appeared in the light industry. At that time, there was no concept of mechatronics; automation was achieved by pure mechanical methods, mainly cam mechanisms. For example, the motion of the cutting tool in an automatic lathe in both longitudinal and lateral direction was controlled by cams. A distribution shaft (originally, the cam drum) as shown in Fig. 7.10, was the soul of the machine. The inventor, C. Spencer, called it the "brain wheel" (Rolt 1965). With the rotation of the distribution shaft, cams on which commanded the components to move according to the prescribed motion.

In general, the speed of cams in automatic lathes was not very high. A more important application of cam mechanisms was in internal combustion engine

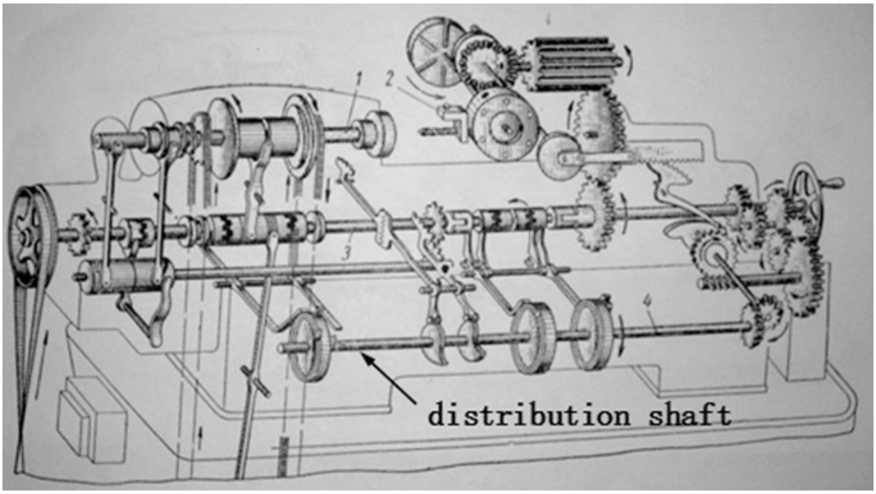


Fig. 7.10 A20 single-spindle automatic turret lathe

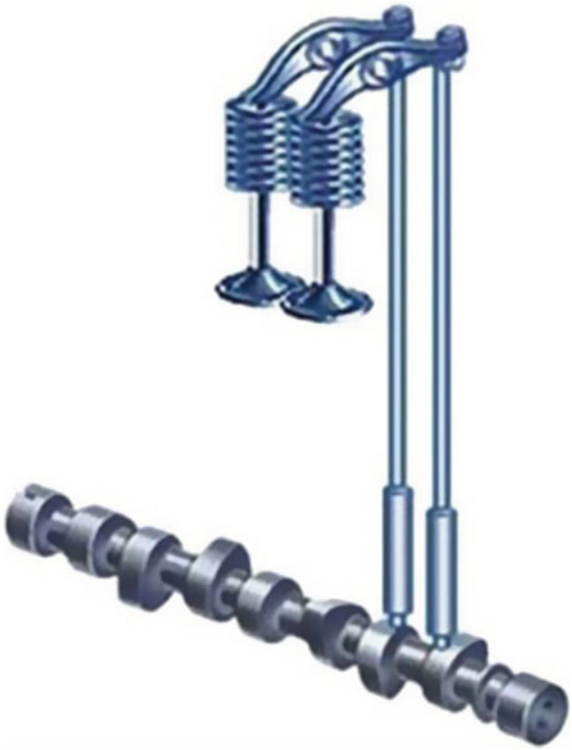
(Fig. 7.11), and later in various automatic machines in the light industry. Since the 20th century, the continuous increasing of speed of the internal combustion engine and automatic machines have been the direct driving force for the study on dynamics and design of cams.

7.2.3.2 Force Analysis

Following the development of the internal combustion engine, force analysis of the cam mechanisms appeared at the end of 19th century. The purpose was two-fold. First, the surface contact force and the force applied on the follower system need to be determined for the purpose of strength calculation. Second, to avoid the follower from jumping from the cam, a spring of closure needs to be designed properly. Force analysis at the early stage was conducted in the static and kineto-static level (Zhang 2009).

In the first half of the 20th century, the cam speed was not very high. The static design method was adopted based on two implicit assumptions: (1) Elasticity in the system is ignored and the mechanism was considered rigid; (2) the cam rotates at a constant speed. Under these two assumptions, the follower could be considered to move completely in accordance with the law of motion selected (Zhang 2009).

Fig. 7.11 Cam mechanism in a 4 cylinder gasoline engine



7.2.3.3 Follower Motion Program

Early cam designers relied strongly on experiences and tests of prototype. Determining of the cam profile mainly depended on graphic methods. At that time, there was no CNC machine tools to machine cam profiles with high precision (Zhang 2009).

At that time, a designer selected the follower's motion with the consideration of only kinematics. Dynamics was rarely taken into account. When dynamics had to be considered, the peak value of the follower's acceleration was used to roughly estimate the inertial load. The effect of the acceleration in a whole period on dynamics was not yet known. As such, a motion diagram with parabolic acceleration was viewed as a good option, and widely used because it has the minimum peak value of acceleration (Fig. 7.12). Nowadays we know that singular points exist in the acceleration curve of this motion, where the jerk is infinitely large, and the jerk causes severe vibration of the system; however, at that time, people knew nothing about this (Chen 1982; Peng and Xiao 1990; Zhang 2009).

In the early 20th century, engine speed rose sharply. Since the 1920s, research work was published in the U.S., the Soviet Union, Japan and other countries,

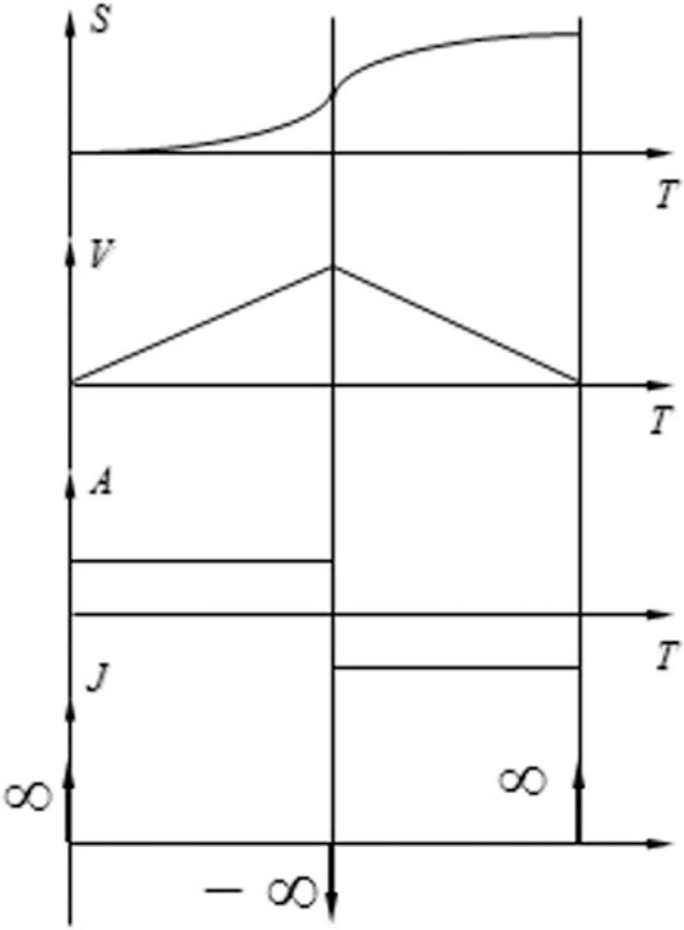


Fig. 7.12 Kinematic parameters for the motion law with parabolic acceleration

generally related to the valve mechanism in a internal combustion engine (Zhang 2009; Furman 1921; Решетов 1934). However, the elasticity of parts was not considered in all these studies; vibration theory was not applied either.

7.2.3.4 Intermittent Motion Mechanism

The earliest intermittent motion mechanism is the ratchet mechanism, which could only be used at very low speeds. Later, Geneva mechanisms were invented by a watchmaker in Geneva, the Swiss watch-making center, and widely used. One application is in film projectors for driving the film as shown in Fig. 7.13. It was also widely used in machine tools and light industry machines to produce

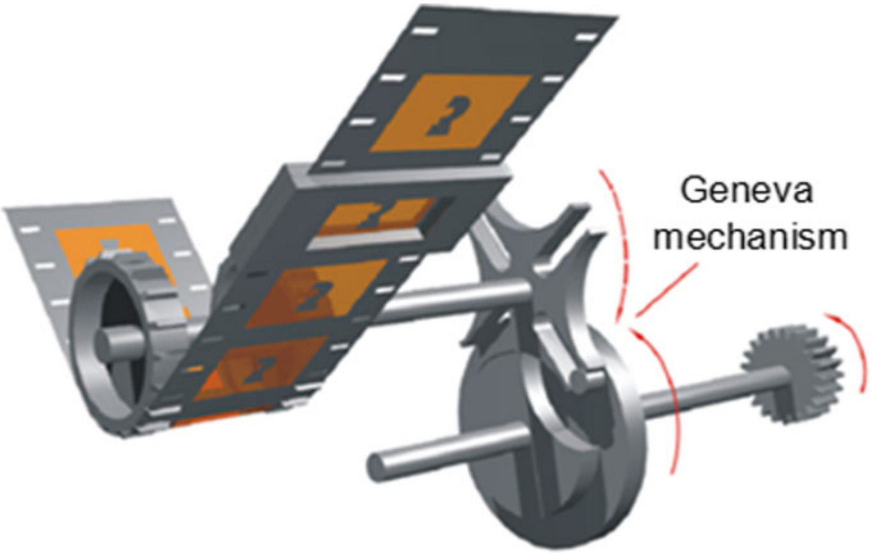


Fig. 7.13 Geneva mechanism in a film projector

intermittent rotation of a worktable. When designing a Geneva mechanism, once the indexing number is determined, the ratio between rotation time and stop time is determined as well, and cannot be changed any more. This feature tuned out to be a main drawback of Geneva mechanisms. A Geneva mechanism has lower vibration and noise compared with a ratchet mechanism; however, the driven wheel in Geneva mechanisms experiences sudden changes of acceleration at the starting and stopping instants, leading to severe impacts. Thus, it is not suitable in high speed application.

After WWII (see Sect. 13.2.5), indexing cam mechanisms became the main stream in applications of high speed intermittent motion.

7.3 Mechanical Vibration Theory and Application

The creation of vibration theory was directly related with musical instruments, instead of with industry (see Sect. 6.2.5). During the Industrial Revolutions, machine power and speed were increased. Vibration in machines began to catch attention. Mechanical vibration, being the application of vibration theory in mechanical engineering, became a branch subject, and also the earliest branch of machine dynamics.

The middle 19th century saw a sharply increasing of speed and loading capacity of railway vehicles. In May 1847, the Dee Bridge on the railway from London to Wales suddenly collapsed after only half a year of completion. The whole Britain was shocked by the accident and investigation was conducted following the accident. In the appendix of the investigation report published in 1849, Robert Willis identified the problem was caused by the transverse vibration of a beam under moving loads. This, although only contained in the appendix of the report, became an historical reference in railway bridge construction. George Stokes, a famous British physicist who participated in the investigation, derived the differential equation of the vehicle-bridge system, and obtained an exact solution with the series expansion method. This was the earliest documented research on vibration under moving load (Timoshenko 1928). Research on beam vibration under moving load remains active today; the dynamics of a high-speed train passing a bridge, for example, is still an extremely challenging engineering problem.

During the Second Industrial Revolution, motors, generators and steam turbines appeared. The high-speed shaft in these machines was the weakest part, and the bending vibration of the high-speed rotor became a serious problem. Then, to deal with this problem rotor dynamics was born (see Sect. 7.4.2).

At the beginning of the 20th century, the automobile industry was born, and engine speed increased greatly. Some dynamic problems became prominent. One of them was the vibration of the crankshaft in a multi-cylinder engine. The other was the problem of torsional vibration of shafts, which was originated from the complex kinematic chain of machine tools. In 1921, a German scholar, H. Holzer, proposed a calculation method of torsional vibration of shafts (Holzer 1921).

The kineto-elastodynamics of mechanisms, shortened as KED, gradually took shape as a subject in the 1970s. However, the term *elastodynamics* was not adopted in the shaft vibration analysis despite vibration of shafts has a long history starting in 1921. Vibration of shaft has been regarded as a specific topic in applied mechanics or mechanical vibration theory.

John Rayleigh pointed out in his *Acoustic Theory* (1894) that the vibration equation could be decoupled if the damping matrix could be expressed as a linear combination of the mass matrix and the stiffness matrix (today called the proportional damping). However, he did not present his idea with the matrix algebra. The modern form of Rayleigh's statement, decoupling vibration equation of damped system with multi-degree of freedom, was completed in the middle 20th century (Timoshenko et al. 1974). In 1931, J. Den Hartog proposed the equivalent viscous damping to express the Coulomb friction force.

Although research on nonlinear vibration already started at the end of 19th century, study of linear vibration was dominant in the first half of 20th century. By the middle 20th century, the theory of discrete linear systems was already mature. However, due to the limitation of computing capacity, only systems with limited number of degrees of freedom could be calculated. Also, accurate analysis of continuous systems was limited to simple shaped parts.

Initially, researchers of vibration, including those from Huygens to Rayleigh, were mainly mathematicians and dynamicists. They focused on vibration theory and explanation of vibration phenomena. After the Second Industrial Revolution, engines, vehicles, machine tools, and airplanes appeared; and many practical vibration problems, such as balancing of machines, torsional vibration of shafts and gear systems, vibration in turbines, reduction and isolation of vibration etc., came up. In response, some researchers shifted their effort from vibration theory to solving real vibration problems in engineering.

Because vibration study was turning to real engineering problems, it became necessary for mechanical engineers to be trained with some vibration knowledge. S. Timoshenko (Степан Тимошенко) was a pioneer in this regard, who made the earliest attempt to deliver vibration knowledge to engineers. During the 1920s and 1930s, he and Den Hartog, then working at Westinghouse Electric Company located in Pittsburgh, the U.S., started teaching mechanical vibration to engineers. Based on the teaching materials, Both Timoshenko (1928) and Den Hartog (1934) published influential books on vibration. Both books have been reprinted many times in dozens of countries.

Another notable contribution by Timoshenko is the vibration model of beams with account of the effect of shear deformation and rotary inertia, the so-called Timoshenko beam theory (Timoshenko et al. 1974).

As the detrimental effect of mechanical vibration became more and more serious, the need for reduction and isolation of vibration became increasingly urgent. Thus, research on vibration reduction, in both theory and experiment, began in the early 20th century in the main Western countries (Ding 1988). By the middle 20th century, vibration-reduction already became an integral part of the mechanical vibration theory (Den Hartog 1934, 1956).

There is a need to eliminate or reduce unwanted vibration. The theory and relevant techniques are termed vibration control. Two types of vibration control problems exist (Fig. 7.14). One is to control the effect of environmental vibrations on machines, such as precious machine tools. The other is to limit the transmission of vibration created by machines, such as forging hammers, to the environment. For

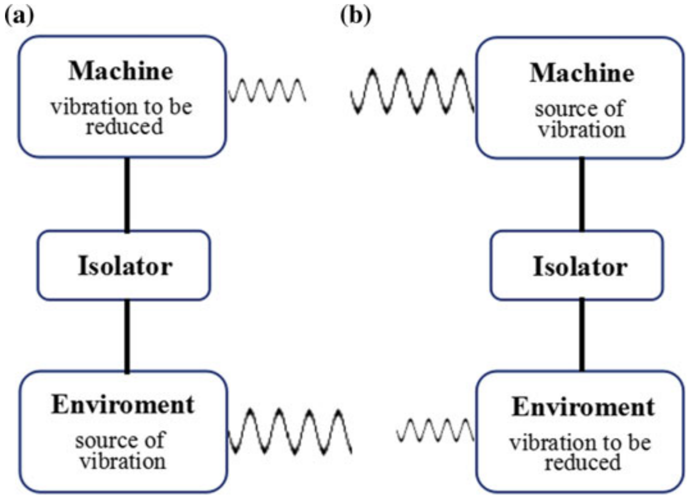


Fig. 7.14 Isolation of vibration. **a** Passive isolation, **b** active isolation

both problems, it is common practice to insert a vibration isolator, in the form of a spring or rubber mount, between the machine and the ground. In theory, the vibration isolator is modeled as a spring and a damping (Ding 1988).

At the end of the 19th century, spring-damping isolators started to be applied in motor cycles and automobiles.

The classical methods of vibration reduction and isolation have been treated as discrete vibration systems with 1 or 2 degrees of freedom in almost all textbooks of mechanical vibration after Timoshenko and Den Hartog.

7.4 Machine Dynamics in Modern Times

7.4.1 Dynamic Analysis Methods

During the last two centuries, 4 different force analysis methods, namely static analysis, kineto-static analysis, dynamic analysis and elastodynamic analysis, have been formed. The impetus behind the development of machine dynamics was the continuous demands for high speed, large capacity, high precision and light weight. The high speed, in particular, has been the first driving force for development of machine dynamics.

This section briefly describes the historical trajectory of development in dynamic analysis and design methods.

7.4.1.1 Early Development

The primary function of a machine is to produce motion and transfer forces and/or torques. The magnitude and variation of forces and torques between elements are the basis in choosing the prime mover, designing the structure of kinematic pairs, analyzing load capacity of elements and bearings, and selecting the method of lubrication. Therefore, kinematics and static analysis were firstly developed.

In the early stage, machine’s operational speed was low; thus, inertial loads were generally ignored. In addition, the materials of the parts were not very strong. Overdesign was common, and parts had very large rigidity. Thus, static analysis with all parts assumed rigid body was acceptable.

With the increase of operational speed, the inertia loads became significant, and had to be accounted for in analysis. In the 19th century, the D’Alembert principle was introduced, based on which a new force analysis method, the so-called kineto-static analysis method, was formed. In this method, the external and inertial loads are known, and the balancing force or torque applied to the driving element and the reaction forces in the kinematic pairs are solved for. Systematic graphical methods, detailed in the *graphic dynamics* (Wittenbauer 1923), were developed by the German school for this type of analysis.

In fact, the Russian school started their research on machine dynamics even earlier than the German school (Артоболевский 1953). In 1914, N. Merthalov (Николай Мерцалов) published the world's first textbook on dynamics of mechanisms.

To determine the power of the prime mover, or to design a flywheel, the driving force or torque is needed to be known, while the reaction forces in the kinematic pairs are not necessarily required. Based on the principle of virtual displacement, N. Zhukovsky (Никола́й Жуковский) (Fig. 7.15), a Russian scientist and pioneer in astronautics, proposed the so-called "Zhukovsky lever method" (Артоболевский 1953), in which the driving force or torque is directly solved out by using the velocity polygon of the mechanism. In the era without computers, this method greatly simplified the force analysis.

After Watt's engine, application of flywheels became more and more common in various machines. To design a flywheel, it needs to know the true motion of the machine. For some machines starting and stopping frequently, it is also necessary to know the true motion because of the large inertial load. To find the true motion, dynamic analysis was developed.

In the analysis of speed fluctuation and design of flywheels, the reaction forces of joints are generally not needed, and only the true motion under a given driving force or torque is required. For this type of problems, the best tool to find the true motion is the Lagrange equation. Most mechanical systems, with the exception of some robots and other special machines, have only one prime mover. In another word, the system is of single degree of freedom. For such systems, the dynamic analysis to

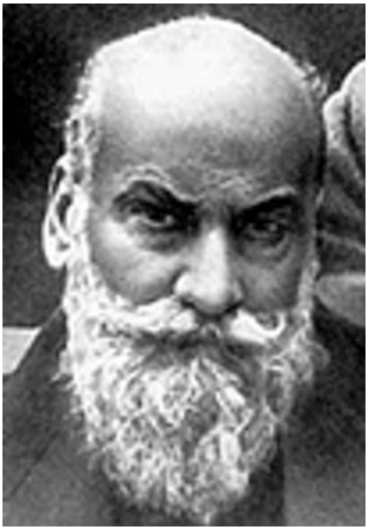


Fig. 7.15 N. Zhukovsky

obtain the true motion under the assumed driving force or torque could be implemented through an equivalent model derived from the Lagrange equation. This model was first developed by a Russian scholar, K. Rerich (К. Рерих), in 1916 (Артоболевский 1953) and is covered in most undergraduate texts nowadays.

7.4.1.2 Limitation of Early Methods

The early methods in force analysis had a series of limitations.

The research developed before the 1950s was basically at the level of kineto-static analysis, also called inverse dynamic analysis. The solution was heavily dependent on graphic methods.

In direct dynamic analysis, the true motion of a system under given forces is to be solved for. Practical steps for direct dynamic analysis were not yet formed in English textbooks until the 1950s. Thus, analysis was only limited to the stage after the machine reached a steady operation. For the transient stages, analysis could not be made. Consequently, it was impossible to compute accurately the stresses or bearing forces in moving components under unsteady conditions. As a result, new machine development had to go through designing, fabricating and testing with repeated iterations, prolonging the development time.

The difficulty with direct dynamics problems stemmed from the need to integrate highly nonlinear differential equations, which was almost impossible at that time. Inverse dynamic analysis, or kineto-statics, on the other hand, only leads to algebraic equations, which could be solved with graphic methods (Erdman 1993).

In terms of direct dynamics, Soviet scholars went ahead of scholars in other countries at that time. They discussed the problem of the true motion of machines under external forces. However, their studies were confined to a few very simple cases in which the solution could be easily obtained (Артоболевский 1953; Зиновьев and Бессонов 1964). No general solution methods were formed.

7.4.1.3 Smoothening of Speed Fluctuation

For the manufacturing of large forging parts in steam engines, steam hammers appeared in 1842. Jaw crushers were invented in 1858. At the end of the 19th century, electric powered presses went into fast development. In all these machines, the working load varied significantly during one cycle, resulting in large fluctuation of speed. The driving motor determined based on the peak load, thus, is over-sized.

Speed fluctuation also has detrimental effects on spinning machines, generators and precision machine tools. These detrimental effects include producing additional dynamic loads in kinematic pairs, exciting vibration, degrading accuracy and precision, and reducing reliability of the machine.

In order to smoothen the operation, Watt mounted a flywheel on the output shaft of his engine. This was a very critical innovation which made Watt's engine able to drive various working machines.

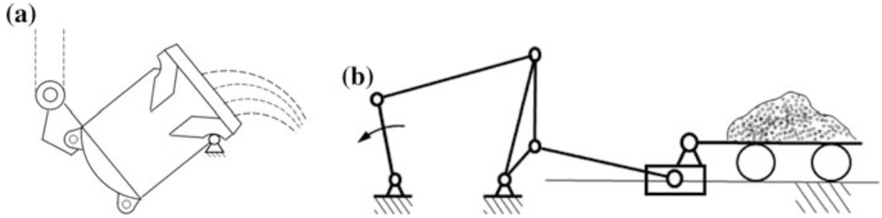


Fig. 7.16 Mass-varying mechanical system. **a** Ladle, **b** vibrating griddle

For regulation of non-periodic variation of speed, the centrifugal governor used by Watt in the steam engine was the earliest recorded application of automatic regulating device in history, which played a key role in the widespread application of steam engines (see Sect. 4.2).

Both the German and Russian school conducted research on speed regulation with flywheels and governors. In German textbooks, this is termed as power balancing (Wittenbauer 1923).

7.4.1.4 Dynamics of Mass-Varying System

There is a kind of machines whose mass changes in the course of motion. For example, the ladles used in metal casting experience changes in total mass, mass center, and inertia moment during tilting and pouring the liquid metal into molds (Fig. 7.16a). Other examples include the paper roll in a printing machine, the spindle in a spinning machine, the vibrating griddle shown in Fig. 7.16b and the blast furnace hopper (Зиновьев and Бессонов 1964).

The dynamics of mass varying system was put forward as early as in the middle 19th century. In 1897, a Russian scholar, I. Meschersky (Иван Мещерский), derived the dynamic equation of the mass varying system. In 1929, A Soviet scientist, K. Tsiolkovsky (Константин Циорковский), proposed to use multistage rocket for space navigation, making important contribution to mass varying system dynamics. The theory of mass varying system dynamics, now, has been mature, and applied to various machines.

7.4.2 Rotor Dynamics

7.4.2.1 Balancing of Rigid Rotors

To control vibration of unbalanced rotors, balancing became an important measure. Rotors working at a speed lower than the minimum critical speed are called rigid rotors.

For rotors with attached disks which have a diameter far larger than the thickness, the relative simple static balancing is applicable. The early history of grinding wheels was not clear; however, serious accidents caused by cracking of grinding wheels were documented well. It is commonly thought the static balancing technology was closely linked with grinding.

With the invention of motors, rotors having thickness comparable with the diameter appeared. Engineers thus were confronted with the dynamic balancing problems. In fact, dynamic balancing machines were initially developed for the needs of motors. In 1870, only 4 years after the invention of generator, a Canadian, H. Martinson, filed a patent of dynamic balancing technology. In 1915, Schenck Company made the first double-face balancing machine, and quickly occupied the world market (ANON1 n.d.). To this point, the problem of balancing of rigid rotors was basically solved.

7.4.2.2 Early Research on Rotor Dynamics

Rotors working at a speed higher than the fundamental critical speed is regarded as flexible rotors. The rotor in a large turbo-generator unit is a typical and the most important example of flexible rotors (Fig. 7.17). Balancing of a flexible rotor is much more complicated than that of a rigid rotor. Rotor dynamics is the branch of machine dynamics devoted to the study of flexible rotors.

In 1869, William Rankine, a British physicist, published the earliest recorded paper on flexible rotors. However, the model he used in the analysis was not appropriate, leading to a wrong conclusion: for a rotor of a given length, diameter and material there was a limit of speed, and supercritical operation was impossible. The wrong conclusion influenced for half a century (Nelson 2003).

At the beginning of 20th century, the need for better understanding of rotor dynamics became more urgent with the increasing of turbine speed. For the 30 years from 1889 to 1919, several scholars and engineers conducted theoretical and experimental studies on this topic. First they realized supercritical speed

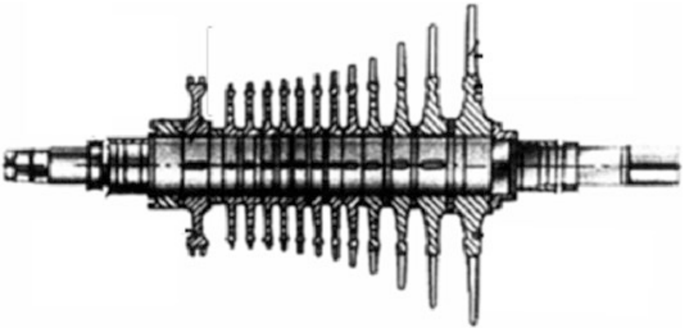


Fig. 7.17 Rotor of turbo-generator unit

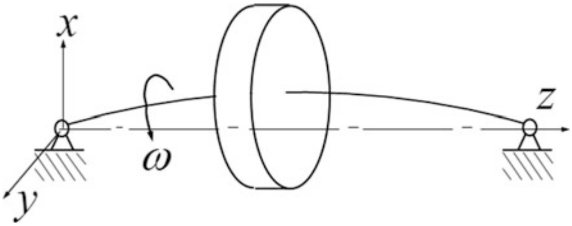


Fig. 7.18 Jeffcott's rotor

operation on a steam turbine through experiments and published their papers. Then, they obtained the steady-state solution under an operation speed higher than Rankine's limit through theoretical analysis, and gave the experimental evidence for the existence of the second-order critical speed. All these were apparently in distinct contradiction with Rankine's theory. To this point, Rankine's error should have been corrected. However, Rankine was so famous in his field and his wrong prediction was so widely accepted that his wrong conclusion remained influential for almost 50 years after the right work done by the above scholars.

In 1916, the Royal Society of London commissioned Henry Jeffcott to resolve this conflict between Rankine's theory and the practice of engineers. In 1919, Jeffcott published his classic paper using a rotor model depicted in Fig. 7.18 in which the curve of the vibration amplitude against frequency was given. He concluded that self-centering effect was created when the rotor operating at a super-critical speed and the amplitude would tend to a constant value with further increase of rotational speed (Jeffcott 1919). The existence of stable super-critical speed was an important new finding which laid the theoretical basis to design turbines, pumps and compressors with higher speed and efficiency.

Soon in 1920s, flexible rotors operating at super-critical speed were designed according to the new finding. In this period, turbo-generator units developed very fast.

Jeffcott became an iconic figure in rotor dynamics, clearing up the obstacles for further development of the subject. His model was thereafter called Jeffcott model, which was widely adopted as a simple model in various branches of rotor dynamics.

7.4.2.3 Rotor-Bearing System Dynamics

In all the studies before but including Jeffcott, an underlying assumption of rigid bearings was taken for granted. Therefore, they could be only used to examine the dynamic behavior of the rotor itself.

After the appearance of flexible rotors, a new problem was discovered very soon. A blast furnace blower developed by General Electric (GE) in the U.S. was found vibrating severely when operating above the super-critical speed. Thus, it was very difficult to increase the speed to the doubled critical speed. In 1924, Belt Newkirk, an engineer at GE, reported the experimental results and pointed out that this was self-excited vibration which was never reported before. He went further estimating that this vibration might be originated from the oil film in a paper (Newkirk and Taylor 1925) which has been regarded since then as the first paper on stability of rotor system.

Since then, scholars continued to explore this form of vibration caused by oil film, and mathematical expressions were derived. In 1937, H. Swift revealed that for a light loaded bearing, the angular frequency of rotor whirl was approximately half the rotation speed (Swift 1937; Nelson 2003). This was the so-called half speed whirl with which the difficulty to increase the blower speed to the doubled critical speed could be well explained.

Newkirk's work revealed a fact that the rotor dynamic behavior was related not only to the rotor itself, but also to the supporting bearings. Newkirk's work marked the beginning of rotor system dynamics, which became the main topic of rotor dynamics in the 1960s (see Sect. 13.4.5).

Nelson (2003) pointed out that *Rotor dynamics has a remarkable history, largely due to the interplay between its theory and its practice. Indeed, one could argue that rotor dynamics has been driven more by its practice than by its theory. This statement is particularly relevant to the early history of rotor dynamics.*

7.4.3 Balancing of Mechanism

With the increasing of speed of engines, vibration, noise and wear caused by the reciprocating motion of piston became prominent. Thus, balancing of inertia loads of mechanisms was brought forward to engineers and scholars.

Due to the inertia force and moment produced in motion, a mechanism exerts a periodical shaking force and shaking moment on the frame. Balancing of only the shaking force is called static balancing, while simultaneous balancing of shaking force and shaking moment is called dynamic balancing. The mechanism balancing problem, in essence, is a kind of dynamic synthesis on the basis of kineto-static analysis. In German textbooks it is referred to as the mass balancing (Wittenbauer 1923).

Study on mechanism balancing started at the beginning of 20th century, initially focusing on static balancing.

Otto Fischer, a German scholar, was the first person studying the theory on mechanism balancing. In 1902, he concluded that the sufficient and necessary condition of full balancing of the shaking force was that the total mass center of all moving components in the mechanism remained stationary (Arakelian and Smith 2005). This is well known today and covered in main undergraduate mechanism texts. He also put forward the principal vector method for complete balancing of shaking force.

However, Fischer's work on complete balancing of shaking force did not draw much attention. After Fischer, partial balancing of the shaking force became the mainstream until WWII. From the 1900s through 1930s, internal combustion engines gained wide application in ships and airplanes and the running speed of

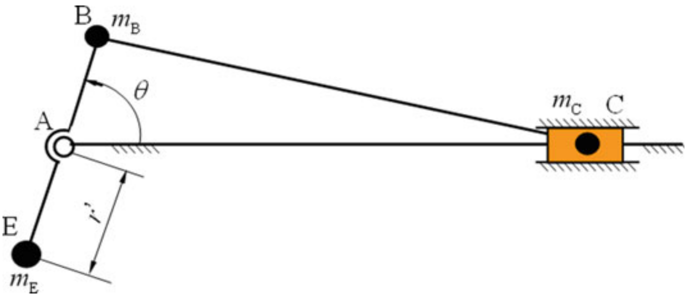


Fig. 7.19 Partial balancing of shaking force of slider-crank mechanism

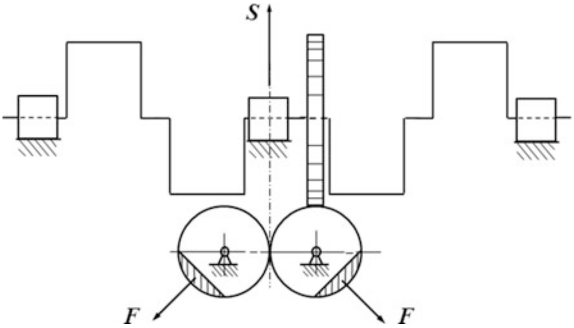
engines increased from 800 to 3400 r/min. Thus, balancing of internal combustion engines became an urgent need for this period. Research effort was focused on balancing the slider-crank mechanism, which is the core of an internal combustion engine. Obviously, people realized that too large counterweights were needed to achieve a full force balancing; thus, partial balancing became the mainstream.

The primary method of engine balancing is based on harmonic analysis. A large quantity of works on this topic were published (Arakelian and Smith 2005). In this method, the unbalanced inertia force is decomposed into a Fourier series. Reduction of the inertia effect is achieved by installing a counterweight on the crank to balance the first order harmonic of the inertia force. This method, as illustrated in Fig. 7.19, was widely used.

To balance the shaking force of the second order harmonic, Frederick Lanchester, a British automobile engineer, designed the Lanchester balancer (Lanchester 1914) (Fig. 7.20) which still finds application nowadays. In modern automobiles, balance shafts are installed to balance the inertia force in four stroke engines. These shafts are driven by the crank through the gears or a synchronous toothed belt with a 2:1 transmission ratio. Counterweights on balance shafts balance the second-order shaking force. The design is the same with the original Lanchester balancer in principle.

As a theoretical problem, complete balancing of both shaking force and shaking moment of linkages, was solved in the 1960s (Arakelian and Smith 2005).

Fig. 7.20 Lanchester balancer



7.5 Evolution of Mechanical and Hydraulic Transmissions

7.5.1 Mechanical Transmissions

Motors and internal combustion engines have replaced steam engines, becoming the mainstream prime movers in most applications. Both motors and internal combustion engines in general run in much higher speed than that required by working machines. Therefore mechanical transmissions to change the rotation speed of the prime mover to a suitable speed of the working machines are widely applied. The requirements for the transmission device are different in transmission ratio, load capacity, volume, weight, and economic constraints; therefore, various transmission, including gearing drives, worm drives, belt drives, chain drives and screw transmissions etc. have been developed.

The need for higher operational speed and load capacity have been a constant driving force to develop new types of transmission and to upgrade the design and manufacturing level. High speed tooth chain, high-speed belt drives and new type of worm drives all came into existence under such a background.

7.5.1.1 Gear Transmission

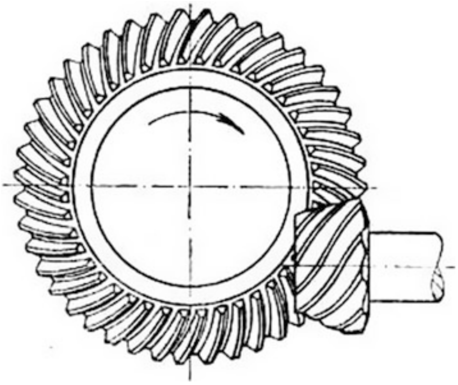
With the development of clock and watch industry, several mathematicians explored the problem of tooth profile in the 18th century. In 1765, L. Euler first proposed to use involute as the tooth profile (see Sect. 3.2.2).

In 1841, a British scholar, R. Willis, put forward the law of meshing of planar curves (Litvin n.d.), and determined the basic relation of the angular velocities between two links with higher pair contact. He also pointed out that involute gears had the advantage that angular velocity ratio keeps constant when the center distance of the gears changes. The work of Willis was very important in the design of higher pair mechanisms. Soon a French scholar, T. Olivier, established the theory of gear meshing in geometric form in 1842, and H. Gochman, a Russian scholar, reached the same result with a analytical method in 1887 (Артоболевский 1953).

To meet requirements of higher operation speed of machines, spur gears developed into helical and herringbone gears for parallel shaft transmission.

Through the 19th century, involute gears were made with the form-cutting method which has a very limited accuracy and quality. In the Second Industrial Revolution, gear drives of high speed and large load capacity began to be applied in ships and power plants, requiring higher accuracy of machining. At the same time, the machine tools and automobile industry demanded for higher productivity in gear machining. During the period between the end of 19th century and early 20th century, generation methods were invented, so that both quality and productivity were greatly improved (see Sect. 5.4.1). It is unimaginable to achieve mass production of automobiles in the 20th century without the progress in gear machining methods.

Fig. 7.21 Hyperboloid gearing



In 1899, a German engineer, O. Lasche, first used gears with profile shift (仙波正莊 1966), which could avoid undercutting, improve performance of gears, and allow for little changes of the center distance.

Bevel gears were once used at the rear axle of automobile to transmit motion between intersected axis. In the 1920s, speed of automobile increased greatly; thus, it required to lower the center of gravity of the vehicle. In 1916, the US Gleason gear company developed the spiral bevel gear and the machine tool to cut it. In 1927, Ernst Wildhaber, the company's consulting engineer, made the main contribution in the design of hypoid gearing, which transmits motion between two crossed axes with an angle of 90 degree as shown in Fig. 7.21. By this new gear technology, the mass center of the vehicle was largely lowered. Thus, hypoid gears soon replaced bevel gears in the automobile. Wildhaber was a famous inventor in gear design and manufacturing; he was granted 279 patents in his lifetime (Litvin n. d.).

The first patent of planetary gear transmission appeared in Germany in 1880. Planetary gear transmissions have a compact structure and provide a large transmission ratio. In the 20th century, various types of planetary gear transmissions were rapidly developed, and widely used in automobiles, airplanes, ships and various other machines.

Around the turning of 19th and 20th centuries, the method of strength calculation of gears was established (see Sect. 7.6.5).

7.5.1.2 Worm Gearing

During the Industrial Revolutions, various machines, such as presses, conveyors, elevators and rotary worktables, appeared. In these machines, worm gears were widely used. In fact, the machine tools cutting gears with generation methods contain a precision worm gear under the rotary worktable of the workpiece, which connects the cutting tool and the workpiece. Thus, the accuracy of this worm gear directly affects the accuracy of gears being made. Consequently, the emergence of gear hobbing machines and gear shaping machine put forward a requirement to improve the accuracy of the worm gearing.

Starting from the end of 19th century, attention was paid to improve the load carrying capacity and life of worm gear mainly due to the need for large capacity elevators (Litvin n.d.).

Double enveloping worm gearing was invented independently by a German engineer, Friedrich Lorenz, in 1891 and a American inventor, Samuel Cone, in 1924, respectively. Despite the different geometry, both have a higher contact ratio than traditional worm gears, thereby increase the load capacity. Research revealed that the high efficiency of double enveloping worm gearing is mainly due to its more favorable lubrication condition. The complex geometry, special lubrication condition and the forming of the tooth surface stimulated a lot of researchers to analyze the meshing of worm gears (Litvin n.d.).

In 1915, a British engineer, Francis Bostock, proposed the involute worm gearing, also known as the ZI worm (Litvin n.d.).

7.5.1.3 Belt and Chain Drive

The earliest idea of chain drive was proposed by L. da Vinci, who drew a sketch of the roller chain. In 1770, a Frenchman, Jacques de Vaucanson, invented the modern chain drive and applied it to silk machines (Temple 1986). In 1880, a Swiss engineer, Hans Renold, invented sleeve roller chain through improving the existing pin roller chain, and immediately applied it to the bicycle invented by J. Starley. He also invented the toothed chain (also known as silent chain) in 1885 (Zheng et al. 1984). At that time, the most important application of chain drive was used as the timing chain to drive the camshaft in an internal combustion engine. The progress of chain drive in the 1880s was synchronized with the invention and development of engine.

After invention of the steam engine, flat belt drive was widely used in workshops to transmit and distribute motion and power from the line shaft to individual machines on the floor. An American, John Gates, invented V-shaped belt in 1917 (ANON2 n.d.). The original intention of V belt was to solve the problem of slippage of the flat belt; however, its fast and wide application was mainly due to its large friction force, high transmission capability and compact structure.

Early in the 1670s, Robert Hooke analyzed the ancient universal joint, discovered its non-uniform motion and put forward a solution. Since then, the universal joint was also known as Hooke joint (Gunther 1930). In the 19th century, it was already widely used in various applications, among which the most famous was the application in automobile.

7.5.1.4 Appearance of CVT

Early in 1490, L. da Vinci proposed a concept of continuously variable transmission (CVT). In 1879, Milton Reeves, an American engineer, invented a CVT for a sawing machine. He also used it in his first car in 1896. The first V-type rubber CVT, specially designed for automobiles, was patented in 1886 by G. Daimler and K. Benz, the inventors of automobiles. After entering the 20th century, various CVTs appeared, among which, at least 20–30 types were commercialized. However, due to limitations of material and production conditions, fast development did not come until WWII (Cheng 2008).

Development of automobiles and motorcycles has always been in pace with CVTs. The reason is that the CVT can make the engine working in the optimum condition, regardless of the speed of the vehicles. This can also minimize the exhaust pollution (Cheng 2008).

7.5.1.5 Complexity of Transmission

To meet the requirement of machine tools, automobiles and aircrafts, mechanical transmissions become more and more complex, offering a variety of functions, such as changing of speed, reversing and splitting of transmission, composing and decomposing of motion etc.

Since each machine tool was equipped with an independent motor, the overhead line shaft was abandoned. Consequently, gearboxes of machine tools emerged so that the spindle could run at various speeds to adapt to the different cutting conditions.

Soon after the birth of automobile, G. Daimler invented the gearbox and differential consisting of bevel gears in 1889. In the earliest vehicles, motion was transmitted from the engine to the rear axles by a chain drive, similar to a bicycle. The use of universal shaft did not begin until 1898.

Some gear cutting machines, such as gear hobbing machines and gear shaping machines, contain the most complicated transmissions, requiring almost all the functions described above.

7.5.2 Hydraulic Transmission

Hydraulic transmissions are a technology based on the hydro-static principle proposed by Blaise Pascal in the 17th century.

7.5.2.1 Early Development

The first hydraulic press in the world was invented by a British engineer, J. Bramah, in 1795 and this was generally regarded as the beginning of modern fluid power technology. By the 1920s, hydraulic presses had become the most widely used machine next only to steam engines (Sullivan 1989).

Because the steam engine could not be miniaturized, hydraulic center station appeared. Hydraulic power was initially applied in Britain to drive lifts and cranes in ports, canal gate and open bridge as well as machines in steelmaking production.

In 1851, a British engineer, William Armstrong, started to design and build hydraulic cranes (see Sect. 4.3.3). In places where water pressure was not available on site for the use of hydraulic cranes, Armstrong often built high water towers to provide a supply of water at pressure. However, when the cranes were used at New Holland, he was unable to do this because of the unstable sandy foundations. To solve this problem, he produced the hydraulic accumulator which had a piston in a vertical closed cylinder loaded by dead weight ballast. Energy was stored by upward movement of the piston and recovered on its descent. Thus, the accumulator acted as a pressure sustaining device between the high-pressure pumps and the hydraulically operated machines connected to the system. The accumulator was a very significant invention, with many applications in the following years (McKenzie 1983).

Around 1860, hydraulic presses with a capacity of 700–1200 tons appeared in Vienna railway factory for forging locomotive components. To 1893, the capacity of the forging press reached 12,000 tons.

However, with water as the working medium, sealing had always been a problem. At the same time, electrical power was in fast development, competing with hydraulic power. It seemed that hydraulic technology faced a loomed future. The beginning of the 20th century saw a growth of petroleum industry. Mineral oil in general is more viscous, thus, has good lubricating and better anti-corrosion properties. In 1905, Reynolds Janney, an American engineer, started using oil to replace water as the working medium of the presses. This greatly improved the working quality of the presses (Li 2011).

After oil was used as the working medium of hydraulic power, it was needed to develop a variety of oil pumps for use in different conditions. In 1907, two American engineers, Harvey Williams and Reynolds Janney, developed the first axial piston devices (Fig. 7.22), which could be used as either a pump or a turbine. This device was used in 1906 in warships to drive the turret (Li 2011). Its application in machine tools came, however, much later.

At the turn of the 19th and 20th centuries, hydraulic planers were made in Germany, and hydraulic turret lathe and grinding machines in the U.S. (Zhou and Yu 2008).

Hydrodynamic transmission, involving one or more torque converters, is another type of fluid transmission. Fluid couplings originated from the work of a German engineer, Hermann Föttinger. He patented the fluid coupling in 1905. The hydrodynamic transmission was first applied in ships in 1912. In this application, some

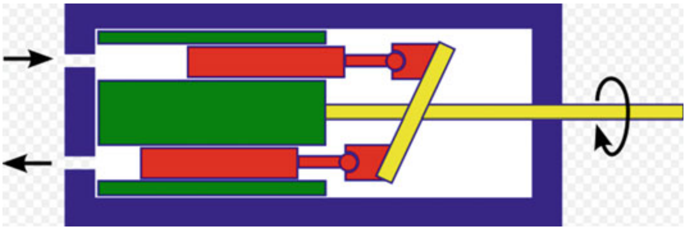


Fig. 7.22 Axial piston pump

characters of hydrodynamic transmission, such as automatic variation of turbine speed with load, shock absorption of hydraulic elements, were realized. These properties are extremely important for vehicles. In the 1930s, a Swedish engineer, Alf Lysholm, designed another type of torque converter and applied it to bus. Since then, the hydrodynamic transmission has been successfully applied in many vehicles.

7.5.2.2 Large Scale Application

Gear pumps were invented in the 17th century (see Sect. 3.2.3). With the growth of machine tool industry, gear pumps, featured with high pressure and small flow rate, were widely used in machine tools for supplying lubricating oil. A Danish-American, Jens Nielsen, invented the internal gear pump, and built it in 1911.

The hydraulic transmission and hydraulic control were first applied to aircrafts. The fighters during WWI were propeller planes. In 1917, a Romanian scientist, George Constantinesco, invented the synchronous gear controlled by a hydraulic system in Britain. This was a very smart innovation which made the machine guns on the plane being able to fire bullets in the clearance between rotating blades. Consequently, the planes could fire in front, achieving great success in air fighting without damaging the plane itself (GSHCAS 1985).

Wide spread application of hydraulic technology did not come until the beginning of the 20th century. Before then all the hydraulic elements were specially designed and made for specific systems; therefore, application of hydraulic technology was greatly limited. Industrialized production of hydraulic elements began during the period between the 1890s and 1910s, and was gradually standardized. The standardization of hydraulic elements greatly speed up the application of hydraulic drive after WWI. To the 1920s, a booming period appeared, hydraulic power was widely applied to machine tools and various construction machines.

Large machines, including vehicles, aircrafts and ships, required large capacity transmission units. To meet this requirement, high power density and good controllable characteristics are necessary for hydraulic elements. In 1922, a Swiss engineer, Hans Thoma, invented the radial piston pump (Fig. 7.23) which can

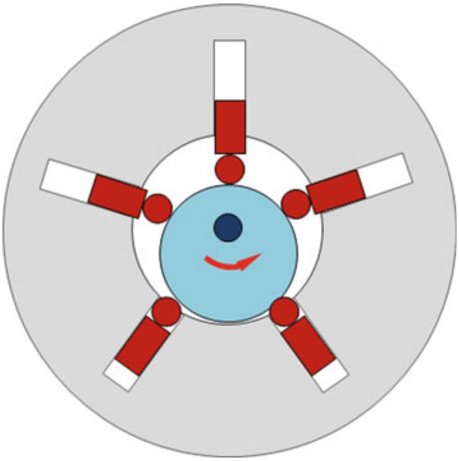


Fig. 7.23 Radial piston pump

provide especially high pressure and relatively small flows. Subsequently, other types of piston pumps and hydraulic motors appeared. These new progresses made the performance of hydraulic transmissions further improved (Li 2011). In 1925, Harry Vickers, an American industrialist, invented the pressure balanced vane pump. All of these laid the foundation for the establishment of the modern hydraulic elements industry and hydraulic technology.

By 1927, hydraulic transmissions, hydraulic trackers, magnetic tapes and electromagnetic valve control were applied to milling machines, symbolizing the start of semi-automatic era of machine tools.

In 1933, hydraulic systems were successfully applied in aircrafts to operate the landing gear, flaps and ailerons. By 1938, hydraulic systems and electromagnetic control greatly motivated the invention of copying milling machine. In addition, their application extended to planers and other machine tools. After the 1930s, electromagnetic valves and limit switches were used for control in almost all kinds of machine tools (GSHCAS 1985; Sullivan 1989).

7.5.2.3 Hydraulic Control

In 1922, Nikolai Minorsky, a Russian-American scientist, published a paper on the concept of integral and derivative controller for marine servo mechanisms (Flügge-Lotz 1971). This paper was one of the earliest formal discussions on control theory, and is considered as a pioneering and fundamental work to control theory. In 1927, another American, Harold Black, proposed a negative feedback method to improve the performance of amplifier, which was considered the most important breakthrough of the 20th century in the field of electronics, since it has a wide application in many areas (Kline 1993). In 1930, a German, G. Wuensch, proposed a method to adjust pressure and flow. In 1932, a Swedish-American, Harry Nyquist, put forward the stability criteria of the system according to the frequency response (Li 2011). The Nyquist stability criterion can now be found in all textbooks on feedback control theory. In 1936, a American, Harry Vickers, invented series hydraulic elements of tube type. So, Vickers was called the father of the hydraulic industry by ASME.

7.6 Modern Machine Design

7.6.1 Development Stages of Machine Design

Design activities have existed since human began to make and use tools. Design activities in different historical stages can be categorized into four types, namely intuitive design, empirical design, semi-empirical design, and semi-automatic design, based on the level of theoretical abstract, method and means used.

7.6.1.1 Stage of Intuitive Design

The stage of intuitive design mainly happened in the ancient times when there were no theories of mathematics and mechanics. The design idea was formed mainly on intuition and the inventor made the machine by him-self. This pattern was true even for very complex machines.

7.6.1.2 Stage of Empirical Design

The stage of empirical design roughly covers the period from the Renaissance to the beginning of the Second Industrial Revolution. In this stage, mathematics and mechanics were formed, and provided theoretical basis for the design activities. The success of the Industrial Revolution greatly promoted invention and applications of machines, so machine design activities were developed vigorously. In the 17th and 18th centuries, the mechanical research and design activity mainly depended on two kinds of people, scholars and craftsmen. Scholars, such as Euler and the school of French theoretical kinematics, were mainly engaged in research, but were not involved with much detailed design. Craftsmen, including Watt, Newcomen, Bramah and Maudslay, were working on workshops, and playing the main role in the invention and design of machines in the First Industrial Revolution.

During the First Industrial Revolution, design began to be separated from manufacturing. At the early 19th century, mechanism theory became a subject; however, design of machine elements remained a part of applied mechanics. No books dedicated to machine design were available. In addition, machine manufacturing was limited in small workshops, not being an engineering subject yet. At that time, machine design included the design of mechanism, and components. The designers were mainly craftsmen with rich practical experiences complemented with some theoretical knowledge. The design mainly relied on the designer's experiences and talent in addition to intuition and inspiration. Although mechanics theory was developed, systematic design theory was not formed yet. In general, design in this period was highly empirical, and consistent calculation methods were not formed yet, and involved many assumptions and approximations.

7.6.1.3 Stage of Semi-empirical Design

The stage of semi-empirical design existed for a period of roughly one hundred years from the Second Industrial Revolution to the 1950s. This period is characterized with the following:

(1) After the first World Expo in 1851, a lot of complicated mechanical products appeared.
(2) The German school and Russian school of mechanism arose; design methods of machine components were formed, but still with many assumptions and approximations.
(3) Mechanical engineering was formed as a modern discipline; engineering education was developed; engineers and scholars became the main body of designers.
(4) Engineering drawing appeared and standardization started, making design more efficient, improving design quality, and reducing design cost.
(5) Design still contained some empirical factors, which, however, were not the main component any more. Tests on key mechanical components were carried out. At the same time research on special machines started. Gray area in design kept decreasing.

However, design was not fully studied yet.

After WWII, the wide spread application of computers brought machine design into the fourth stage—semi-automatic design (see Sect. 11.1).

7.6.2 Descriptive Geometry

Descriptive geometry was founded by Gaspard Monge in his youth, who later served as the president of the Paris Institute of technology (O'Connor and Robertson 1999).

In 1764, Monge drew a city plan for his hometown at the age of 18. Because of this work, he was recommended to a military school for a position of drafter. Fortification was one of the most important courses of this school at that time. A key component of this course was to carefully design fortifications so that no part of the fortification was directly exposed to the enemy's fire. This required lengthy arithmetical calculation. Sometimes, a fortification of already-built had to be pulled down and started design and construction over again. Monge attempted to simplify the design process, and invented the descriptive geometry in the course.

In his method, a three-dimensional body could be represented clearly by two projections on the same plane. Thus, the complicated calculation was replaced by a graphical method. After a short training, any drafter could do the job. In recognition of his invention, Monge was immediately offered a position to teach this new method to the future military engineers.

He was required to swear not to disclose his method; thus, the descriptive geometry was carefully kept as a military secret for 15 years. By 1794 Monge was allowed to give a lecture at the Paris Normal College. In 1799, Monge published the book *Descriptive Geometry*, laying the theoretical foundation for this subject. Later on, scholars across the world enriched continuously the subject with new theories and methods in projection transformation, axonometric drawing etc. making the subject approaching mature.

Descriptive geometry was the mathematical basis of engineering graphics. Without Monge's creative work, the tremendous development of mechanical manufacturing in the 19th century was almost impossible.

7.6.3 Independence of Machine Design

There are two crucial steps in machine design. The first is to design the proper mechanisms for the desired function. The second is to design the individual components in the mechanisms. Machine design involves component type, component structure, manufacturing, standardization, failure, evaluation of load capacity etc. Obviously, it is far more than only a problem of mechanics. Even the evaluation of load capacity goes far beyond only a mechanics problem, being closely related with material science, heat transfer and other subjects. Thus, to the second half of the 19th century, it was the time for machine elements design, the core content in machine design, to be separated from applied mechanics.

In addition to kinematics, Franz Reuleaux, the founder of the German school of mechanism, also made outstanding contribution to the formation of the subject of machine elements design. He was a well-known professor, and also a consulting engineer. In 1861, he published a book, *The Constructor*. It was a practical manual book for machine design, covering many practical contents, such as fasteners, joints, shafts, bearings, couplings, gears and various mechanical transmissions. This book was very popular in Europe and translated into French, Swedish and Russian. In 30 years, it was reprinted with four editions. The fourth edition was translated into English in 1893 (Reuleaux 1893).

From nowadays view point, this book, of course, has its limitations. For example, it did not involve dynamic analysis. The static analysis was limited to only graphical methods. In the gearing part, only the geometrical calculation was given without covering the evaluation of load capacity. Shafts were considered under only torsion with bending neglected.

An expert of early 20th century once commented this book as "recipe book" (Lienhard 2000). This comment is somewhat unjust to him. The real significance of this book lays in the fact that it is the first textbook or handbook dedicated to design of machine elements, marking the fact that machine elements design was separated from applied mechanics, and became an independent subject.

In fact, the predecessor of the *Constructor* was already published in 1854 when Reuleaux was only 25.

7.6.4 Strength of Mechanical Structures

Mechanics of materials is a part of solid mechanics, and also the important theoretical basis of mechanical structure strength. Mechanical structure strength is the base of mechanical component design, and closely linked with specific component types under design.

7.6.4.1 Fatigue Failure

About 50–90% of failures of machine elements is caused by fatigue (Fuchs and Stephens 1980).

The study on fatigue failure was a result of the First Industrial Revolution. With the use of steam engines, the speed of locomotives and ships was greatly increased. Thus, accidents often happened. In the 1860s, 200 people on average died from train derailment caused by failures of wheels, axle and tracks in Britain. It was found that these parts, however, completely met the strength requirement in static strength test. Also the failures of the axle always occurred at the shoulder. Some scholars started investigation on the failures of the locomotive axles from 1829. In 1839, the term “fatigue” was first used in France to describe the process of gradual exhaustion of the load-taking capacity, and final rupture of the material under alternating loads.

In 1847, August Wöhler, a German railway engineer, began to systematically study metal fatigue (Wu 2000). In 1850, he designed the first fatigue testing machine capable of rotational bending fatigue tests of full size locomotive axle. Later, he carried out tests with large number of specimen. The test results were published in 1870 as a paper in which the relationship between the fatigue life and the cyclic stress was discussed in detail, and represented by the *S-N* curve (Wöhler curve). In this paper, he also brought forward the concept of fatigue limit and clearly pointed out that stress amplitude was the decisive factor to fatigue failure. Wöhler’s work laid the foundation for conventional fatigue design and he was recognized as the founder of fatigue research (Timoshenko 1953).

In 1924, a Swedish, Arvid Palmgren, put forward a linear assumption of the fatigue cumulative damage in research on life of rolling bearings. In 1945, M. A. Miner formulated this assumption and formed the well-known Palmgren-Miner rule, which has been widely used in fatigue design.

In 1924, a comprehensive work *The Fatigue of Metals* (Gough 1924) was published. The conventional fatigue design method appeared in the second half of the 20th century.

7.6.4.2 Contact Problem

A German scholar, Heinrich Hertz (Fig. 7.24), published a paper on contact stress of ball bearing in 1881. The classical theory of contact mechanics was established during 1886–1889 (Johnson et al. 1971). This theory has very important significance to mechanical engineering given that contact stress exists in many mechanical systems, such as gears, cam-follower systems, rolling bearings, wheel and rail system etc. In many cases, the contact stress is the main limiting factor to the load carrying capacity. Plentiful study on the characteristics of contact failure and the contributing factors to the damage have been conducted. The findings of the study were well reflected in the formulas for the strength and life calculation of gears and bearings.

7.6.4.3 Creep

Around in 1910, a British scholar, Edward Andrade, began to study property changes of metals under long-time constant stress. He clarified relevant physical factors in the creep phenomenon. In 1935, Richard Bailey reviewed the prevailing theories of creep at that time and made effort to apply them to engineering design (Williams et al. 1978).

Fig. 7.24 H. Hertz

7.6.4.4 Starting of Fracture Mechanics

In 1921, a British aeronautical engineer, Alan Griffith, looked into the problem that the actual strength of glass was much lower than the predicted value from the analysis of its molecular structure. He attributed this phenomenon to cracks existing in the material, which caused stress concentration. He gave a fracture criterion (applied to brittle materials) for the crack size, the so-called energy criterion (Ewalds and Wanhill 1984). Griffith is viewed as the father of fracture mechanics.

Inspired by Griffith's work, aircraft designers immediately understood why some structures still failed although a large safety coefficient in strength was used. They quickly turned to improve the structure strength by upgrading the surface finish of the metal structure to remove possible cracks. In the 1930s, partially due to this measure some outstanding aircraft, such as Boeing 247, appeared.

However, this was just an engineering case inspired by fracture mechanics, not a direct application. Due to the fact that Griffith' research was based on glass, which is a completely brittle material and rarely used in engineering, his theory did not find direct application at that time. In fact, further development of the theory did not happen until WWII (Erdogan 2000).

7.6.5 Formation of Design Method for Machine Elements

Mechanics of materials, along with fatigue theory and contact mechanics, made it possible to establish systematic design methods of machine elements.

7.6.5.1 Gear Drives

Since the invention of steam engine, machines obtained unprecedented power. Strength calculation of gears began to be discussed. Two types of failures in gears, tooth breaking and surface pitting, first caught people's attention.

In 1785 when developing the steam engine, Watt estimated the bending strength of gear tooth by considering it as a cantilever beam with rectangular cross-section. During the 18th and 19th century, at least 15 people published formulas for calculating gear strength. In 1868, the concept of dynamic load factor was firstly proposed (Zhang 2009).

In 1893, W. Lewis, an American scholar, proposed a formula for estimating tooth bending stress based on the assumption of cantilever beam. In 1908, a German scholar, E. Videky, established the method of calculation contact stress of tooth surface based on Hertz theory (Zhu and Zhongkai 1992).

These two formulas contain multiple assumptions and simplifications. For example, in the Lewis formula, the force is assumed being applied at the top of the tooth profile; the tooth is considered as a cantilever beam; the force component along the radial direction is ignored; single pair teeth contacted is assumed all the time and stress concentration at the root is ignored. Many corrective factors in today's formula were not taken into account in Lewis and Videky formulas.

The works of Videky and Lewis laid the theoretical foundation for calculation of load capacity of gears. In 1932, the world's first standard for strength calculation of cylindrical gears established in Britain. Over the next decades, various gear strength calculation methods were put forward in Germany, the U.S., the Soviet Union and other countries, and became standard of the nation or company. However, ISO (International Standard Organization) established its standard for strength of involute cylindrical gears pretty late in 1996.

Beginning from the 1890s, steam engines on ships were replaced by steam turbines, and the gear drive tended toward higher power and higher speed. For example, the power of a ship reducer reached 804 kW in 1910, and the circumferential velocity of the pitch circle exceeded 30 m/s (Sa 1986). High-speed gearing developed rapidly during WWI. Other machines requiring high-speed gears include generator units and air compressors.

In high-speed gears, the dynamic load became significant. So, in the first half of the 20th century, research on gear dynamics, aiming at estimation of the dynamic load, was started.

American Society of Mechanical Engineers (ASME) organized a special research committee on strength of gear teeth in 1923. Earle Buckingham at MIT participated the research. He compiled the research results and published in the form of research report in 1931(Buckingham 1931) in which a dynamic load formula, the so-called Buckingham formula, was proposed on the basis of impact theory. He pointed out that instantaneous separation and the subsequent collision occurred between teeth due to the tooth pitch errors. The report emphasized three factors influencing the dynamic load, namely, inertia of the system, teeth errors and the linear speed. In 1949, Buckingham published a book titled *Analytical Mechanics of Gears*, which was a representative work of gear dynamics based on impact theory (Buckingham 1949).

In addition to the above work, Buckingham et al. summarized 6–8 types of failures in gears. Later, formulas for anti-adhesion and anti-wear of gears were proposed as well.

7.6.5.2 Shafts

Today, shafts are treated with combined bending and torsion in mechanics of materials. The strength calculation involves the maximum shear stress and shear strain energy. Henri Tresca proposed the third strength theory during 1867–1878.

The works of Maksymilian Huber and Richard Mises in the fourth strength theory were published in 1904 and 1913, respectively (see Sect. 6.2.3). The moment diagram and the differential relationship determining the position of the maximum moment, $Q = \mathrm{d}M/\mathrm{d}x = 0$, were already proposed in the 1850s (LaoLiang 1993).

Obviously when F. Reuleaux revised *The Constructor* for the fourth edition in 1893, the third strength theory had already been available. However, he still determined the diameter of the shaft based on pure torsion, without taking the bending stress into account. He insisted on that bending effect was trivial, and including bending would end up with too complicated calculation.

Therefore, the strength and stiffness calculation of shafts in today's textbooks appeared in the 20th century.

7.6.5.3 Rolling Bearings

Primitive ball thrust bearing already appeared in the 1st century. To the 16th century, a variety of rolling bearings were described in L. da Vinci's notes, and in books published in Swiss. From the middle 18th century to early 19th century, patents of rolling bearings were granted in Britain and France.

The modern rolling bearing industry was established after the 1850s (Morton 1965). Two things were critical to the establishment of the bearing industry. First, bicycles approached practical after continuous improvements. Second, the Bessemer process made the production of good quality steel possible. In 1883, A German mechanic, Friedrich Fischer, designed a special grinder for grinding of steel balls, achieving mass production of steel balls with accurate diameter and shape for the first time. This was considered a landmark in the establishment of rolling bearing industry (FAG 1991). In the same year, Fischer established the FAG Company, which was recognized as a pioneer and leader in rolling bearing technology. By 1920, various types of rolling bearings, such as tapered roller bearing and thrust bearing, were developed. Now, FAG can manufacture rolling bearings with diameter ranging from 3 mm to 4 m.

Fatigue pitting under contact stress is the main failure form of rolling bearings. Theories on fatigue and contact mechanics were already created in 1870 by A. Wöhler and in 1882 by H. Hertz, respectively. Seemingly, theoretical base for estimation of rolling bearing's life was laid well; however, it proved later that the problem was not that easy. A. Palmgren started to work on bearing life prediction and published his instrumental paper in 1924. However, the problem was not solved until 1945 by G. Lundberg and A. Palmgren (Zaretsky 1997).

7.6.5.4 Sliding Bearings

Human already noticed the phenomenon of friction in Ancient times; however, research on friction advanced very slowly. L. da Vinci, G. Amontons and C-A Coulomb are the three most prominent figures making outstanding contribution to the establishment of the classical friction law (see Sect. 3.2).

In 1839, an American goldsmith, Isaac Babbitt, invented a bearing made of a low-friction tin-based metal alloy, known as Babbitt metal, which has been widely used as a bearing material (Hellemans and Bunch 1988).

The classical friction law is applicable only to dry friction. Although people in Ancient times already realized that lubricant could significantly reduce friction, very little research effort on friction with lubrication was documented until the Industrial Revolution when metal parts were able to be made accurately. At that time, the increase of train speed put an urgent need to find a way to reduce the friction in the wheel bearing. N. Petrov (Николай Петров), a Russian engineer, made the first attempt to investigate the friction with fluid film lubrication in locomotive axle bearings, and derived the formula, the well-known Petrov's equation, in 1883 (Петров, 1883).

In 1886, a Irish-British scholar, Osborne Reynolds, derived the famous Reynolds equation based on fluid mechanics, with which the mechanism of forming hydrodynamic pressure was well explained (Hamrock et al. 2004). As such, it laid the foundation of hydrodynamic lubrication in theory. All the lubrication theories appeared thereafter were based on the Reynolds equation, and hydrodynamic lubricated bearings have been widely used.

In 1901, a German engineer, Richard Stribeck, systematically studied the variation of friction between two liquid lubricated surfaces with a dimensionless lubrication parameter

$\eta V/P$, where η is the dynamic viscosity, V the speed (e.g. revolutions per minute of a bearing) and P the load projected on to the geometrical surface. On the basis of the Stribeck curve, the regimes of lubrication between sliding surfaces is divided into three distinct states, namely full film, mixed film, and boundary film lubrications (Hamrock et al. 2004).

The Reynolds theory did not give boundaries of hydrodynamic lubrication. For example, if the unit load was high and the relative velocity was very low, it was still difficult to form oil film with a sufficient thickness even with oil of high viscosity. In 1922, William Hardy studied the boundary lubrication in detail, following which, non-hydrodynamic lubrication states were extensively explored in all aspects (Hamrock et al. 2004). Reynolds equation, along with later complementary, contributed greatly to the development of bearings in both application and theory.

Hydrostatic bearings were invented by a Frenchman, L-D Girard, in 1851, who first applied high pressure water-fed bearings for railway propulsion system (Rowe 2012).

7.7 Modern Machine Manufacturing

7.7.1 Introduction

The origin of modern machine manufacturing industry is traced back to the watch-making in Switzerland in the 16th century, which prepared technicians and skilled workers for a modern manufacturing industry. Following the steam engine were a booming period of invention of machines, such as J. Bramah's hydraulic press, H. Maudslay's screw lathe, and J. Whitworth's standard of screw, to name a few. The modern machine manufacturing industry was first born in England. At that time, there were no school for engineering education, let alone a machine building subject. Machines were invented and built by technicians or craftsmen; thus, knowledge on machine building existed mainly in workshops. The accumulation in the experience and knowledge of these technicians and craftsmen was the seed of later development of the machine manufacturing subject.

Mechanisms developed from experience into the subject of mechanism theory in the early 19th century, and machine elements design was formed as a subject through separation from mechanics during the middle 19th century. The time for manufacturing to become a engineering subject was relative latter.

In the following section, the development of the machine manufacturing subject in the Soviet Union is taken as an example to illustrate the historical evolution.

A. Sokolovsky (A. Соколовский), an expert of manufacturing in the Soviet Union, stated his work process in the preface of his textbook (Соколовский 1947). He first collected materials on machine manufacturing in the Soviet Union and other countries during the period of 1932–1935 and published them in 5 volumes. Subsequently, in 1938–1939, he systematically organized these materials and published a book titled *Basis of Machine Building* (Соколовский 1938, 1939). As the third step, he published a textbook, *Course of Technology of Machine Building* for universities and colleges in 1947 based on these materials (Соколовский 1947).

In the introduction of this textbook, the author stated "*It was not long ago for machine manufacturing technology to exist as an independent course in the Soviet Union. With the fast growth of the machinery building industry, engineers in factories encountered technical problems every day to solve which, a good textbook and help from universities were needed. Wide consultations with engineers and administrators in the industry led to the birth of this course.*"

This course stemmed actually from two independent courses offered in Soviet universities, namely *Metal Forming* and *Machining Technology*. In the late 1920s at the beginning of the first Five Year Plan of the Soviet Union, the two courses were decomposed into a few independent courses, including Machining Cutting Tools, Theory of Metal Cutting, Tolerance and Production Organization. As Sokolovsky stated: "*However, there was a need to develop a new course, which could directly answer all questions practical engineers might encountered. To meet this need, some courses with different name and coverage were added to the curriculum of some universities in around 1930. To the year of 1934, the position of* *the new course in the curriculum was confirmed and it was given a consistent name, Machine manufacturing technology*".

This statement clearly outlined the path in Soviet Union how the workshop knowledge and experience in machine manufacturing evolved to the level of theory, and further went into university curriculum as a course. In Western Europe and the U.S., roughly similar timelines were followed.

The main components in the modern machine manufacturing subject are as below: the theory of metal cutting, design of metal cutting tools, machine manufacturing technology (includes fixtures), design of machine tools, machining accuracy, and so on.

The pushing force behind the development of modern machine manufacturing technology was the higher and higher requirement on productivity and accuracy.

One main measure to improve productivity is to increase cutting speed which is limited by the tool materials. Therefore, in the Second Industrial Revolution tool material took the lead in the progress of manufacturing technology. Research on metal cutting theory started around 1850 or so when high carbon steel and alloy steel were the main materials for cutting tools. With the invention of high-speed steel in 1898 and the commercial production of carbide in 1926, a wave of research on machinability of materials and durability of tools appeared. Corresponding to the progress in tool materials, machine tool speed was greatly increased, causing severe machining vibration, and producing more cutting heat. Thus, higher strength and stiffness of the machine tools were required.

The continuous increasing of machine speed pushed the improvement of machining accuracy, which required a theory to systematically analyze the machining accuracy and the influence of various factors on the machining accuracy. Machining vibration and the thermal deformation caused by machining heat are two important factors which have to be considered in the machining accuracy.

Manufacturing processes are basically experience-based, being summarized from the practical manufacturing operation. The design of machine tools involves mainly mechanical transmissions and structure parts. As stated before, cutting tool material is the core of the subject of machine manufacturing. The theory of metal cutting and the theory of accuracy are the most important two cornerstones with unique characteristics in the subject.

7.7.2 Theory of Metal Cutting

The theory of metal cutting could be traced back to the 17th century. Early in 1679, Robert Hooke published a book on cutting. However, metal cutting was not treated as a scientific subject until the second half of the 19th century. During the Second Industrial Revolution, steel quickly replaced iron, becoming the most common structural material in industry. Cutting tools of high carbon steel were not satisfactory in wear-resistance when machining steel work-pieces. Thus, a very low cutting speed had to be adopted and the cutting cost was pretty high. Consequently, it was an urgent need to increase the cutting speed, and to find solution to improve the durability of cutting tools.

The historical development of theory of metal cutting in the past more than a hundred years could be divided into the following three stages.

7.7.2.1 First Stage: Elementary Research

The first stage roughly covers the second half of the 19th century. In this stage, high carbon steel and alloy steel were the two most common tool materials. Initially research was focused on cutting force and energy. In 1851, a French researcher, H. Cocquilhat, studied the energy consumption in drilling for different materials. In 1864, another French scientist, Joessel, studied the cutting forces and their relationship with tool geometry (Smith 2008).

Later on, research was switched to the mechanism of chip formation and the plastic shear occurred during machining. In 1870, a Russian scientist, I. Timme (Иван Тимме), proposed that chip was formed due to shear deformation. During the period of 1864–1872, Henri Tresca, a French scientist and mechanical engineer, formulated the yield criterion according to the maximum shear stress after a series of metal extrusion experiments. This work marked the beginning of study on the plastic constitutive relation. Later, Tresca further proposed in the period of 1873–1878 that chip was formed in the process of shear deformation in the plane perpendicular to the cutting direction (Finnie 1956; Boothroyd 1975).

7.7.2.2 Second Stage: Tool Durability and Machinability

The second stage covers the period from 1900 to 1930. In this period, the fast development of automobile, machine tools and aviation raised a need to further increase machining speed. New tool materials, such as high-speed steel (1898) and carbide (1926), emerged.

New tool materials greatly improved productivity. As stated by E. Trent, "*emergence of high speed steel cutting tools caused a revolution in metal cutting practice, greatly improving the productivity of machining, and demanded to completely change the structure of machine tools. It was estimated that in the first few years, engineering production in the USA had been increased by $8000 million through the use of $20 million worth of high-speed steel.*" (Trent 1991)

However, accompanying the increase of cutting speed were some issues, such as tool durability, surface quality, and chip removal etc.

Frederick Taylor was the first person to study the relationship between cutting speed and tool durability. After working for 26 years, cutting off 30,000 tons of chips, and obtaining more than 100,000 sets of experimental data, he proposed a famous formula of cutting tool durability in 1907. Although Taylor's data were rarely directly cited nowadays, his work still has great significance and frequently referenced in current literature. (Taylor 1906; 中山一雄 1978).

The concept of machinability was first proposed by a British scholar, W. Rosenhain, in the 1920s (Boothroyd 1975). At that time, this word meant mainly the relationship between cutting speed and tool durability, without much involvement of surface quality, chip removal and dimensional precision. It was considered as an important material property related to hardness and toughness.

7.7.2.3 Third Stages: Complete System of Cutting Theory

The third stage refers the time after the 1930s. In this stage, the theory of material cutting gradually took shape with systematic and complete contents.

In 1941, M. Merchant published a famous paper on mechanics of metal cutting process (Boothroyd 1975). M. Merchant, Milton Shaw, and several other American scholars conducted active research in this period; through considering the phenomena occurred in cutting operation with plastic deformation, and the theories of failures and thermal conduction, a complete system of cutting theory was established.

Research on cutting theories reached its peak in the 1960s and 1970s when various new theories and methods were proposed. Computer technology became a powerful tool in the study of metal cutting. Theoretical and experimental results were applied to production in an unprecedented scale.

It is worth noted that the cutting process is very complicated, involving many factors. Thus, highly idealized and simplified theoretical models may not be able to provide accurately quantitative information. The significance, however, lies in that the qualitative information obtained from theoretical models can interpret some very important material-cutting phenomena (中山一雄 1978).

After the 1980s, research gradually shifted to the combination of machining process with computer technology and automatic control. In contrast, studies on the mechanism of metal cutting process itself became rare. It can be predicted that new challenges and research topics will continuously come up with the progress in new materials, new machining process, and the application of new technologies, computers and automatic control technology in particular.

A British scholar, Trent (1991), and an American scholar, Shaw (1984), gave comprehensive summaries on the theoretical and experimental researches on metal cutting processes during this period.

7.7.3 Theory of Machining Precision

Eli Whitney made the first interchangeable parts in 1798. The world earliest standard of tolerance, however, was compiled by Newall Company in Britain in 1902. It was over 100 years between the two landmarks regarding machining accuracy. This fact indicated that machining accuracy progressed pretty slowly. The reason behind is that knowledge was accumulated mainly through practice, lacking the guidance of theory.

7.7.3.1 Early Development of Tolerance and Measurement

The concept and development of interchangeability were mainly driven by production. Before the interchangeability concept, the drawing only contained nominal dimensions, and a specific shaft (male part) had to be fitted with a specific hole (female part) through trial and error if fit was required. In the process, much trial assembly and filling work was involved.

Later, to get accurate clearance between mated parts, fixed gages of high precision, including plug gages and snap gages, appeared. Snap gages were used to check outside diameter whereas plug gages are used to check inner diameter. With these precision gages, desired clearance could be obtained and checked. As a result, an individual hole did not have to fit with a specific shaft. Rather they could be made and checked separately. It was reported that what Whitney used in fabricating the guns were fixed gages. In Russia, fixed gages were used in the 1760s, earlier than Whitney by 20 years (Li 1984). To make fitted parts through the fixed gages requires the shaft and the hole to be manufactured with very high precision. This greatly limited its application.

It was later found that the clearance between the hole and the shaft was not necessary to be so accurate as long as the clearance variation was controlled to a certain range. Thus, the concept of tolerance appeared. Limit gages, also known as go/no-go gages, are designed to check the dimensions with tolerance. A limit gage often is made with one end for checking the lower limit and the other end for the upper limit. With the concept of tolerance, the unnecessarily high precision on machining of mated parts could be greatly relaxed and mass production with interchangeability became dominant thereafter. Limit gages were first used in Britain, France, Germany, Russia and the U.S. (Li 1984). With the experience accumulated, some manufacturing companies gradually established rules on the proper amount of tolerances for different sizes and mating conditions. In 1902, British Newall Co. compiled a “Limit table”, which was the first documented standard of tolerances and fits in the world. It was estimated that the appearance of limit gage should not be much earlier than this year. The snap gages have been in existence and referred to by that name since at least 1898 (Wikipedia 2015).

In the first half of the 20th century, Britain, Germany, and the Soviet Union developed their national standards; the ISO also followed the steps in the establishment of one of the international standards for fits and tolerances (Yang 2010).

7.7.3.2 Geometric Dimensioning and Tolerancing

It was much later for the creation of geometric dimensioning and tolerancing.

In the 19th century, accuracy was limited to dimension; tolerance and fit were the two main concepts. People did not realize yet the importance of geometric accuracy. The application of limit gages and standards of tolerance greatly increased manufacturing accuracy, bringing the geometric accuracy into notice. However, if the geometric accuracy was achieved through tightening up the dimensional tolerance, it would lead to more complicated manufacturing processes and increase dramatically the manufacturing cost. On the other hand, with the improvement of machining accuracy, machine tools gained some capacity in controlling the geometric accuracy. Then the concept of geometric tolerance came into existence, greatly releasing the unnecessarily high requirement on dimensional tolerances (Wang and Tang 1991).

The first application of geometric accuracy on drawings was in 1938, and credited to an Englishman, Stanley Parker (Parker 1940). It was much later that geometric tolerance was developed into national standards in Britain and the U. S.

7.7.3.3 Machining Errors

Errors in machine tools are the main source of errors in the workpiece. Thus, to improve machining accuracy, the first consideration is to improve accuracy of the machine tool.

Cutting force and cutting heat are two important factors in machining metals, causing deformations to the work pieces under machining.

Many problems of machining accuracy raised from machining production. Some less theoretical ones were solved by practical engineers. Some others were brought to researchers at institutions and universities. As A. Sokolovsky stated in his book: "*the theory of machining accuracy came into being in the need of solving real production problems.*"

Soviet scholars made great contributions to the establishment of the theory of machining accuracy (Соколовский 1947; КАК 1951). From the end of WWII to the 1960s, some Soviet scholars already studied machining processes using the method of probability and statistics (Колкер 1976).

7.7.3.4 Vibration in Machining

High machining speed improves productivity. In addition, high machining speed is favorable for machining thin walled parts. However, high machining speed causes severe vibration, especially when the workpiece-tool system has inadequate rigidity, such as with relatively long cutter and/or thin-walled workpiece. Vibration has obvious detrimental effects, such as causing noise, surface quality deterioration, and tool damage. This dilemma in fact limited the adoption of high machining speed.

Frederick Taylor was the pioneer in the study of machining vibration. As he pointed out in his paper that machining vibration problem was the most intractable and the least understood by mechanical engineers (Taylor 1906). This assertion is still not completely obsolete today. Systematic investigation on machining vibration occurred during the period between the late 1940s and 1960s (see Sect. 12.3.6).

Although vibration can be modeled and simulated, vibration control in practice is a much more challenging problem.

The mechanism of machining vibration and its characteristics were not fully understood until the first half of the 20th century. In practice, the following measures were often followed to control machining vibration:

- increasing the rigidity of the workpiece-tool-machine system as far as possible;
- choosing cutting tools which excite less vibration;
- choosing proper cutting speed, and tool parameters, such as tool angles and size, to make the exciting frequency away from the natural frequencies of the system.

In real production, the cutting speed and various parameters were usually chosen based on the traditional trial and error. The effect of each individual parameter, including cutting depth, tool path, workpiece layout and cutter geometry, was obtained through experiments. However, these empirical methods gained in one factory may not apply to the others. If the problem was too complicated and needed theoretical support, experts stepped in to diagnose through measurement and calculation. Then the spindle speed and tool parameters were modified accordingly.

Linear vibration theory could not solve the problem of machining vibration well. Machining vibration is essentially a self-excited vibration, which is obviously nonlinear. Research on self-excited vibration of machine tools was not started until the 1940s. Thus, it is reasonable to say that analysis of machining vibration was not on the right track yet during the upper half of the 20th century.

7.8 Evolution of Discipline in Modern Time

It has been about 200 years since the mechanical engineering became an discipline. Since then, the scope of mechanical engineering has been greatly expanded, with ever rich contents covering a group of subjects. In this section, we briefly look back the development of the mechanical discipline; we believe this is helpful to predict where the discipline will go in the future.

A historian on higher education in the U.S., Walter Metzger, once summarized in 1987 subject development of the U.S. higher education during the 19 century up to the early 20 century. He concluded the following 4 modes: (1) subject parturition, (2) subject signification, (3) subject dispersion and (4) subject affiliation (Metzger 1987).

Taking reference to Metzger's classification, the authors categorize the evolution of mechanical engineering into the following 4 different modes: (1) subject parturition, (2) subject advancing, (3) subject extension, and (4) subject intercrossing.

During the two Industrial Revolutions, the mechanical engineering mainly experienced subject parturition and subject advancing.

7.8.1 Subject Parturition

The subject parturition here means the process of a discipline first developed in a mother subject and finally separated from it.

Foe a long time after the start of the Industrial Revolution in Britain, engineering was divided into civil engineering and military engineering. At that time, mechanical and civil engineers made up the largest part of the British Professional Society of Civil Engineers. With the rapid growth of machine building industry in Britain, more and more mechanical engineers appeared. As a result, the Institution of Mechanical Engineers was split from the civil engineering society, gaining independency in 1847.

Since then, civil engineering has been used to describe the discipline that deals with the design, construction, and maintenance of the physical and naturally built environment, including roads, bridges, canals, dams, airports, sewerage systems, pipelines and railways. It might be a surprise to think that we, mechanical engineers, used to be in the same family with civil engineers.

The first sub-discipline formed in mechanical engineering is the theory of mechanism. Although human had already used mechanism for thousands of years before, no systematic theory was formed. L. da Vinci and J. Watt did not contribute to a theory either despite their revolutionary inventions. Before the Industrial Revolution, L. Euler and G. Mozzi began to look into the theory of gear profile and screw theory. During the 1820s and 1830s, scholars of the French school of theoretical kinematics started works on instantaneous center and motion trajectory. These works, however, were isolated and scattered, far from systematic. In addition the work was mainly conducted by mathematicians as part of research in applied mathematics. The offering of mechanical courses in the École Polytechnique attracted more attention, leading to the kinematics (of mechanism) recognized as a sub-discipline.

Obviously mechanism theory was born from applied mathematics. In 1861, the publication of the book by F. Reuleaux, the Constructor, marked the birth of machine design, the other branch of mechanical engineering.

7.8.2 Subject Advancing

Subject advancing means that the knowledge in a subject is greatly expanded and grown through absorbing knowledge from other scientific and technological subjects, leading to the birth of new sub-subjects.

Subject advancing is differentiated from subject parturition in that the new subject created from subject advancing is still a branch of the original subject, while in the subject parturition an independent subject is created.

The subject of technology and process of machine manufacturing came into being through subject advancing.

For a long time, knowledge of machine manufacturing existed in workshops as business secret in the form of personal experience, personal skills and special process etc. The knowledge was handed down from generation to generation through apprenticeship without documents like papers or textbooks, which we are all familiar with today. This conservative practice was followed in Britain at the initial development of machine building. However, the situation was finally changed after the establishment of higher education in engineering in France, Germany, the U.S. and Russia.

A. Соколовский, a Soviet scholar, clearly stated the evolution process of machine manufacturing technology and process from individual practical experience to a systematic subject (see Sect. 7.7.1).

In forming the subject of technology and process of machine building, large amount of knowledge in mathematics and physics was absorbed. For example, probabilistic theory was incorporated into the theory of machining accuracy; mechanics was used in theories of cutting forces, machining error, and machining vibration. In addition, physics was applied in the study on machining heat.

During the Second Industrial Revolution, mechanical transmission was developed into a subject through influx of knowledge from mathematics, mechanics and thermal dynamics.

With the knowledge from physics, chemistry, technology and process in non-traditional machining, such as chemical machining, thermal machining, and water jet machining etc., was formed. On the other hand, the advance in solid mechanics continuously upgrade strength analysis and theory of mechanical systems. After WWII, non-traditional machining and mechanical strength become two fast-growth subjects.

In addition to the fundamental sciences, technical knowledge also acts as a pushing force in the development of mechanical engineering. For example, hydraulic control and relay control appeared in the effort to achieve automation of manufacturing processes. Machine design also absorbed knowledge from the theory of creative thinking.

Subject parturition is the way for creation of the mechanical engineering and its two cornerstone subjects during the First Industrial Revolution. The afterward development and the formation of the many subjects have mainly taken the form of subject advancing. This development mode has been the main form after WWII.

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Chapter 8
Modern Higher Education in Mechanical Engineering

> *University autonomy, academic freedom, unity of teaching and scientific research.*
> —Wilhelm von Humboldt (founder of the Humboldt University of Berlin, 1767–1835)

Education has played a critical rule in the advance of mechanical technology and industry. It is the critical factor to train the talents and prepare the workforce, moving the profession and the industry forward.

Engineering education has been in continuous evolution, changing with the society which it embed in all the time. The mechanical engineering education is a part of the general engineering education, and closely related with the social development in the country. In view of this fact, the discussion in this chapter on the mechanical engineering education is mainly conducted in the context of general engineering education.

The discussion is cut off to the Modern times inclusive, without covering the contemporary development. This treatment is based on the following two considerations:

Some concepts and practice in the contemporary education, such as CDIO and creative education, are still in evolution; thus, the contemporary engineering education has not yet taken a clear shape.

History, being called history, is the iteration and evaluation of events happened in the past. A clear picture and objective judgement can only be obtained through looking-back. There is no exception for the two main components of this book, science and technology, and education. Two Chinese proverbs vividly describe these two components. The first goes as "growing a tree takes tens of years", and the second as "shaping man takes 100 years".

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8.1 Modern Engineering Education in 19th Century

The establishment of École Polytechnique (Paris) in 1794 marked the birth of modern engineering education. In 1806, it started to offer courses in mechanical engineering, symbolizing the beginning of modern mechanical engineering education. The time range of the development of mechanical engineering education in Modern times starts from this starting point, through the whole 19th century and ends in the later part of the 20th century, covering almost one and a half centuries.

During this period, the science, technology, and education centers of the world shifted several times. Each shift had its special economic, political and social reason behind, from which people nowadays can learn a lot. For this purpose, the emphasis of this chapter is placed on the reason causing the shifts, and the route which the shift took, rather than on the details in the education development.

8.1.1 Britain: Declining

8.1.1.1 Empirical Model: Apprenticeship

The Science Revolution happened in England where Newton created the classical mechanics theory. The science knowledge created during the revolution trickled down to the ever-wealthy citizens and ever-skillful craft workers, creating a favorable social and economic environment for inventions, such as J. Watt invention of the steam engine.

In the late 18th century, apprenticeship was the only way to learn mechanical skills. Skills were kept as secrets by business owners and individuals for competition purpose. Taking Britain as an example, H. Maudslay, the inventor of the metal cutting lathe, was once apprenticed by J. Bramah who invented the hydraulic press. More inventors, including R. Roberts, J. Whitworth and J. Nasmyth, once worked as apprentices at Maudslay's workshop. All these great talents were trained through apprenticeship without formal engineering education (McNeil 2002).

At that time, there was no formal technical education. The places for the craftsmen and working class to obtain science knowledge were very limited and scattered. These included public lectures, and various societies, such as the Working-class Societies, the Literary and Philosophical Societies and The Lunar Society etc. Watt was a member of the Lunar Society of Birmingham. However, real skills won't be taught on these educational occasions for consideration of competition. Engineering had not yet entered school's curriculum.

Seemingly, this status of technical education did not match the high industrial level of Britain in the Industrial Revolution. It might be considered as backward. However, other countries were even far behind the Britain in terms of technical education. For example, France did not have any school for mechanical engineering education; Germany and Italy were in the state of division, not being united countries yet; Russia was still a serfdom society.

To keep its supremacy in industry, Britain chose to limit the export of critical industrial equipment and devices, and the migration of skilled workers to other countries. This led to two consequences. First, some technical talents moved to the United States because of its freedom. These immigrants made important contribution to the development of mechanical industry in the States. Second, the continental European countries, such as France and Germany, were forced to develop their own technical education routes.

As Dowson (1998) pointed out, "*It is a curious and interesting fact, much discussed by historians, that while England was establishing a dominant position in practical engineering, the foundations for studies in engineering science were being laid across the English Channel in continental Europe*".

8.1.1.2 Britain's Decline

Britain kept being the world leader in science and technology before 1870. During the 100 years before 1870, the main development of industry and transportation in Europe was originated from Britain. However, the turning point came in 1875 when the growth of iron and other industrial products produced in Britain began to decline. Accompanying the Britain's declining was the rapid catching up of other countries. This fact was clearly demonstrated by the two World Expos. In the Great Exhibition of 1851 in London Britain took most of the medals for manufactured and industrial products. When it came to the International Exposition of 1867 in Paris, Britain only won 12 awards. In addition to the changes in industry, technical education schools began to be established in the continental Europe. Engineers with formal education gradually displaced those trained through apprenticeship (Singer et al. 1958).

Lyon Playfair, an assessor at both exhibitions, wrote a letter published in a journal reflecting his observations at the Paris Exhibition as below (Dowson 1998):

> …opinion prevailed that our country had shown little inventiveness and made little progress in the peaceful arts of industry – – The one cause upon which there was unanimity of conviction is that France, Prussia, Austria, Belgium and Switzerland possess good systems of industrial education for the masters and managers of factories and workshops, and that England possesses none.

This letter caused great sensation in Britain. Responding to the letter, the Britain government established a select committee in 1867 to inquire into the state of scientific education in the country. The committee looked into the provisions for giving instruction in theoretical and applied science to the industrial classes and made a comparison with other country's systems. A report was formed in 1868 which became the turning point in Britain's education. However, the reform was painfully slow at the beginning because of the fighting between the supporting and opposing sides. Undoubtedly, competition from other countries was an important driving force to this transformation.

Although Britain realized already its education fell behind the continental European countries and measures were taken for improving, technical education was still defined in the Technical Instruction Act 1889 as "*shall mean instruction in the principles of science and art applicable to industries, and in the application of special branches of science and art to specific industries or employment*" (Evans 2009). In this definition, it did not include "teaching the practice of any trade or industry or employment". Consequently, technical education in Britain split into two parts. Training in workshop was resided on the industrial employer, while the complementary theoretical instruction was given in educational institutions (Williams et al. 1978). The English didn't want to give up the practice to keep technical skills as business secret. This may serve as a sign of the long-standing stereotype of "conservative English".

After entering the 20th century, Britain experienced another period of rapid development in industry (Singer et al. 1958). The zigzag development of technical education in Britain left a lot of retrospect to us.

8.1.2 France: Pioneer of Modern Engineering Education

As stated before, other countries in continental Europe, France the first, and followed by Germany, were forced to establish their own technical education system under the Britain's limit on exporting critical industrial products and emigration of skilled workers.

8.1.2.1 Birth of Higher Engineering Education

In the 18th century, France already established a number of technical institutions offering courses in civil, mining, military and marine (Green 1995). After the Revolution, the government of Napoléon Bonaparte created a series of technical schools, including the famous École Polytechnique (Fig. 8.1), which soon became the foremost technical school in Europe.

The creation of École Polytechnique marked the starting of modern higher education in engineering. As a landmark university in the history, its teaching was organized in a way which was substantially different from the traditional methods (Timoshenko 1953; Wu 2000).

Teaching was carried out in the form of lectures to large group of students, dramatically different from the traditional way in apprenticeship.

Before entering specific engineering disciplines, all students were required to learn courses in fundamental sciences, such as mathematics, mechanics, physics and chemistry, in the first 2 years. Engineering courses were taken from the 3rd year. This drew a line between common courses in general science and engineering

Fig. 8.1 École Polytechnique

courses of specific disciplines. Lectures to large group of students also required textbooks. Thus, some professors organized their lecture notes into textbooks for publication. These books were well read with substantial influence on the relevant disciplines.

These practices are common in present universities, however, were ground breaking at that time.

École Polytechnique was also a pioneer in the education of mechanical engineering. Knowledge in machine design was handed down in Britain through apprenticeship. École Polytechnique, under the advocating of G. Monge, was the first in history to cover mechanism theory in the curriculum, pushing the mechanism theory to be recognized as an independent subject (see Sect. 7.1).

However, the course consisted only of 30 h lecture to 1850, far from establishing the complete frame of the mechanical engineering education. This task was later implemented by Germany.

8.1.2.2 First Wave in Modern Engineering Education

École Polytechnique created the first wave of engineering education in Europe and North America.

Following the model of École Polytechnique, technical schools of the same type were established across continental Europe, the U.S. and Russia. Examples include the Vienna Polytechnic Institute (1815) and the Swiss Federal Institute of Technology at Zurich (1855). These newly established technical schools, following the steps of École Polytechnique, placed engineering on the foundation of science and mathematics. The British model based on empiricism was obviously given up (Wall 2010). Some schools went even further, directly using the syllabus of École Polytechnique. The French model of engineering education had apparent influence on some technical schools in Germany before the 1830s, those in Berlin and

Munich in particular. To the end of the 19th century, a series of polytechniques were established in France, among which École Polytechnique was the flagship.

In Britain, however, engineering entered the curriculum of universities pretty late and slowly. In 1840, the University of Glasgow in Scotland was the first to teach engineering among the British universities, then followed by Cambridge University in 1875.

8.1.3 Germany: Creation of Modern University and Leader in Mechanical Engineering

When the Industrial Revolution started in Britain, Germany was still in a state of division, consisting of numerous German States, among which Prussia and Austria were the largest. Compared with Britain and France, Germany, even Prussia and Austria, was poor and less developed in industry. However, under the influence of Enlightenment, Germany finally got on the track, although late, that Britain and France took already: abolishing serfdom, freeing peasants from the obligation of personal services to the lord, reforming agriculture and developing mining and manufacturing. At the same time, a system of technical education was to be established under the initiation of some figures with far vision.

8.1.3.1 Wilhelm von Humboldt

In 1810 Wilhelm von Humboldt (Fig. 8.2), a German reformer, founded the University of Berlin (now the Humboldt University of Berlin). He also set up the basic principles for this new university, including corporate autonomy for

Fig. 8.2 W. Humboldt

universities, freedom of study for students and a unity in teaching and research. These principles have long-lasting profound influence on the development of higher education in Europe and the world. Thus, University of Berlin has been widely called "the mother of all modern universities".

The principle of unity of teaching and research profoundly changed the function of university. The University of Berlin is also a pioneer in modern postgraduate education.

The creation of University of Berlin, along with the widely adoption of the Humboldtian model, laid the foundation for the rapid progress of Germany in science and technology. This also contributed to the unification of the country, making Germany a main player of the Second Industrial Revolution. To the middle 19th century, Germany already surpassed Britain, becoming the center of science and technology in Europe. Among the 42 Nobel recipients of the world before WWI, 14 were from Germany. 8 of them came from the University of Berlin. Germany experienced its glorious time partially attribute to its university system.

8.1.3.2 Higher Engineering Education in German

Humboldt did not advocate teaching specialized knowledge, or engineering knowledge, in university. What he proposed is the unification of teaching and research of pure science. However, at that time the growth of industry in Germany created an ever-urgent need for more engineering and technological talents.

Following the model of École Polytechnique, some technical schools were established in Germany during the 1820s and 1830s. The first one was the Karlsruhe Institute of technology established in 1825 (Klimenko 2017).

The curriculum and duration of these technical schools at early days indicated that they were initially created as middle technical school (Gewerbeinstitut), not higher education institutions. At the beginning, they only offered fundamental courses of mathematics and science in secondary level and some technical courses. Later on they were developed into 'technische hochschule' during 1865–1885, leaving the lower and middle level education to public schools (Ahlström 1978). To the end of the 19th century, nine such schools, also called technische universität, including Aachen, Karlsruhe, Berlin and some others, were established.

The information on these school's websites naturally traced back to their polytechnical starts; however, one should be clear that the initial polytechnic schools did not meet the standard of "higher education".

To the later-half of the 19th century, all the industrialized countries established their engineering education systems following the French and German models.

8.1.3.3 Redtenbacher and German Model

The French École Polytechnique model obviously influenced the initial technical education of Germany. However, German, as a nation with long and profound cultural tradition and science potential, was bound to build its own system. The development of industrial technologies in Germany has been well featured with the inter-dependency between science and technology. Technologies build on science; while science supports technologies. The Germany has kept a long tradition of unifying fundamental science and practical engineering in its education system. When it comes to the education in mechanical engineering, the German model took shape in the middle of the 19th century, lasting through the whole 19th century to the 20th century. The formation of the German model was greatly attributed to an eminent educator, Ferdinand Redtenbacher who is widely accepted as the founder of the German Model.

Redtenbacher (Fig. 8.3), a graduate from the Polytechnic School in Vienna, came to the Polytechnic School in Karlsruhe (Fig. 8.4) in 1840 first as a professor of mechanical engineering, later the director (Wauer et al. 2009).

The situation in Germany then was not encouraging. Machines in the factories were mainly purchased from Britain. Only minor modification could be made. Britain, the mother land of the machine building industry, accumulated abundant capital due to colonial and slave trade (Wauer et al. 2009, 1608), showing no interest in institutional engineering education.

In the 1830s, no courses in mechanical engineering was yet offered and practice was mainly taught in workshops. In addition, courses in fundamental science were totally disconnected from practice. Students in mechanical engineering and engineering chemistry took the same fundamental science courses.

Fig. 8.3 F. Redtenbacher

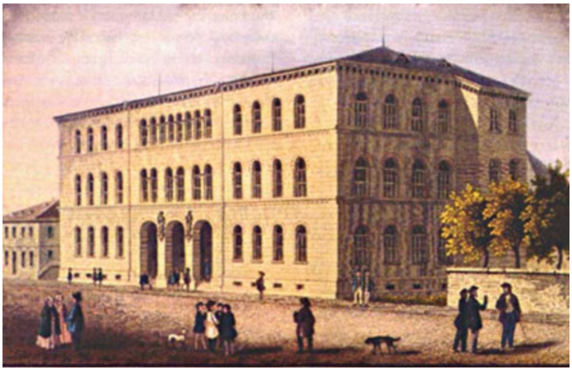

Fig. 8.4 Karlsruhe Polytechnische Schule, 1850

To become a mechanical engineer, students generally started from practice, understanding the mechanisms, reading manuals of machines and examining models for machines and mechanisms. Dimensions of machines were often determined based on designer's experience or through trial-and-error. There was no theory for strength calculation.

Redtenbacher determined to change the situation. He once made the following statement:

> We on the continent, have neither the financial power nor the extent of experience in the design of all the specialities to follow the purely empirical way only and therefore, we are obliged to compensate or to support the missing money and the restricted experience by intellectual power and scientific insight. (Wauer et al. 2009)

His answer was "*to consult the sciences*". In another word, Redtenbacher wanted to place mechanical engineering on the foundation of not only practical experience, but also theories of mechanics and mathematics.

Redtenbacher obtained his engineering training of the École Polytechnique style in Vienna where emphasis was put on fundamental science. Soon he realized that the theories in the general scientific books were hard to be applied in practice. On the other hand, practical engineers, who inherited the Britain empiricism tradition, did not like theory. In view of this, he dedicated his life time trying to build a bridge between theory and practice.

In 1846, the chemical and mechanical programs in Karlsruhe were separated, becoming two independent programs. Both programs gained world-wide reputation in later years.

In 1857, Redtenbacher was appointed as the director of the school, quickly becoming a renowned professor. This provided him a platform to implement his philosophy in engineering education.

Students in the mechanical program at Karlsruhe started as apprentices in factory, then switched to study theories of mathematics and mechanics. However, theories were taught in different ways from the École Polytechnique pattern as he put "*at a polytechnic school, scientific speculations that are not adequate for any application and are only valuable for mental exercise are not allowed to appear*".

His education philosophy and practice were widely spread through his teaching, books and administration, and were adopted all over the world.

The technical universities in Germany formed their unique feature through placing engineering on solid theoretical foundation of science. This German model, combining theory and practice tightly, was adopted by many other countries, This also contributed to the success of Germany in mechanical technologies and the machine building industry during the 19th and 20th centuries.

The Karlsruhe became one of the three best German universities in the 19th century. A long list of eminent graduates came from this school, including F. Reuleaux, the founder of the German school in mechanism theory, K. Benz, one of the inventors of automobile, and many leading members in the machine industry.

The French offered the first course of mechanism theory; however, the complete curriculum of machine design was formed by the German. This was mainly credited to one of Redtenbacher's student, F. Reuleaux.

8.1.4 U.S.: Rising in Engineering Education

8.1.4.1 Start of Engineering Education in U.S.

At the end of the 18th century, American invented the model of interchangeable production, which required high-precision machine tools and measuring tools. To the time of 1820s and 1830s, the U.S. already got to the forefront of the world in machine tools. The spirit of freedom and competition provided enormous opportunities for those who liked adventure and hard-working, attracting many European inventors to the new land. As a result, the world center of mechanical technology shifted from Britain to the U.S.

With the ever-increase of complexity in invention, engineering education was brought front.

The first school in the United States to offer engineering education was the Military Academy at West Point in 1802, followed by another military academy in Norwich (Vermont), later known as Norwich University, in 1820 (Issapour and Sheppard 2015). Rensselaer Polytechnic Institute also started engineering education in 1824. Education in mechanical engineering has historically been based on a strong foundation in mathematics and science (CUP 2000). Although many outstanding engineering schools appeared in the U.S., Rensselaer Polytechnic Institute is still well recognized in keeping strong practice in its engineering program.

After 1840, some elite universities, such as Yale and Harvard which used to look down upon engineering education, started offering classes in civil and mechanical engineering.

8.1.4.2 Land-Grant Colleges

A revolutionary boost of engineering education in the U.S. happened in 1862 when president, Abraham Lincoln, signed the Morrill Act proposed by the Representative from Vermont named Justin Smith Morrill (1810–1898), in response to the technological need of rapid agricultural development. This gave each state 30,000 acres of public land for each Senator and Representative. The land was then to be sold and the money from the sale of the land was to be used to support the colleges in each of the states. The Morrill Acts became a major pushing force to the establishment of an engineering educational system in the U.S. (Botkin et al. 1982).

The Act fundamentally changed the picture of American universities. Old universities only offered education in liberal arts; while these newly founded institutions under the Acts put more emphases on practical education with an aim to serve the society and economy. These schools, including MIT (1865), University of California at Berkeley (1873), Johns Hopkins University (1876) etc., were created with the market principle of "survival of the fittest". The second Morrill Act passed in 1890. The Morris Acts gave American engineering education special benefit over its European counterparts from the very starting point, placing American engineering education on a fast track (Fig. 8.5).

With the boost of engineering education, the need for instructors became an urgent issue which created the first wave of postgraduate education in the U.S.

8.1.4.3 William Rogers and MIT

William Barton Rogers (Fig. 8.6) was born into a family with good educational tradition in Philadelphia (Rogers 1896). While William held his faculty position at the University of Virginia in the 1840s he frequently traveled north to the New

Fig. 8.5 A postage stamp to commemorate land-grant colleges

England area which was the highest-developed area in America. Since 1846, he started effort to create a new university dedicated to technical and scientific education. After 16 year's hard-working and persistence, his dream came true thanks to the Morrill Act.

MIT was created in 1865 with a humble start as a small private school with an enrolment of only 15 students. However, it has now become one of the most prominent research universities in the world (Fig. 8.7). This great achievement has a lot to do with its first president, William Rogers (Angulo 2009).

MIT was neighbored with the elite, Harvard University. To grow outside the Harvard's shadow, MIT started with more practical programs, which were in urgent need by the society and economy, including civil, mechanical and mining engineering. Unsurprisingly this caused strong criticism from old universities, Harvard in particular. Harvard attempted to merge MIT many times; however, MIT rebuffed all of them (Rogers 1896).

As the first president of MIT, Rogers put special emphasis on combination of theory and application, recruited talents worldwide and appointed them to proper position. In addition, he respected professor's freedom in teaching and research. More specifically, he enhanced practical teaching, invested heavily in laboratory and built the first machine shop in American universities for practical teaching (inspired by Russia system). After 5 year effort, MIT squeezed into the top technical universities in the U.S. Its mechanical engineering has occupied the first place in the U.S. for many years.

Rogers' first presidency term lasted until 1870, meanwhile he gained very high reputation within MIT due to his excellent administration. In 1878 when MIT was facing severe financial challenges, he was appointed the second term at the age of 74. During this term, he worked to choose a successor given his high age and health condition. Unfortunately on one day of May in 1882, Rogers died after collapsing

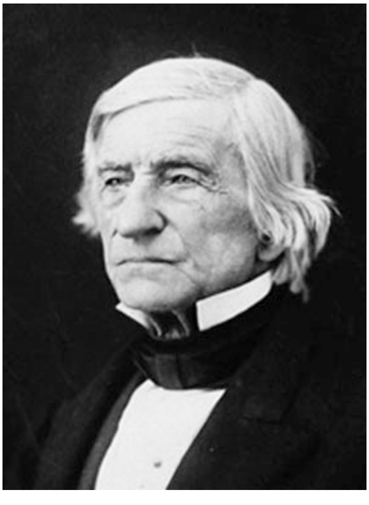

Fig. 8.6 W. Rogers

Fig. 8.7 Tradition and fashion of MIT

during a speech at commencement. He dedicated almost his life time to MIT, even the last moment of his life being at the post serving MIT.

In the Great Exhibition of London in 1851, the U.S. was still not in a position comparable to Europe. However, to the time of 1876 when the Centennial International Exhibition was hold in Philadelphia, U.S. already became a power nobody could overlooked. 10 years later, the U.S. completely displaced the UK, becoming the strongest economy in the world.

Entering the 20th century, new factors in favor of the development of science, technology and education in America appeared, pushing the U.S. to the center of the world in almost all aspects, such as science, technology and education, after WWII.

A long list of new technologies and scientific subjects were born in MIT, to name a few, numerical controlled machine tools, CAD/CAM, computer graphics, electro-hydraulic servo-mechanism, random vibration etc.

8.2 Mechanical Engineering Education in First Half of 20th Century

8.2.1 Soviet Union: Extremely Narrow Specialized Education

The world center of institutional education in mechanical engineering was first born in France, shifted first to Germany and then to the U.S. Soviet Union had never been in the center position in terms of mechanical engineering education. However, the Soviet model in engineering education is quite different from the American model, and influenced the engineering education in many countries, including China.

8.2.1.1 Early Development of Engineering Education in Russia

Peter I (Пётр I, 1672–1725) was a Russian czar best known for his extensive reforms and attempt to establish Russia as a great power. Following the main European countries, he strongly pushed the westernization of Russia and also established the earliest university in Russian history.

During the early 3 decades of 19th century, several engineering schools, including Moscow Craft School, were created in Russia. This school was later reorganized into Imperial Moscow Technical School, and evolved finally into the current Bauman Moscow State Technical University, which was in the leading position in the Soviet engineering education (Fig. 8.8).

Russia was completed defeated in the Crimean War (1853–1856), leading to the hard realization of its inferiority in military practices and weapons. The Tsar Alexander II determined to reform his country starting with abolition of the serfdom. A series of technical universities were established on the basis of the engineering schools created before the 1830s.

The development of engineering education in Russia was roughly in parallel in time line to that in Germany.

8.2.1.2 Engineering Education in Soviet Union

After the Bolsheviks took power, higher engineering education in Soviet Union experienced fast growing to meet the demand to develop its industry. Here in this book, we focus on the system and philosophy of the higher engineering education in Soviet Union, rather than detailed data.

Fig. 8.8 Today's Bauman University

Soviet Union established a highly centralized, planned economy and political system. Correspondingly, almost every aspects of higher education, such as educational policies, curriculum and the length of study, were under the control of government through regulations or laws; thus, everything was seemingly well planned with good consistency (Bu 1985). This status matched the highly centralized economy in the country.

To adapt to the wholly government-controlled economy, very narrow specialization was introduced in engineering education. Taking the mechanical-related programs as an example, almost each industrial ministry (or department) in the government had a matching specialization. There were 43 specialization in 1956. To the year of 1975 and 1982, the number increased to 47 and 54 respectively (RIHE 1987). There were even specialization like film equipment, boiler manufacturing, and helicopter manufacturing etc.

The basic engineering degree, diploma, generally required 5 year study (Balzer 1993). The number of instruction hours was very high with an average of 4700 h for a 5 year program. This narrow specialization system, undoubtedly, had its advantages. A graduate from such a system could directly take the duty of a junior engineer immediately if assigned to a matching factory. However, the shortcoming was that the very narrow, specialized knowledge of the students made it very difficult for the students to adapt to the rapidly changing, and comprehensive technologies. It was very hard as well to change a job after graduation. Actually the Soviet government realized the issues of its system, and proposed in 1986 to solve the two most outstanding problems, too narrow specialization and too heavy work-load (An 2006). Now only a few of programs in mechanical engineering are left in Bauman Moscow State Technical University.

In fact, France and Germany also had specialization under major in engineering, which is obviously different from the American general education model. In Germany, a graduate of technical university could be directly awarded an engineer certificate. Obviously, the German system can be regarded as specialized education model. Soviet pushed the specialized model to an extreme.

Due to the extremely narrow specialization, the specialized subjects could therefore be covered with more detail and in-depths. Thus, Soviet made special contribution in development of specialized subject courses relevant to machining building. At the early days of Soviet Union, metal processing and technology of machine building were already in the curriculum. To the end of the 1920s when the first five year plan was started, these two courses were split into machine tools, cutting tools, tolerances and measurements and organization of production (Соколовский 1947; De Witt 1955).

8.2.2 Jewish Refugee Wave

Adolf Hitler came into power in Germany in 1933; the totalitarian policies of the Nazi Party quickly ruined the German status as the world center of science and culture. Hitler immediately took steps expelling Jewish scientists and professors out of universities, throwing away the "Lern- und Lehrfreiheit" (Academic freedom), which had been kept as the spirit of German universities since W. Humboldt (Duggan and Drury 1948).

The Jews under the Nazi political and racial persecution escaped from Germany, Italy, and German-occupied Europe, forming an unprecedented wave of refugee. Most of the refugees were well trained in a field or college educated, and many were brilliant scientists, thinkers, professors, and engineers. A large number of those "knowledge" refugees moved to and finally settled down in the U.S. (Li 2013).

The record from the Immigration and Naturalization Service of the U.S. indicated that about 22,000–25,000 refugee scientists arrived in the U.S. during 1933–1944 (Duggan and Drury 1948). Another statistics published in 1969 analyzed 300 most outstanding refugee scientists, and concluded that 79% of the scientist, or 238 out of the 300, were Jewish from Germany or German controlled countries (Li 2013). These refugee scientists laid the foundation for many new technologies and subjects for the U.S.

Here, we only name a few as examples.

A. Einstein, the German-born Jewish theoretical physicist, was a professor at the Berlin Academy of Sciences. He was visiting the U.S. when Adolf Hitler came to power in 1933 and settled there without going back to Germany. He became American citizen in 1940.

E. Fermi was an Italian-American physicist. After receiving the Nobel Prize in Stockholm in 1938, he headed to New York with his family without going back to Italy, in order to escape the new Italian racial laws that affected his Jewish wife.

R. Mises was a Jewish scientist and mathematician working on mechanical areas and mechanics. He held a professor position in the University of Berlin before moving to Turkey in 1933. Later in 1939, he continued to move to the U.S.

F. Freudenstein was the "Father of Modern Kinematics", and the founder of the American school of mechanism theory. He was born into a Jewish family in Frankfurt, and fled the Nazi Germany with his family at the age of 10. In 1942, at the age of 16, he with his mother and two sisters moved permanently to the U.S.

Von Kármán, a Hungarian-American mathematician, took action even before the refugee wave. He, apprehensive about the developments in Europe, accepted the invitation from California Institute of Technology to take the director position at the Guggenheim Aeronautical Laboratory.

The loss of many prominent scientists left long-lasting damage to the German higher education system. In the top 200 QS World University Rankings 2011, Heidelberg University, being the best in Germany, took the 53 position. In the 2013 ranking, München Technological University took the 50 position.

8.2.3 *U.S.: New World Center of Science, Technology and Engineering Education*

Table 8.1 gives the statistics of the Nobel recipients in physics, chemistry, physiology and medicine from Europe and the U.S. in 3 time periods (Li 2015).

(1) During the early 40 years after the establishment of the Nobel Prize, European countries, mainly the UK, Germany and France, received the most prizes. However, the U.S. succeeded Europe after 1951 and has been in the leading position up to now.
(2) The Soviet Union came into existence in 1922 and collapsed in 1991. During the 69 years, it only got 8 prizes, forming a dramatic contrast with the 158 that the U.S. grabbed during the same period.

The apparent success of the U.S. in attracting prominent scientists and Nobel Prizes recipients can be summarizes as below.

(1) The U.S. government and society were in a consensus that scientific research, basic research in particular, was critical to the health, prosperity, and security of the country and its society. Early in 1863, the National Academy of Sciences was established under the approval of the Senate, the House of Representatives, and President Abraham Lincoln. On the eve of the victory of WWII, President Franklin Roosevelt (1882–1945) wrote a letter in November 1944 to the director of the Office of Scientific Research and Development requesting for recommendations to stimulate the peace time economy through application of the scientific knowledge obtained through research for war purpose, and to maintain the level of scientific research through discovering and developing scientific talent in American youth (Bush 1945).

Table 8.1 A statistics of Nobelist

Time period	Europe	U.S.
1901–1939	103	13
1943–1950	15	15
1951–2012	119	225

(2) The spirit of freedom, and stable, peaceful and safe society have attracted immigrants to the U.S. since its independence. Large number of scientists, engineers and other talents came to the U.S. from Britain in the Industrial Revolution, from Soviet Union after the October Revolution, and from Germany and Italy during the Nazi time. These talents brought their knowledge, research projects, business plan and the European tradition in science and technology to the new land, greatly enhancing American power in science and technology. Even now young students from all over the world go to American universities to study almost all subjects, making an important reservoir of scientific and technological talents.

After WWII, the U.S. became the world leader in science, technology, and engineering education. Unsurprisingly, quite a large portion, if not the majority, of new findings and advance in theory, process and mechanical engineering were made by American scholars and engineers. Examples include theory of mechanism, robotics, computer graphics, CAD/CAM, NC machine tools, machining centers, finite element method, reliability design, rapid prototype, 3D printing, FMS, CIMS, and web-based collaborative design etc. The most important contributions to these progresses were made by universities, the research-intensive universities in particular, among which MIT has been always the leader.

In the 2014 world university ranking, 23 among the top 30 universities were in the U.S. The top 4, including Harvard, MIT, UC Berkeley and Stanford, were all American universities.

8.3 Two Models of Engineering Education

8.3.1 General Education and Specialized Education

Two typical models exist in modern engineering education, namely general education and specialized education.

The primary goal of general education is to lay foundation for further technical training or graduate study through providing broad, yet focused, survey of courses. If students join the work force after graduation, specialized training at work is needed. This educational model emphasizes on broad fundamental subjects as well as their development and crossover, but is short of practical engineering training in the specialized field. America is a representative of the general education model. In fact, the general education model has very rich contents, being a result of long time evolution. The above statement is highly condensed with regard to engineering education.

Specialized education provides training in specialized area on top of the fundamental theories. The students are supposed to be able to work immediately on a job of the trained area. Time has to be allotted to practical training and specialized courses; thus, two consequences are inevitable. One is the study load for the students is relatively heavier due to the squeezing in of the specialized subjects. The other is the more specialized courses inevitably weaken fundamental courses. The systems in France and Germany belong to the specialized education, while the Soviet system is an extreme case of this model. (Xiang 2004, Li 1990).

8.3.2 *Case Study and Comparison*

Table 8.2 gives the data from two American universities and one Chinese university of the curriculum in mechanical engineering program (Liu and Chen 2010). China adopted the narrow specialization of the Soviet model in the past, while in recent years measures have been taken to absorb some American practices. In essence, however, the Chinese system was still in the category of specialized education. In this table, the courses are roughly divided into 7 groups as humanity and social science, general science, general engineering, specialized engineering, elective specialized engineering, course and thesis projects, and free elective. From this table, we can clearly see the following: (1) In the Chinese curriculum, the weight of general science and general engineering courses is obviously less than American, (2) the sum of specialized courses (prescribed and elective), course projects and thesis project makes up 34.5% of the total in the Chinese curriculum, while this number in the American universities is less than 20%, (3) the weight of courses in humanity and social science courses in the Chinese curriculum, although quite a large portion of which is politics-related, is much lower than that in the Wisconsin. The data in this table clearly indicates the difference between the general education and the specialized education.

Table 8.2 Curriculum of mechanical engineering from 3 universities of America and China

	Wisconsin U.			Carnegie Mellon U.			Dalian U. of Tech.		
	Credit hours	Percentage		Credit hours	Percentage		Credit hours	Percentage	
Humanity and social science	34	25.4		24	18.9		40.5	23.5	
General science	32	23.9	55.2	32	25.2	54.3	33.5	19.4	42
General engineering	42	31.3		37	29.1		39	22.6	
Specialized eng.	14	10.4	19.3	5	3.9	14.9	22.5	13	34.5
Elective specialized eng.	9	6.7		6	4.7		16.5	9.6	
Course/thesis projects	3	2.2		8	6.3		20.5	11.9	
Elective	0	0		15	11.8		0	0	
Total	134			127			172.5		

Note The credit hours of American universities are transformed from total instruction hours

Table 8.3 Curriculum for mechanical engineering program of Moscow State University of Technology "STANKIN"

Courses	Hours	Courses	Hours
Calculus, computer application in technology and economy	509	Lifting machines	34
Physics, chemistry	440	Machine tools (structure, hydraulic, pneumatic and electrical device)	186
Descriptive geometry and engineering drawing	247		
Theoretical mechanics, strength of materials	401	Metal cutting theory and cutting tools	305
Mechanism theory, machine components	213	Machine building technology, design of fixtures	286
Interchangeability, standardization and measurement	54	Introduction to automation	56
Metal processing, materials	332	Automatic machine tool and fixtures	140
Thermodynamics, hydraulics and hydraulic transmission	155	Automation in industrial process	70
Electrical and electronic engineering	193	Principle of art design	28
Political and humanity courses	658	Economy, organization and management of industry	154
Physical education	140	Other courses	172
Total	3342	Total	1431
Total	4773	Length of training: 5.5 years	

Table 8.3 gives the curriculum for mechanical engineering program of Moscow State University of Technology "STANKIN" (FESEG 1979). It is clearly seen that the specialized engineering courses make up 30% of the total class hours, while the general science courses only take 20%. When it comes to the humanity and social science courses, mainly political courses actually, only 13.8% is assigned. This makes a sharp contrast with the American universities.

Germany is not a communist country; however, all its universities are public. It has highly developed free market economy, but nationally consistent curricula are adopted. This differs from America obviously, being more similar to Russia (Soviet Union). Table 8.4 gives an example of German curriculum for undergraduate in the specialization of machine design (Feng 1989). The typical length of study theoretically lies in between 4.5 and 5 years. However, most students need 6 plus years to complete given the heavy study load. Upon graduation, students are awarded the Diplom degree which is regarded as a qualifying degree for an engineer (Sato et al. 2008). Clearly, the German system, falling in the category of specialized education, is in between the American system and the Soviet one with regard to curriculum and studying load.

Table 8.4 Curriculum of machine design in a German university

Basic stage (2 years)					
Course	Lecture credits	Course	Lecture credits	Course	Lecture credits
Higher mathematics	12 (8)	Mechanics	12 (6)	Numerical analysis	4 (4)
Engineering materials	4 (4)	Technical design eng.	8 (10)	Production and manufacturing eng.	4 (0)
Electronic technology	4 (3)	Physics	4 (4)	Chemistry	2 (0)
Fundamental of mechanical design	2 (2)	Thermodynamics	4 (3)	Total	104
Note The figures in the brackets are the tutorial credits					
Professional stage (2.5–3 years): courses					
Core course		Restrained elective		Free elective	
Measurement and control technology	4	One general engineering course	4	One course in science and technology area	>4
Methodology of design	4	One course in manufacturing process	4	One course in technological area one course in humanity and social science	>4
Strength design	4	One specialized course	4		
Production technology	4	Total			>36
Professional stage (2.5–3 years): practices					
Measurement practice	4	Design practice	300 h	Lab experiment	4
Research work	500 h	Degree work	13 weeks	Industrial practice	13 weeks
Analysis practice	2	Total		10 credits + 800 h + 26 weeks	

Total credits during the whole study term
Each credit equals 16 h, 800 h are translated to 50 credits
The 26 weeks can be translated into 32.5 credits if 20 h is assumed in each week
Total >232.5 credits (or >3720 h)

8.3.3 Comparison of the Two Models

8.3.3.1 Evolution of the General Education Model in America

A presentation on the detailed evolution of the general education model in America requires a long paper; this is not the purpose of this book. In short, it is a result of the debate between the classical liberal education model and the more practical, career oriented specialized education model. The fighting between Harvard and

MIT is an example. With the development of economy and society, higher education in America became accessible to the general mass, not only the rich as it used to be. As such, the old literal education model focusing on literary works, philosophy, foreign languages, rhetoric, and logic showed inability to meet the societal need for more practical education preparing students for work upon graduation. However, if the specialized education was left to individual institutions without proper regulation, consistency could not be achieved. The general education model, formed after more than 100 year's evolution, stands in between the classical liberal education and the specialized education, stressing on the provision of broad fundamental scientific courses along with selective humanity and liberal courses. It combines the teaching of narrower specialized knowledge and the well-versed ability to think and solve problems (Xiang 2004). In summary, the general education model builds the specialized education on a broader liberal and humanity basis, better meeting the social and economic needs of America.

In the early days of America, business owners were mainly immigrants of technical talents and inventors from Europe, Britain in particular. They brought the long-standing apprenticeship tradition into America. Although apprenticeship went to an end later, the tradition to provide on-job training to employees has been well kept. The vibration course provided by Timoshenko to engineers in the Westinghouse Electric Company (discussed in the Sect. 7.3) and the creativity course in General Electric (to be discussed in Sect. 11.2) are good examples of this type of training. This practice fills the hole of practical training which the general education model is short of.

8.3.3.2 Difference in Broadness of Knowledge and Study Load

Major is a word with much broader sense in American universities where teaching is conducted on departmental bases (Li 1990). Normally there is no specialization under the department of mechanical engineering (termed major); however, more elective courses are available to the students. Thus, individual students have the freedom to form his/her knowledge stream through electives on the common base of prescribed and core courses.

In German universities, however, there are specializations under the department. For example, at the University of Stuttgart, product development and design, production technology, computer aided engineering, and MEMS and precocious instrumentation can be chosen under the departmental umbrella of mechanical engineering. In addition, machine design and machine building are separated (Feng 1989). In some other schools, you may find specializations in internal combustion engine, machine tools, turbines, as well as hydraulic machines. Generally 5–7 years are needed for students to complete the program with a degree of diplom which qualifies the students for engineers. It would be impossible to be qualified as engineer without the enhanced specialization under the department.

Soviet Union and China before the Reform and Opening went to extremely narrow specialization. Later China attempted to adopt the American system, clustering all mechanical engineering into one major named ‘mechanical design, manufacturing and automation’. Irrespective of the past adoption of the Soviet system or the newly inclination to the American’s, students in Chinese universities have little freedom in choosing courses.

In terms of class burden, the Soviet model is the heaviest, the American’s is the lightest, and the German’s in the middle.

8.3.3.3 Education with Broad Specialization: The German Model

The American model lays a solid foundation in general science as well as humanity and social science. With the support of a solid graduate education system, this model is favorable for training the leaders in academics and technology. Institutions in the specialized education system, research intensive universities in particular, should learn this from the American.

In most developing countries, engineers working directly in the industry are most needed. Thus, specialized education should be the right model. The failure of extremely narrow specialization of the Soviet system does not assume a failure of the specialized education model. Comparatively, the Germany system with broader specialization, lying in between the general American system and the narrow Soviet one, may be appropriate for most countries. Students in this system are heavily burdened with class, but qualification for engineers is obtained upon graduation. However, one issue for the German system is that it is not easy to have 6 years in a row completing the Bachelor and Master degrees (equivalence to the German Diploma).

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Chapter 9
Third Technological Revolution

> *The First Wave of change—the agricultural revolution—took thousands of years to play itself out. The Second Wave—the rise of industrial civilization—took a mere three hundred years. Today history is even more accelerative, and it is likely that the Third Wave will sweep across history and complete itself in a few decades.*
> —Alvin Toffler (American writer, 1928–2016): *The Third Wave*, 1980

After WWII, the Third Technological Revolution appeared in the horizon, which has been unprecedentedly influencing all aspects of human society.

The First and Second Technological Revolutions are both centered around power, while the third one is developed around information. Mechanical engineering, being backbone in the past two revolutions, was shifted aside and gave place to information, although it is still a corner stone in the economy.

In this chapter, we will discuss the scientific and social background forming the Third Technological Revolution as well as the main contents of this revolution.

9.1 Scientific Background

9.1.1 New Revolution in Physics

Since I. Newton established the theory of classical mechanics, modern science, such as mechanics, electromagnetics, chemistry and thermal dynamics, had made large progress to the end of the 19th century in about 200 years. The new findings in science became direct driving force behind the two Industrial Revolutions.

The modern science, represented by Newton's physics, did well in describing macroscopic objects in motion at low speed; however, it met severe challenges in explaining the physical phenomena found in micro-world, such as atoms. Consequently, a new revolution in physics started around the beginning of the 20th century (Agar 2012).

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9.1.1.1 Three Findings Inside Atoms

In 1895, Wilhelm Röntgen, a German physicist, produced and detected the X-rays or Röntgen rays which carry very high photon energy. Later it came out that X-rays are produced when high energetic electrons interact with matter. In 1896, Henri Bacquerel, a French physicist, discovered that uranium was with natural radioactivity. Later in 1898, Marie Curie, a Polish and naturalized-French physicist and chemist, discovered that radium was also with natural radioactivity. It was further found that the natural radioactivity was a result of decay of unstable atomic nuclei. In 1897, Joseph Thomson, an English physicist, proved through experiments with cathode rays that the cathode rays were actually composed of negatively charged particles, namely electrons.

These three important findings brought human's knowledge to the inside of atoms. The old cognition that atom is undividable and element is unchangeable was broken.

9.1.1.2 Theory of Relativity

In 1905, Albert Einstein (Fig. 9.1), a German-born theoretical physicist, determined that the speed of light in vacuum was independent of the motion of all observers. This was the theory of special relativity. After 10 years, Einstein expanded it into the theory of general relativity which established the interrelation between time, space and matters.

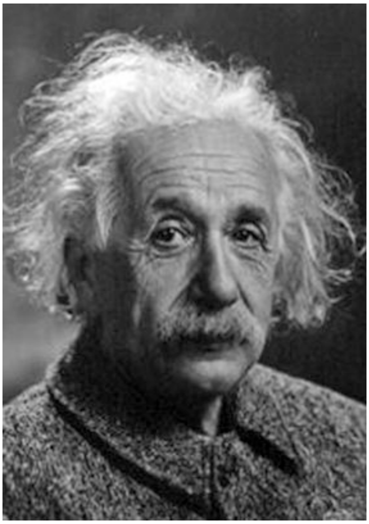


Fig. 9.1 A. Einstein

9.1.1.3 Theory of Quantum Mechanics

Max Plank, a German theoretical physicist, introduced the word "quanta" in solving the black-body radiation problem in 1900. On this basis, many scientists continued to work; the most noticeable included a German physicist, Werner Heisenberg, and an Austrian physicist, Erwin Schrödinger. To the 1930s, their works evolved into a systematic theory, quantum mechanics. This theory describes nature at the micro-scale, atoms and subatomic particles.

9.1.1.4 Nuclear Physics

Einstein's theory of relativity indicated the possibility to obtain huge energy from atom, laying the theoretical foundation for utilization of nuclear energy. Quantum mechanics describes the atomic structure and the motion of electrons, answering the question how to harness the nuclear energy. The theory of nuclear physics cleared the way in theory toward making atomic bombs and hydrogen bombs as well as constructing nuclear power stations.

Pierre Curie and Marie Curie developed the technique for isolating radioactive isotopes in 1898. Enrico Fermi, an Italian physicist, found nuclear fission of uranium in 1934. These European scientists already laid the foundation for utilization of nuclear power before WWII.

9.1.1.5 Discovery of Laser

Einstein established the theoretical foundation of laser. During the 1950s, Two Soviet scientists, N. Basov (Николай Басов) and A. Prohorov (Александр Прохоров), and an American physicist, Charles Townes, conducted extensive research on laser. They all found the phenomenon of laser, explained the principle of laser and investigated the ways to generate laser.

Due to their prominent contribution, all the above cited scientists won the Nobel Prize in different times. These revolutionary findings in physics paved the way toward the Third Technological Revolution. Computers won't be possible without the discovery of electrons; development of nuclear power relies on the discovery of radioactivity. Similarly, laser cutting would be impossible without the finding of laser.

9.1.2 Birth of Systems Science

To the end of the 1940s shortly after WWII came to an end, several ground-breaking progresses were made in science, including the creation of information theory, cybernetics and systems science.

9.1.2.1 Information Theory

Information theory studies the basic characteristics, quantification, acquiring, communication, storage, processing of information. It was initiated from communication engineering. The paper by Claude Shannon (Fig. 9.2), an American scientist, published in 1948 (Shannon 1948) was regarded as the land mark for the birth of information theory.

Shannon's main contribution and conclusions include: (1) communication is basically the transformation of information. He developed the model of a communication system based on probability and statistics with which information in transformation and processing could be quantified. (2) Objective of communication is to retrieve the information accurately or approximately at the receiving end. The information at the receiving end is only a copy of that in the sending end, having nothing to do with the inherent meaning of the information.

On the basis of Shannon's information theory and Wiener's cybernetics, information science was formed which studies information problems in much broader areas, such as computer science, artificial intelligence, psychology, sociology, economy and so forth. However, the information science is still under fast development and far from mature partially due to its broad scope.

Shannon's information theory provided theoretical guidance to information technologies which has created enormous impact on the machine industry and relevant technologies.

Fig. 9.2 C. Shannon

9.1.2.2 Cybernetics (Control Theory)

During WWII, German fighters already reached a speed close to that of the shells of anti-aircraft guns. The direct manual aiming method did not work any longer; thus, an American mathematician, Norbert Wiener (Fig. 9.3), stepped into the area of automatic aiming and firing of anti-aircraft guns. He formed some critical concepts during his research, including prediction, filter and negative feedback. Two important symposiums were organized which attracted many scientists from different backgrounds. In 1948, he published the landmark book, *cybernetics*, marking the birth of a new discipline (Wiener 1948).

In this book, the two fundamental concepts, information and feedback, were defined and clearly discussed. In addition, the basic rules in information transformation and feedback control were also revealed. Thus, a firm theoretical foundation for simulation of human and animal behaviors was laid out.

New methods of research were created in cybernetics, such as simulation and black boxes. These methods go far beyond cybernetics, gaining wide application in many other subjects, such as machine dynamics.

In 1954, the publication of the book *Engineering Cybernetics* in U.S., authored by a Chinese scientist, Hsue-Shen Tsien (Qian Xuesen) (Fig. 9.4), marked the creation of an important branch of the cybernetics (Tsien 1954). It created direct and enormous effect on the application of cybernetics in engineering.

The practical application of cybernetics has gone through the following three stages.

Fig. 9.3 N. Wiener

Fig. 9.4 Qian Xuesen (H. S. Tsien)

(1) Classical control theory, represented by Tsien's book, deals with linear time-invariant systems with single-input and single-output. Ordinary deferential equations (ODE) with constant coefficients are the mathematic representation of such systems for which the Laplace transformation of input and output can be calculated. A closed loop controller can be formed with the introduction of feedback. Transfer function and frequency response are the basic tools for analysis and synthesis of such a system. The application of classical control theory is mainly on a one machine system.

(2) During the 1960s and 1970s, control theory moved to deal with time varying systems with multi-inputs and multi-outputs. This movement was mainly driven by the need in control of missiles, space shuttles and multi-machine systems. This is termed as modern control theory. In this stage, the systems are modeled mathematically with state space and ODE, the solution of which often requires computers. The main control strategies include optimal control and random adaptive control.

(3) After the 1970s, it further moved forward to large-scale system control, which deals with the control of complex systems with multi-factors and multi-hierarchies. Intelligent control is the commonly used strategy aiming for the application in the control of complex automation systems. It also finds applications in social, and economic systems.

Wiener compared in his book the similarity between computing machines and human nervous systems, and for the first time proposed the concept of self-reproducing machines which constitute the core of an automatic factory. The theory of cybernetics has created dramatic impact on every aspects of mechanical engineering.

9.1.2.3 Systems Theory

Chinese and Greek in the Ancient times already had some basic and primitive ideas about systems. The contemporary systems theory is an interdisciplinary scientific theory which studies the nature of complex systems in society and science. It was proposed in the 1940s by an Austrian biologist Ludwig von Bertalanffy (Fig. 9.5). He started publishing papers from 1945, and a book in 1949 which marked the birth of general systems theory (Bertalanffy 1949).

In the systems theory, a complex part in reality is treated as a system which can be mathematically modeled to predict its structure and behavior. A system is defined as a complex interacting, and interdependent elements forming an integrated whole. It is at the same time an element in a larger system. L. von Bertalanffy pointed out systems were more than the sum of their parts in function. He promoted the idea of "organicism" in which any life was regarded as dynamic all the time. Living systems maintain themselves in a steady state through importing information and energy as an open system. As can be seen, the systems theory emphasizes the interdependent and interacting relationship between the whole and a part, between parts and parts, and between the system and its surrounding.

It has been common practice to treat a mechanical element as a part of a machine, or an individual machine as a part in a larger mechanical-electrical-hydraulic system. The theoretical origin of this practice is from the systems theory.

Fig. 9.5 K. Bertalanffy

9.1.2.4 Systems Science

Information theory, control theory (cybernetics) and systems theory were originated from communication, automatic aiming of guns and biological systems respectively. Although with different origins, their basic ideas and concepts are in great similarities. In addition, each of them has developed into a discipline with much broader application than its origin. Nowadays these three theories are in the position guiding other subjects in philosophy and methodology (Quan 2002). Their creation and development indicate that science has evolved into a new stage of converging after long term diverging.

These three theories are termed as “the three old theories” in China. Later in the 1970s, some other theories, including theory of dissipative structure, synergetics and catastrophe theory, appeared which are the so-called “the three new theories”.

The term, systems science, was proposed later. The systems science is highly comprehensive, covering not only the three old theories and the three new theories, but also wide range of other subjects, such as operations research and nonlinear science. It has become a science branch with the fastest growth since 1950s (Kenneth 2005). The famous Chinese scientist, Qian, proposed that the systems science should be in a parallel position with the natural science and humanity science (Qian 2011).

In mechanical engineering, the systems science has wide application, such as measurement technology, machine dynamics, automated production system and automatic control of machines.

9.1.3 Nonlinear Science

Nonlinear science started from nonlinear vibration. To the 1960s it went beyond vibration after the finding of chaos. Since then nonlinear science has evolved into a science of interdisciplinary with wide application in different fields.

9.1.3.1 Discovery of Chaos

In 1890, a French mathematician, Henri Poincaré, found that no exact solution existed for the “three body problem”. In seeking a partial solution using series of approximation of the orbits, he further discovered that the solutions were tangled (random), indicating no stable orbit. This led to what was later known as chaos theory (Wu 2000, Peterson 1995). Poincaré realized a disturbing fact: “a very small change in initial conditions would lead to vastly different orbits”. This was the first statement of “sensitivity to initial condition” which is a key feature of chaos. It proved that the disturbing and strange phenomenon, Poincaré found but did not understand then, was in fact ground-breaking of science. However, his work did not catch much attention at that time.

One reason responsible for Poincaré's giving up and the less attention his work received might be that the research required numerical solution. However, the computation needed was overwhelming for the time without a computer.

Poincaré's work was rediscovered in 1963 by Edward Lorenz (Fig. 9.6), an American meteorologist well trained with mathematics, who is regarded as the founder of modern nonlinear science and the chaos theory (Lorenz 1963).

Lorenz used a digital computer to numerically solve a weather prediction model which consisted of a deterministic system of nonlinear differential equations. The simulation had to be stopped due to some unexpected reasons, and resumed with the new initial values which were taken from the simulation results before the stop. In this process, round-up approximation was made due to the nature of numerical computation. To his surprise, the very tiny round up errors in the initial values led to completely different final simulation results. He found a perfect example of the proverb "a miss is as good as a mile". Lorenz actually rediscovered Poincaré's "sensitivity to initial conditions" which is a key character of nonlinear systems. Lorenz found a phenomenon of nonlinear systems, termed "chaos" later. This discovery made him question the reliability of long-term weather forecast. He expressed it as "*Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?*" "Butterfly effect" has become an iconic remark well known across the world. The Lorenz system now is a stepping stone to the study of chaos theory, and Lorenz is regarded as the "father of chaos".

Fig. 9.6 E. Lorenz

9.1.3.2 Formation of Nonlinear Science

Traditionally, modern science, represented by Newton's classical mechanics, tended to simplify a real problem into linear systems. For example, the Newton's second law of motion in mechanics, the Maxwell's equations in electrics, and the Schrödinger equation in quantum mechanics are all linear. Linear science achieved great success in the past, leading to a stereotype of thought that everything is linear. In this case linearity is regarded as normal and essential, while nonlinearity is thought exceptional, ill and nonessential. When it comes to the modeling of a real system, linearization is always applied. The nonlinear factor is at most treated as a perturbation to the main linear system.

The U.S. and Soviet Union were two centers of the world in nonlinear science. In fact, a Soviet mathematician, A. Kolmogorov (Андрей Колмогоров), made discussion qualitatively on chaos early in 1954. In the 1960's, the other Soviet mathematician, W. Arnold (Влади́мир Арнольд), and a German mathematician, Jürgen Moser, proved and expanded Kolmogorov's work. Their works were collectively named the KAM theorem (Chen 1993). The KAM theorem and Lorenz work marked the starting point of chaos theory in mathematics and numerical analysis respectively.

The famous journal, *New Scientist*, credited the chaos theory as one of the top 10 most influential scientific theories in human's history, among which include Darwin's theory of evolution and Einstein's theory of relativity (Chen et al. 2007).

Lorenz discovery caused great sensation and inspired wide interest in exploring various problems of complexity in society and the universe. At the same time, it greatly changed the traditional way of thinking and perspective of the world. Thereafter, chaos of various deterministic systems were found. After the 1970s, research focus was moved from individual cases to finding the common features in different nonlinear areas of science.

Nonlinear science, similar to information theory, cybernetics and systems theory, is a complex and interdisciplinary subject, having universal applicability. It provides guidance to all other subjects. However, it is still under continuous evolution, not being a mature subject yet. Generally, nonlinear systems are more difficult to handle, and there is no consistent mathematic method available. Most works so far have focused on special cases, and very limited quantitative analysis. In spite of the immaturity, it is certain that nonlinear science will greatly influence many areas of science, such as engineering, ecosystems, medical diagnosis and economy.

The application of nonlinear science in mechanical engineering focuses on nonlinear vibration. It can be anticipated that it will play an critical role in dynamic stability and fault diagnosis of critical mechanical equipment.

9.2 Social Background of Third Technological Revolution

9.2.1 WWII: Midwife of New Technological Revolution

When it comes to the background of the third Technological Revolution, several aspects should be reviewed, such as the social and economic development after WWII; the support of science to technology and the interaction between different technological fields. The impact of WWII should come first when we review the third Technological Revolution.

Science and technology, which used to tip the balance of opposing powers, played an important role in the War.

Science and technology equipped both parties in the War. In return the War greatly stimulated the development of science and technology. WWII put many scientific and technological results into military use. In this sense, WWII was unprecedented in war history. Although some theoretical concepts and technological prototypes in the Third Technological Revolution had been conceived in the prewar period, the military needs from WWII greatly sped up the pace of development. In a sense, WWII spawned the Technological Revolution (Peng 1995).

The development of WWII was closely linked to the inception of the Third Technological Revolution. The war greatly stimulated the rapid development of military-relevant technologies, in particular the atomic energy technology, the computer technology and the rocket technology. These three inventions directly accelerated the advent of the Third Technological Revolution.

9.2.1.1 Atomic Energy (Nuclear Power)

On the eve of WWII, although initial progress had been made in the research of atomic energy, scientists considered its application as far from practical. However, the outbreak of the War gave a powerful stimulus to its fruition.

In early 1939, the Nazi authorities organized scientists to study nuclear fission. And scientists in the United States realized that one day Adolf Hitler might be able to build an atomic bomb. President F. Roosevelt (1882–1945) took Einstein's advice, ordering the development of the atomic bomb. It was not until the eve of Pearl Harbor incident in 1941 that the research plan, the Manhattan Project, was at last formulated (Jones 1985). Scientists, including these originally from the United States and these who fled to the U.S from European countries, gathered in Manhattan, New York, and made unified efforts for the anti-fascist and scientific cause.

Fig. 9.7 E. Fermi

Under the leadership of Enrico Fermi (Fig. 9.7), an Italian-American scientist, the nuclear chain reaction experiment with artificial control was successfully conducted in December 1942. In 1943, J. Robert Oppenheimer (Fig. 9.8), an American scientist, served as the director of Los Alamos National Laboratory, and led the development of the actual atomic bomb. In July 1945, the first atomic bomb test proved successful.

Dropping of the atomic bomb accelerated the death of Japanese militarism. Equally importantly, it was a prelude to the post-war peaceful use of atomic energy.

9.2.1.2 Electronic Computer

The calculation of nuclear fission and ballistic trajectory required the computer of high performance. In 1941, the University of Pennsylvania's Moore School of Electrical Engineering was commissioned to calculate trajectory data for the U.S. Army. At that time, to calculate artillery firing table with the mechanical computer required 200 people working together for two or three months. John Mauchly, an engineer, proposed to use an electron tube computing device, which was actually the first scheme of the electronic computer. The proposal immediately attracted the U.S. Army's great attention (Goldstine and Goldstine 1946).

In February 1946, the first electronic computer ENIAC (Electronic Numerical Integrator and Computer) was successfully developed. The technologies used in ENIAC, such as radio, radar, microwave and pulse technology were just invented before WWII. The birth of electronic computer was indeed accelerated by WWII, although it did not come in time to be of any use to the calculation of the firing table in the War.

Fig. 9.8 J. Oppenheimer

9.2.1.3 Rocket

The Nazi Germany established a research center in Peenemünde specialized in the rocket technology led by Wernher von Braun. In 1942, the V-2 rocket (Fig. 9.9), the first long-range guided missile powered by liquid propellant, was developed successfully (Kennedy 1983). After only one year, the V-2 was launched cross the English Channel in bombing London. Neither Soviet Katyusha nor American Calliope at that time were comparable with it in power.

After the Allied forces seized Germany, von Braun surrendered to the Americans, along with 126 key technical personnel and large amount of hardware and documents, which occupied 16 full ship-loads in transportation to the U.S. The Soviet captured the majority of the production facilities in Peenemünde and re-located them to the Soviet Union. After the War, a race was started between America and the Soviet Union to develop large rockets on the basis of V-2.

In addition, a series of technologies, including supersonic aircraft, precision manufacturing, laser, semi-conductor, digital communication, synthetic fiber and petrochemistry, were directly developed for the War. Following these technological breakthroughs were the establishment of the nuclear industry, the aerospace industry, the semiconductor industry, the petrochemical industry and the precision manufacturing industry after the War.

Fig. 9.9 V-2 rocket in Peenemünde (a replica)

9.2.2 *Post-war World*

After WWII, peace was resumed, creating a favorable environment for economical, scientific and technological development worldwide.

9.2.2.1 Peace

Although WWII came to an end, many fundamental social contradictions remained. Conflicts continued in the form of local wars, such as the Korean War and the Persian Gulf War. Although some of the local wars were pretty fierce, most were not lasting long, and confined to certain areas. Countries involved were also limited. In general the world has been kept in peace for more than half a century.

During the peaceful time, the world economy grew significantly. Great progress was made in science and technology. Exploration activities to the outer space and deep seas were also started for the long term benefit of human society. In addition, collaboration in science and technology was widely established between countries. Thus, scientists and experts from all over the world were able to work on scientific problems of common interests. International standards and codes were established in wide range. Some "big science projects", such as the International Thermonuclear Experimental Reactor and particle physics, were initiated.

The economic growth greatly lifted the living standard of people. Correspondingly requirements on products were raised higher, constituting the main social driving forces to the advance of science and technology.

9.2.2.2 Competition

The peaceful time brought forward economic growth worldwide. The market competition became more intensive. Businesses strived to improve productivity and product quality to meet the ever-tougher, and higher market requirement on every aspect of the product, including performance, cost, appearance, comfortability, environment, delivery time etc. This was the economical impetus to the advance of science and technology.

In addition to market competition stated above, a special form of competition, the Cold War, was formed between the two blocs of countries led by the United States and Soviet Union. The Cold War formed from the end of WWII and ended in 1991 when the Soviet Union collapsed. During the Cold War, the two blocs of countries were in great tension and race in almost all aspects of economy, politics and military. Military in particular was the most intensively competed area; each bloc invested heavily and had dedicated research institutions on weapon development. New technologies were always first used in weapons for both groups. Competition was even extended to the space. The Soviet launched the first earth satellite in 1957, while the United States won in the first landing on the Moon later. To gain a more favorable position in the competition, both continuously put the newest technologies into the aerospace exploration, laying the foundation for the progress on aerospace afterwards.

After the Cold War, globalization was started and accelerated, forming a world market. Competition become more and more intensive.

9.2.2.3 Crisis

Two crisis, of resources and environment, have been facing the world.

The two Industrial Revolutions demonstrated the dramatic changes which new powers brought to human's life and society. The human desire was greatly inflated demanding for more and more. The planet was treated in a way as if it could provide limitless resources and absorb any amount of emission. The Industrial Revolutions increased the productivity of machines, speed of automobiles, trains and aeroplane many times. The manufacturing industry brought unprecedented wealth, convenience and comfort to human society and life. Along with the benefit were more energy consumption, more pollution and environmental degradation.

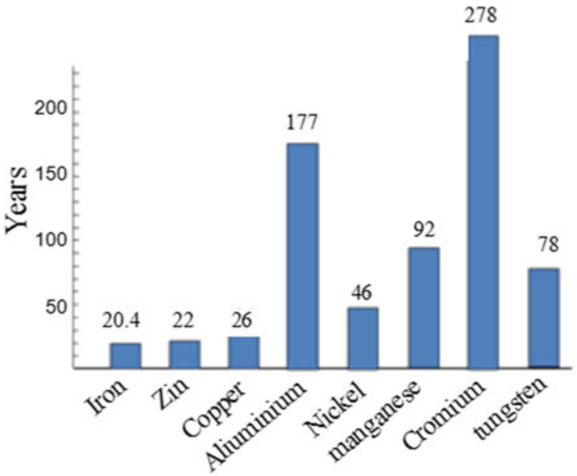


Fig. 9.10 Global recoverable period of important metal mines (2006)

According to a prediction of the United States Department of Energy, the energy consumption of the world will continue to grow by 60% in 20 years, and 70% of the total emission will come from the manufacturing industry.

The environmental challenge inspired the creation of green design and green manufacturing (see Sect. 12.7).

The growth of economy and population created a unprecedented high pressure on various natural resources, such as minerals, land, fresh water, and forest etc. In some countries the limit of available natural resources has become severe obstacles to further economic growth. However, the long term and final consequence is yet hard to be predicted (Fig. 9.10).

Since becoming the dominant energy form of the world, oil has gained such a power that can influence a country's economic and social development fundamentally. In the 1973 Arab-Israeli War, the Organization of Arab Petroleum Exporting Countries (OAPEC) started an oil embargo targeting countries supporting Israel. Through raising oil price and cutting of oil production, the economy of the targeted countries was heavily hit. The embargo caused "the first oil crisis" (or energy crisis) which had many short- and long-term effects on the world economy and politics. The oil crisis led to the greater interest in alternative energy sources, such as renewable energy, nuclear power and domestic fossil fuels.

The crisis also affected the philosophy of machine design. For example, light weight became a widely accepted trend in automobile design.

9.3 Main Contents of Third Technological Revolution

Some breakthroughs were made in science at the end of 1940s shortly after the end of WWII. These include the creation of information theory, control theory (cybernetics) and systems theory as well as the invention of electronic computers.

The Third Technological Revolution represents another great leap after the steam power and electrical power. It is built on the foundation of computer technology, nuclear power technology, and aerospace technology, and involves revolutionary progress in energy, materials, biology, and marine technology. It not only promoted the development in economy, politics, and culture, but also affected the way of thinking and living of human society, greatly uplifting the level of modernization of the human society.

In the section below, the development in the main fields of the Third Technological Revolution is briefly introduced along with its influence on mechanical engineering.

9.3.1 Information Technology

Information technology is the use of computers to store, retrieve, and transmit information. It includes microelectronic technology, sensing technology (or remote sensing technology), communication technology, and networking technology. In this section, we limit our discussion within the part relevant to mechanical engineering.

9.3.1.1 Microelectronic Technology

Electrons were discovered in 1897 shortly after electronic diodes and vacuum triodes were invented. Then a series of technologies, such as broadcasting, television, radio communication, various instruments and the first generation of computers, were developed during the period between 1920s and 1940s. These constitute the main contents of the traditional electronic technology.

John Bardeen and other two scientists working at Bell Labs invented the transistor in 1947, winning the Nobel Prize in Physics in 1956. This invention preluded a revolution in microelectronic technology.

In 1958, Jack Kilby, an American electrical engineer, invented the integrated circuit (IC). A few month after, Robert Noyce, another American scientist, made a similar circuit independently. Kilby won the Nobel Prize in Physics in 2000. In 1971, Intel Corporation created the world's first commercial microprocessor chip based on the integrated circuit technology (Winston 1998).

The invention of integrated circuit opened a new page in the microelectronics. It has become the core and base of modern electronic industry. After its invention, the number of transistors integrated on a chip has gone from several dozens (small scale integration) to billions (very large scale integration) in just several decades. The Moore's law predicted that the number of transistors in an integrated circuit doubled in 18–24 months.

9.3.1.2 Electronic Computer

Electronic computers, one of the greatest inventions of the 20th century, marked a new era in the history of science and technology.

To the 1930s, the prerequisites for an electronic computer were almost ready, including (1) early work on mechanical computers and elector-mechanical computers based on mechanical relays accumulated knowledge and experience, (2) vacuum tubes were invented and the electronic technology was on track of development.

As we stated before, WWII greatly accelerated the birth of electronic computers.

In February 1946, the earliest electronic general-purpose computer designed by John Mauchly, ENIAC (Fig. 9.11), was successfully completed at the University of Pennsylvania (Williams et al. 1958). This computer weighed 30 tons, had very small storage and could execute program instructions embodied in the separate units. However, it was a landmark in the history of electronic computers.

The two most outstanding figures in the history of computers are Alan Turing and John von Neumann (Williams et al. 1958).

Neumann (Fig. 9.12) was a Hungarian-American mathematician. He was the first to describe a computer architecture in which the data and the program were both stored in the computer's memory (stored-program). He also used the binary in computer. The EDVAC, a successor of ENIAC proposed by Neumann, was put in operation in 1952. The principle of "stored program concept" now is called von Neumann architecture.

Electronic computers have gone through 4th generations, from the initial ones based on vacuum tubes to the present ones based on very-large-scale integrated circuit. Meanwhile, computers have become much smaller in volume, much larger in storage space, much faster in speed and much more reliable in performance.

Fig. 9.11 The world's first computer

Fig. 9.12 J. von Neumann

Nowadays computers are developing in two directions, microcomputers and supercomputers.

Microcomputers are more commonly called personal computers (PC) at present. In 1975, Bill Gates and Paul Allen founded the Microsoft Corporation which became the world's largest PC software company (Wallace and Erickson 1992). IBM started making PCs, known as IBM PC, in early 1980s based on Intel's microprocessor and Microsoft software; its success greatly pushed the popularity of personal computers, making the term PC mean any desktop microcomputer compatible with IBM PC. It is estimated that hundreds of millions of microcomputers are now in use around the world in almost all aspects of human society, such as science, economy, production, and daily life.

The United States has long been in a leading position in the supercomputer field. The Cray Research Inc. (later Cray Laboratories and Cray Computer Corporation), has developed a series of supercomputers, such as Cray-1, Cray-2, and Cray-3 etc., since 1975 (Murray 1997). Supercomputers play an important role in the fields requiring intensive and fast computation, such as weather forecasting, airplane design, oil and gas exploration and data processing of earthquake and so forth. Japan also made excellent work in the field during 1980s and 1990s. In recent years, China caught up, becoming increasingly active in the field. Tianhe-2, and Sunway TaihuLight were ranked the fastest computers for several times (Strohmaier et al. 2016).

In addition to the electronic computers, unconventional computers, such as optical computers, DNA computers, neural computers and quantum computers etc., are under active study, and have shown great potential. It is possible for these unconventional computers to increase the computation speed and storage by orders of magnitude (Dumas 2016).

9.3.1.3 Artificial Intelligence (AI)

At the age of 24, Alan Turing (Fig. 9.13), an English mathematician, proposed the concept of the "Turing machine" which he called automatic machine in 1936. He is widely regarded as the father of artificial intelligence.

The term AI was started to be used formally during a workshop at Dartmouth College in 1965, marking the birth of AI as a scientific discipline (Russell and Norvig 2003). AI, also called machine intelligence, combines the theories of cybernetics, information, computer science and neurophysiology. Currently, AI is classified as a sub-discipline of computer science due to its close link to computers. However, it has very wide scope including automated theorem proving, machine game, symbolic computation, machine translation, expert system, speech recognition, pattern recognition and artificial neural networks.

Computers can handle knowledge represented by symbols of different types. This is called computer algebra or symbolic computation. Very complex equations can be derived automatically by computers with the help of symbolic computation. Now several general packages of symbolic computation are already available in market (Buchberger et al. 1983). For example, the derivation of dynamic equations based on Lagrangian equation could be implemented with computers through symbolic computation.

Fig. 9.13 A. Turing

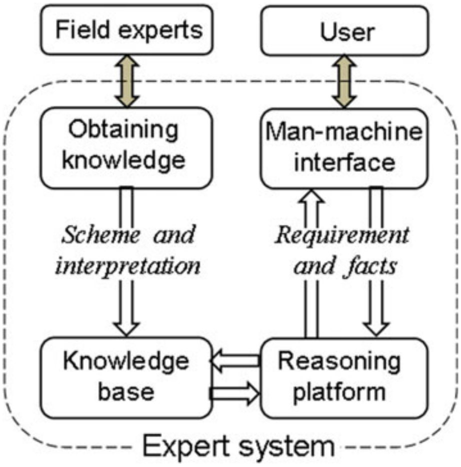
The first expert system on the basis of symbolic reasoning was developed at the end of 1960s (Giarratano and Riley 2005). An expert system is a computer program that mimics the decision-making process of human experts to solve a real problem with pre-established knowledge base (Fig. 9.14). Research on expert systems experienced a booming period in the 1980's when a series of systems were developed with application to medical diagnosis, mining exploration, and troubleshooting industrial processes. Application in machine design and machine fault diagnosis was also found.

It has been a long sought-after goal of human to make a machine with certain thinking ability. Artificial neural networks (ANN), first developed in the 1940s, opened a new route of computing. The remarkable ability of adaptive learning based on complicated and imprecise data makes ANN very suitable to applications in expert systems, pattern recognition, dynamic modelling, intelligent control, trouble shooting, machine vision and information integration. Research on ANN was initiated in the United States, and later followed by Japan, Germany, France, Russia and China.

9.3.1.4 Signal Processing

Signal is generated in human's production and societal activities. The signal needs to be processed, transmitted, and recorded. To abstract useful information, the signal needs to be analyzed properly and quickly.

Fig. 9.14 Principle of expert system



Joseph Fourier, a French mathematician, proposed the theory of Fourier series in 1807. Later in 1822, he further put forward the theory of Fourier transform (Fourier 1822).

Needs for effective signal processing first came from manufacturing of electrical motors, generation and transmission of alternating current electricity. Thus, Fourier transform has been widely applied in electrical engineering starting from the end of 1890s. Signal can be processed in time and frequency domains; however, analysis in frequency domain has many advantages over that in time domain. The signal analysis technique based on Fourier transform is called classical signal processing method.

A Hungarian-born American mathematician, Rudolf Kálmán, invented the filtering technique in 1960. Before computers were applied in signal processing, signal was represented and processed in analog form. However, analog methods have a series of limitations in resolution, processing time and output forms.

Signal is processed currently with digital methods based on computers and Fast Fourier Transform (FFT). FFT greatly enhanced the application of Fourier transform (Bracewell 2000). To the mid-1970s, electronic instruments and dynamic signal analyzer were invented for processing signal on the base of FFT, providing a powerful tool for digital signal processing.

Signal processing constitutes the theoretical base of vibration measurement. It is also widely applied in mechanics, optics, quantum physics and many other fields.

Fourier Transform is applicable to linear problems, but incapable of nonlinear ones. In addition, it is very difficult to determine whether a signal includes a particular frequency at a particular point. To abstract the frequency information in a signal, the whole signal in time domain is needed.

Wavelets well overcome the limitations of Fourier Transform. With wavelets signal can be analyzed within any localized sections in either time or frequency domain. Thus, wavelets are also called “microscope of signal processing”. Wavelets are still being in fast development. Their applications in mechanical engineering include chatter of machine tools and rotor dynamics (Jaffard et al. 2001; Lange and Abu-Zahra 2002; Zou et al. 2004).

9.3.1.5 Network Technology

In 1969, the Advanced Research Projects Agency Network (ARPANET) was established to connect 4 computers located at 4 universities in the United States. This network was funded by the United States Department of Defense. The objective was that in the case of a portion of it was damaged due to some reasons, such as war, the rest part was still able to work. In 1986, the U.S. National Science Foundation (NSF) established the National Science Foundation Network

(NSFNET) to connect 5 supercomputing centers. After further development in about a dozen of years, the Internet gradually took shape. This is another good example demonstrating a civil technology initiated from a military start (Kim 2005).

The Internet, as a ground-breaking information technology, made it possible to quickly acquire and communicate information worldwide. In 1995, the Internet was fully commercialized in the United States. The influence and power of the Internet went far beyond the initial expectation and objectives set out by the NSF.

The Internet brought revolution to the communication technology. It connects the world into a unity, making it possible for investment, technology, knowledge and information to flow freely and quickly all over the world. Now it has become a part of people's daily life, dramatically changing the way of thinking.

After entering the 21st century, the concept of Internet of Things (IoT) was proposed. It is the network of physical devices, vehicles, home appliances and other items on the basis of Internet and traditional communication networks. Each thing in the system is uniquely identifiable through its embedded computing system but is able to inter-operate within the existing network infrastructure.

In the mechanical engineering, collaborative design and collaborative manufacturing networks started to be developed.

9.3.1.6 Sensing Technology

From the viewpoint of bionics, a computer can be viewed as a "brain" which treats and identifies information. Likewise, a communication system is not more than the "nervous system" and a sensor the "sense organs".

Sensors are used in measurement of various parameters, such as those in acoustics, optics, magnetics and various physics. In mechanical engineering, they are widely used in measurement of length, thickness, displacement, velocity, acceleration, force, torque, flow velocity and flow rate etc. In the measurement, change of the measured parameters is translated into electrical parameters, including voltage, current, resistance and capacitance.

In fact, sensors appeared in human history very early. Examples of early sensors include the scales in ancient Egypt, the steelyard, compass, and seismometer in ancient China. However, the sensing technology had advanced very slowly before the 19th century, even after the Industrial Revolutions. Since the late 1800s, the development in physics and electrics has largely pushed the sensing technology. New findings in physics have been always accompanied by new sensors. After WWII, with the emergence of new materials, semiconductor technology, micromachining technology, laser technology and optical fibre technology, various powerful sensors have been developed.

Sensors make up the most crucial part in a control system of a machine.

9.3.2 Aerospace Technology

Space exploration is another important field in which great advance was made after WWII (GSHCAS 1985). The history of space exploration can be broken down to the following three stages.

9.3.2.1 Early Exploration

Theoretical work on space exploration and rockets already started at the early 20th century. K. Tsiolkovsky (Константин Циолковский) (Fig. 9.15), a Russian scientist, was regarded as the founder of the space exploration theory. He proposed the ideas of space traveling through rockets, making satellites of the Earth, and construction of space stations in low Earth orbits (Lewis 2008). His famous remark is as follows: "Earth is the cradle of humanity, but one cannot remain in the cradle forever. …Mankind will not forever remain on Earth, but in the pursuit of light and space will first timidly emerge from the bounds of the atmosphere, and then advance until he has conquered the whole of circumsolar space".

An American, Robert Goddard, launched the first rocket with liquid-propellant in history in 1926. Shortly after, the Soviet Union made its own liquid propellant rockets in 1933 as well. Liquid propellants make rockets fly greater range, paving the way of space exploration.

Fig. 9.15 K. Tsiolkovsky

Fig. 9.16 W. von Braun

9.3.2.2 Development of Large Scale Rockets

After WWII, both the United States and the Soviet Union continued to develop the large scale rocket technology on the basis of the German V-2 as if by prior agreement, marking the 2nd stage of space exploration. In the United States, von Braun (Fig. 9.16) took a leading role in the development. He made great contribution to most exploration activities in the U.S., such as launching the Earth satellite and the landing on the Moon (Neufeld 2008).

9.3.2.3 New Era in Space Technology

In October 1957, the world was surprised by the news that the Soviet Union launched the first earth orbiting satellite of the world, marking a new era in human's space exploration. A few months after in January 1958, the United States followed the Soviet step with a satellite of its own using the rocket technology developed by von Braun. In the half century following, the two superpowers carried out a stunning race in the space technology. The space technology is an indicator of a nation's overall power and technological level, the two superpowers took alternative in the leading position in the race.

In 1961, the Soviet spacecraft, Vostok, sent a pilot into outer space for the first time in history. The United States, on the other hand, started the Apollo 11 which successfully landed two humans on the Moon in 1969. Since then space exploration activities have gone beyond low earth orbit. So far the International Space Station has been established under international cooperation, and space probes have been launched to almost all planets in the solar system.

China also made great effort in space exploration. In 1970, its first earth orbiting satellite was successfully lunched. Now it has become a powerful figure of the world in space exploration with a series of achievements, such as manned spacecraft and unmanned lunar orbiting spacecraft.

However, human's space exploration activities are still at the very beginning stage, still being far from the ultimate goal.

A spacecraft is a very complicated system containing numerous mechanical, electronic and fluid subsystems and components. For example, the solar panels and mechanical arms on a spacecraft that is used to hold or release a satellite are flexible mechanical-electronic systems. The dynamics of spacecraft is basically nonlinear because of many complex factors, such as elasticity, clearance, interaction between fluid and solid etc. to be considered. Also the manufacturing of spacecraft requires very high accuracy. The space exploration pushed the development of machine design and manufacturing through putting forward higher requirements.

9.3.3 New Materials

New materials can be classified as metallic materials, inorganic non-metallic materials, organic polymeric materials, and composite materials on the basis of property.

Based on function, they can be grouped as structural materials and functional materials. Structural materials are those that bear load. Mechanical and chemical properties are the main requirement for structural materials, such as various strengths, rigidity, hardness, high-temperature resistance and wear resistance etc. Functional materials take advantage of some physical properties, such as electrical, magnetic, acoustic and optical properties to achieve some specific functions. These functions include semi-conducting, magnetism, photosensitivity, thermosensitivity and invisibility etc.

Materials have been the foundation of development in human history in which new materials were always the landmarks. The material technology, as one cornerstone of the 3rd Technological Revolution, along with the information technology and biological technology are regarded as the three most promising areas in the 21st century.

Ultra-pure-silicon and gallium arsenide made the manufacturing of large and very large scale integrated circuits a reality. For an aircraft engine, raising the working temperature by 100 °C would give an increase of thrust force by 24%. A combat aircraft made with stealth technology can absorb the electromagnetic wave emitted from the radar to prevent radar tracking. All these are examples of application of new materials.

The progress in new materials caused revolution to information and biological technologies, and dramatically affected the manufacturing industry and logistics. It makes "lab-on-a-chip" a reality, greatly accelerating the progress of biological technology. Now the subject of new materials is under fast development toward making products and components smaller, smarter, more multifunctional and more environment friendly etc.

After the shock by the Soviet launching the first earth-orbiting satellite, a consensus was reached in the United States that the inadequate research on new and advanced materials was mainly responsible for the falling-behind. Then more than 10 research centers were formed in universities focusing on research and development of new materials. Now almost all the main powers in the world, such as the United States, European countries, Japan, and China, set the new material research as a part of its long-term scientific plan and have been investing heavily on developing the key technologies.

9.3.3.1 Nano-Materials

Since the 1990s a wave of research has been formed around the world on nano-materials. Nano materials have many unique properties that traditional materials do not have, showing great potentials for application in many fields. In 2001, the famous computer giant, IBM, successfully made transistors with carbon nanotubes, which might replace the current silicon-transistors, causing revolution in the semiconductor electronics technology. It is predicted that the nanotechnology will become the core of the information era (Li et al. 2005).

In mechanical engineering, nano-bearings and nano-robots have been constructed. It is also expected that significant improvement on wear-resistance, hardness, and life expectancy could be made through coating mechanical component with powder of nano-materials.

9.3.3.2 Ceramics

Synthetic aluminum oxide ceramics was made in 1893 (Kalpakjian and Schmid 2013). This material has a high hardness, next only to diamond, in room temperature. In addition, its hot hardness is much better than traditional alloy tool steels, making it an option for cutting tool material.

During the 1950s, research was directed to structural ceramics. In the last 20 years of the 20th century, ceramic turbine engines were successfully made in the U.S., Japan and China. Ceramics can significantly improve the thermal efficiency of an internal combustion engine. Fuel consumption can be reduced by 30% given that the specific gravity of ceramics is only half of that of steels.

Research is still ongoing on developing high temperature structural ceramics, such as silicon carbide, silica, silicon nitride, boride, toughened zirconia ceramics and fibre-reinforced ceramic matrix composite. These ceramic materials can be used to make blades of gas turbines, pipelines and valves in petroleum industry, and bearing parts (Carter and Norton 2007).

It is hard to cut ceramics; this, in turn, inspired a new field of research, machining of hard and brittle materials.

9.3.3.3 Polymers

There are natural and synthetic polymers. Synthetic polymers fall mainly in 3 groups, namely plastics, artificial rubber and synthetic fibre. Polymers have relatively high strength-to-weight ratio and low electrical and thermal conductivity. Polymers have gained fast and wide applications in automobiles, civilian and military aircraft, sporting goods and toys etc.

Plastics were the first man-made polymer. The United States first made a thermal-plastic in 1856 and registered in 1870 as celluloid. Since then, hundreds of plastics have been invented and widely used in industry, military and daily life. Many mechanical parts, such as gears, are now made from plastics, reducing machine weight and saving valuable metals. In parallel with these applications, molding technology was developed.

Due to limited resources, production of natural rubber was unable to meet the increasing demand from industry, such as bicycle tires. In 1909, polymerizing Isoprene, the first synthetic rubber, was created. To the 1960s, more than 200 types of synthetic rubber had been developed and the output in the world exceeded that of natural rubber. To the 1980s the output of synthetic rubber further increased to more than twice of the natural rubber.

In 1936, polyamide fibre (Nylon 66) was successfully developed. After WWII, polyester, acrylic and polypropylene were invented. To the 1960s, some synthetic fabrics appeared, which had excellent heat-resistance, fire resistance and strength. Now synthetic fabrics have been widely used in applications of agriculture, industry, aerospace and communication.

9.3.3.4 Composites

In very early days, human already knew how to make bricks using straw and mud combined. Later concrete was invented. These can be regarded as ancestors of the modern composite materials that are made from two or more constituent materials. Examples include polymers, metals, and inorganic nonmetallic materials. Composites keep some properties of the constituent materials, and at the same time acquire some unique properties which the constituent materials do not have.

Properties of the composite materials could be optimized through material design. Thus, the two concepts, modern composite material and material design, are always go hand in hand.

The concept of “materials by design” was incepted in early the 1950s when the Soviet Union attempted to design alloys. In 1969 the idea to obtain artificial superlattices through mixing constituent materials was proposed. In 1985, a Japanese scholar put forward the concept of “material by design” for the first time (三岛良绩 1985). In the Chinese high-tech research plan of 1986, “material’s micro-structural design and performance prediction” was listed as a special topic (Xiong et al. 2000). In the United States, the National Research Council also pointed out in its report (1995) that we were in an era of tailoring material's performance through computational and theoretical techniques.

Composites with tailored properties can be created through combining different materials. At present, resin matrix composites are the most common among various composites. Thermosetting materials, in particular, are used widely and most mature in technology. Metal matrix composites are still in the stage of research with applications in aircraft components, space systems and high-end sports equipment. Ceramic matrix composites overcome the major disadvantages of conventional ceramics, such as brittle failure and low fracture toughness. Carbon-carbon composites, on the other hand, are light weight, strong and able to withstand temperatures over 2000 °C without loss of performance; therefore, great potential is shown in military applications. They are also used in automotive applications for making braking systems of high performance cars.

The historical development and a predicted future trend of 4 types of materials, including metals, polymers, ceramics and composites, are presented in Fig. 9.17 in which the year is the abscissa and the relative importance the ordinate (Chen et al.

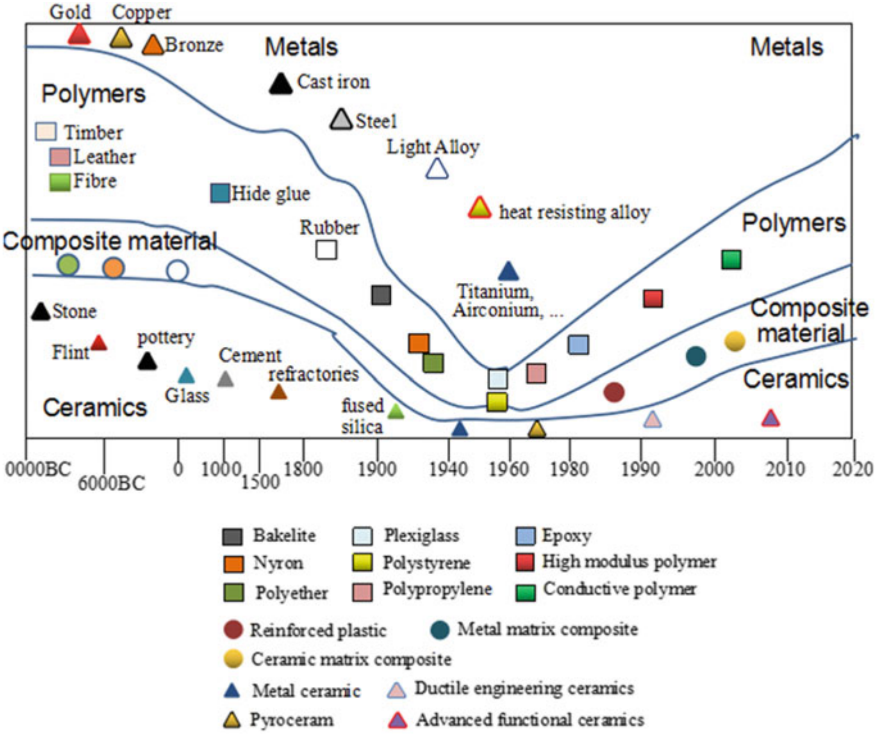


Fig. 9.17 Historical development of engineering materials

1997). Clearly, metals were the most dominant materials in the mid-20th century, and will keep its position in near future. While the other three types of materials will gain more importance down the road to a comparable level with metals.

9.3.4 New Energy

In the United Nations Conference on New and Renewable Sources of Energy held in 1980, the importance of new and renewable sources of energy was stressed. Prioritized developments were recommended, including solar energy, wind energy, biomass energy, tidal energy, geothermal energy, hydrogen and nuclear energy (Wang and Ai 2006).

9.3.4.1 Nuclear Energy

The root of nuclear power is traced back to the New Physics Revolution around the early 20th century. The first application was in military. In 1942, the United States successfully built the first man-made reactor. In 1945, the first nuclear bomb of the world was tested in the U.S. Shortly after, the Soviet Union, United Kingdom, France and China also achieved success in development of nuclear weapons.

In the 1950s, peaceful use of nuclear energy was brought forward. The Soviet Union, United Kingdom and United States developed their nuclear power plants during this period. To 1966, the cost of nuclear power went down below that of traditional thermal power. Up to the year of 1978 more than 200 nuclear power plants with a capacity above 30 MW were in operation all over the world.

During the 1970s and 1980s, the oil crisis hit the world economy, slowing down the demand for electricity. At the same time, two accidents, one happened at the Three Mile Island of the U.S. in 1979 and the other at Chernobyl of the Soviet Union in 1986, caused wide concern on the safety of nuclear power. Then new plant construction in many countries slowed down, and nuclear power went into a low tide.

After the 1990s, great progress was made in making safer and more affordable nuclear facilities; thus, interest in nuclear power was resuming to some degree. A report from the International Atomic Energy Agency (IAEA) indicated that there were totally 438 nuclear power plants under operation in the world up to 2012. These plants generated about 16% of the total electricity output of the world. The largest was the Fukushima Daiichi Nuclear Power Plant in Japan, which, unfortunately, was damaged in the disastrous earthquake in March, 2011.

The first robot in the world was actually dedicatedly developed for moving nuclear fuel in nuclear power plants.

9.3.4.2 Wind Power

Wind power (Fig. 9.18) is plentiful, widely distributed and renewable. It has special significance to some remote areas, isolated islands and communities where power grid may not be available. The United States Department of Energy (DOE) concluded after a survey that the wind power resource in only Texas and South Dakota would meet the electrical demand of the whole country if properly developed.

Wind power has been used by humans for thousands of years. However, relevant technologies once moved very slowly. The first wind mill for generating electricity was built by a Scottish engineer in 1887 on his cottage. Shortly after, wind power systems were built in the United State and Denmark (Cleveland et al. 2004). Denmark made special contribution to wind power development partially because of its scarcity in fossil fuels. In 1957, a wind turbine having 3-blades, a capacity of 200 KW, and a rotor diameter of 24 m was installed in Gedser, Denmark, which became the icon of the "Danish wind turbine" representing several decades of successful development of wind turbines thereafter.

After the oil crisis in the 1970s, the U.S. and West European countries started to invest on the development of wind power technologies. Thereafter wind power went into a fast track along two different routes. The first was to develop large scale wind turbines, Countries going into this route include the U.S., Britain, Germany, Sweden, and Canada etc. Generally the large projects were state sponsored given the complexity and large investment requirement. The capacity and size of the wind turbines have been in continuous increase, and no sign is shown in near future for this trend to stop. In the recent decades, the development of offshore wind power systems have pushed the trend even further. China has also chosen this route and kept a very fast growth in the development. In contrast to the state supported large projects, small wind turbines have also achieved great success, in Denmark in particular. Danish manufacturers have marketed their wind turbines on a large scale in the European countries. Also their products have been exported to the U.S. very successfully (Schaffarczyk 2014).

Fig. 9.18 Coastal wind power station

To the year of 2008, wind power produced more than 1% of the total electricity consumption in the world. China, although starting late, is catching up quickly in this field. In the off-grid wind power in particular, China has the largest turbine manufacturing capacity, maintaining and producing the most turbines in the world (Wang and Ai 2006).

9.3.4.3 Solar Power

Solar power is regarded as the safest, greenest and most ideal renewable energy (Wang and Ai 2006; Liu 2010).

In 1920 solar water heaters started to be widely installed in California of the U.S. In 1954, Bell labs in the U.S. successfully made the 1st practical silicon solar cell. Thereafter interest in solar power started to grow.

After the oil crisis in the 1970s, interest in renewable energy raised. The solar power industry was established. However, this new industry was not economically competitive due to its small scale at the beginning. With the dropping of oil price in the 1980s, the enthusiasm on solar power quickly dropped.

After the 1980s, environmental pollution and ecological damage became a world concern. The United Nations Conference on Environment & Development was held in 1992. The main countries in the world turned sight to renewable and clean energy again. Solar power started to climb up the trough.

The most straightforward way to use the sun energy is by using photovoltaics (Fig. 9.19). The sunlight is directly converted to electricity by semiconducting materials (commonly crystalline silicon). With the rapid growth of solar power, a new industry, so called "photovoltaic industry", has been gradually taking shape, including manufacturing of the refined multi-crystalline silicon, and solar cells. It is expected that the photovoltaic industry will experience explosive growth that the IT and micro-electronic industries have had.

Fig. 9.19 Solar photovoltaic

9.3.4.4 Tidal Power

The usable resource of tidal energy in the world is estimated more than one billion KW.

The first practical large-scale tidal power project in the world was the Rance Tidal Power Station in France built in 1966 (Fig. 9.20). It is located on the estuary of Rance River which has an average tidal range of 8 m and a maximum tidal range of 13.4 m. Electricity is generated when tides come in and go out.

There are more than 20 sites suitable for construction of tidal power stations in the world. All are under consideration or in design process.

9.3.5 Modern Bio-technology

Genetic engineering is in the center of modern bio-technologies. Genetic engineering consists of various techniques to manipulate, modify and recombine the DNA of an organism. Through the transfer of genes within and across species boundaries novel organisms can be produced or improved.

60% of biotechnologies finds applications in the medicine industry, causing a revolution to the industry. In the agricultural field, biotechnologies can make land more productive and food greener. While in the manufacturing industry, they are

Fig. 9.20 Rance tidal power station

used to control pollution and energy consumption. In addition, biotechnologies are also used to recycle wastes and turn them into reusable materials.

Biotechnologies become the primary driving force to the new economy. The Human Genome Project was launched in 1990 and completed in 2003, marking another milestone in the history of science. The incremental value of stocks of biotechnologies in the U.S. in 2000 exceeded the total investment of the previous 5 years. The industry of biotechnologies now is approaching maturity after about 30 year development.

In 1978, the first successful birth of a child with the in vitro fertilisation process occurred. In 1996, the first cloned domestic sheep, Dolly, came to the world. These success, however, caused wide ethical concerns, and debating has never been stopped.

Biotechnologies need support from mechanical engineering, requiring micro-robots to manipulate objects in the scale of micrometers or smaller inside cells.

9.3.6 Marine Engineering

Marine engineering is the discipline dealing with ocean power, offshore drilling, desalination of salty water, exploitation of offshore oil and gas, naval architecture etc.

It is estimated the petroleum deposits in this planet of on-shore, shallow-water and deep-water are in the ratio of 1:10:100. The origin of offshore oil exploitation was traced back to the 19th century in the U.S. Real development, however, did not came until the 1960s. The UK, Norway, and France also have rich offshore oil and gas resources. Norway and the UK made almost all their shipyards focusing on offshore platform construction. Consequently Norway had to purchase all its transportation ships abroad, and the UK only kept warships constructed domestically. The development of the North Sea oil turned both the UK and Norway from oil importers to exporters. It is estimated that the total number of various offshore platforms exceeds 10,000 all over the world.

The oceans with a water depth above 300 and 1500 m are generally referred as deep water and ultra-deep water, respectively. Now exploitation activities are moving toward deep water.

An offshore platform (Fig. 9.21) is generally sized between 4000 and 5000 m^2, and contains various production, service and living facilities. It is designed generally for a life span of 20–30 years, and subjected to very harsh operational environment. Thus offshore platforms are very costly, and the design and construction requirements are very high, involving many engineering areas, such as mechanical, shipbuilding, electronic, metallurgical, and petroleum engineering.

It is estimated that the mineral deposits, excluding oil and gas, under the ocean make up 3/4 of the total on the earth. The U.S. president, Harry Truman (1884–1972), declared in 1945 to move to the boundary of the continental shelf for mining

Fig. 9.21 Marine oil platform

mineral resources. In the 1950s, phosphorite deposit was found along the California coast; later manganese nodules were detected under the Pacific Ocean. With the maturity of deep water oil technology and the increasing price of some precious metals, such as copper, nickel and cobalt, deep water mining is drawing more and more attention. The challenges currently lie in two folds, the mining technology and environment protection.

Marine and mechanical engineering actually are two closely linked disciplines. All offshore structures require dynamic analysis and fatigue strength calculation under various loads. For deep sea drilling and exploitation purposes, remotely operated underwater vehicle (ROV) has been developed.

9.4 Characteristics of Third Technological Revolution

The 1st and 2nd Technological Revolutions are both related to power; while the 3rd one is around information revolution led by computer technology.

9.4.1 Characters of Third Technological Revolution

The 3rd Technological Revolution has some unique features which the previous two did not have (Huang 2006).

9.4.1.1 Team Work and Social Involvement

In the 1st and 2nd Industrial Revolutions, an inventor often did all the relevant work independently, from inception of concept, through design, to construction of prototypes.

To the 1950s, engineering had become so complicated that an individual person's knowledge was not adequate to develop a project or product. Instead team work is common in engineering. In some cases, large projects in particular, the team may be very large, having members from many companies, institutions and government departments. A good example demonstrating this trend was the Project Apollo in which more than 120 universities, 20 thousand companies and 4 million people participated (GSHCAS 1985).

Governments played an important role in the 3rd Technology Revolution, mainly in the development of large projects. After WWII, the governments in the main industrialized countries started to invest heavily on large critical research facilities which were beyond the ability of individual company or institution. These facilities are mainly for basic research and applied research in hi-technologies involving multidisciplinary or multi-institutions. The Manhattan Project in the United States was the first of such large projects; other examples included the International Thermonuclear Experimental Reactor (ITER) and international projects in high-energy physics.

After the 1980s, the main countries in the world proposed or made national plans for science and technology development. The United Stated started the Strategic Defense Initiative of the United States in the 1980s and the Information Superhighway in the 1990s. Japan made its plan for constructing Nation via S&T Strategy. Europe made an intergovernmental organization, EUREKA, to coordinate research and development funding. China launched its science and technology development plan in March of 1986, the so called 863 Program.

9.4.1.2 Multidisciplinary

Two opposite trends are obviously taking shape in the development of science and technology. On the one hand, the appearance of new inter-disciplinary subjects makes the number of disciplines increasing all the time. On the other hand, inter-reaction between disciplines becomes more common. Scientific research and technological development tend to be more comprehensive, involving multiple disciplines.

Knowledge from single discipline couldn't solve all the problems encountered in an engineering project; thus, multi-disciplinary study had to be applied. For example, robotics involves micro-electronics, new materials, computer software and mechanical engineering. On the other hand, new disciplines are formed on the border between different disciplines. Biological engineering and mechatronic engineering are two such examples.

Large science projects clearly demonstrated the multi-disciplinary feature in science and technology.

Some architects and designers made effort to combine computers, 3D printing, materials and biology into a completely new system in which the microorganisms, the occupants, other products inside and the house can exist harmonically and be interacted (Schwab 2016).

9.4.1.3 Closer Link Between Science and Technology

In the first two Technological Revolutions, science and technology were basically separated from each other. In some cases, theory came first, but it took a long time for the theory to cause technological innovation. In some other cases, technologies appeared first and theory was developed after many years to interpret the technology. For example, the steam engine was first invented by Watt; the theory of heat engine was, however, created after more than 30 years by N. Carnot.

The 3rd Technological Revolution linked science, technology and production closer. All the ground-breaking technologies after WWII were developed under the guidance of theories. These technologies, in turn, accelerated the progress and enriched the content of the theories.

9.4.1.4 Faster Technology Transfer and Innovation

Technology transfer became faster and faster. For example, the time it took from invention to application for several technologies is given below:

- Steam engine and electric motor: dozens of years
- Radar: 10 years
- Nuclear energy: 15 years
- Transistor and mobile phone: 4 years.

Besides, technologies upgraded faster than before. According to some statistics from the U.S. Congress, about 40% of the technologies developed after WWII has become obsolete. Electronic computers have developed into the 5th generation in about 40 years. Personal computers have a main upgrading almost every two years.

The closer link between science and technology was attributed as the primary reason for the faster pace. New findings in science were quickly trickled down to ground-breaking technologies or innovations. It took less than 2 years from the discovery of laser to its application in practice.

The closer link between production and technology, and production and science was credited as another reason. Universities and the industry were getting closer. Spin-off companies were created by university professors and students, for example Bill Gates and the Microsoft. In the United States, it is common for some giant companies to do basic research. This type of research may seemingly not be related to the company business, but will benefit the company in long term.

9.4.1.5 Leading Role of the U.S.

The 3rd Technological Revolution started from the U.S. Many theories and ground-breaking technologies, including system science, nuclear energy, electronic computers, were born in the U.S. Thus, the United States have been in the incomparable leading position in this Technological Revolution.

Many reasons are responsible for this fact (Peng 1993).

(1) The United States is favorably located, being rich in natural resources, huge in domestic market, and not neighboured with big power.
(2) The United States was the first constitutional democratic country in the world. Americans consist of immigrants from all over the world. These immigrants brought different cultures and traditions to the new land. This was really favorable for innovation.
(3) In WWII, the U.S. was one of the very few countries whose land was not directly attacked.
(4) The Nazi party seized power in Germany, causing unprecedented "knowledge refugee" (see Sect. 8.2). Many outstanding scientists and talents came to the United States.
(5) After WWII, the U.S. government took important measures to push and advocate the development of science and technology.

9.4.2 New Industrial Revolution

The 3rd Technological Revolution influenced the human society far beyond the previous two counterparts did. It dramatically increased the productivity of the world, becoming one of the most important driving forces behind the human society (GSHCAS 1985).

The 3rd Technological Revolution triggered a new Industrial Revolution. About this industrial revolution no consensus has been reached yet. One view is that it already started in the 1960s and reached its peak around the 1980s. The center of this revolution was the digitalization with computers.

Almost all the main contents of the 3rd Technological Revolution, particularly renewable energy, new materials, internet of things (IoT), 3D printing and robotics, have found their position in and caused dramatic changes to the industry. Some scholars regard this a new stage of the 3rd industrial revolution; while some others tend to call this the 4th Industrial Revolution (Schwab 2016).

The new Industrial Revolution will continue to reshape the world with many changes.

9.4.2.1 Economy Structure Change

The new industrial revolution has basically re-structured the economy of the main industrialized countries in the world. In the first place, the primary and secondary industries dropped while the tertiary climbed up. Secondly, the labor and capital-intensive sectors, such as iron and steel making, mining and textile, came into stagnation or even recession. In contrast, the technology intensive industries, including computers, nuclear energy, semiconductor, aerospace, laser, and artificially synthetic materials, grew fast.

The changes in economy structure brought changes to the society. The number of white-collar workers exceeded that of blue-collars. Taking the United States in the 1970s as an example, the people employed in the manufacturing industry decreased from 30 to 13% of the total labor force; while people working in the service sectors climbed up from 15 to 72% of the total labor force.

9.4.2.2 New Production Mode

Accompanying the other changes were the significant improvement of living standard and more diversified customer needs for commodities. To meet the changes, the production mode was shifted from the mass production, producing large amounts of identical products, to batch production, making small quantities of products with more variation. An extreme of this change is toward the job production, in which customized products are manufactured. Both virtual and real activities are involved in the production. Corresponding to the change in production mode, operation of business will also be changed (Schwab 2016).

9.4.2.3 New Stage of Human Society

After mechanization and electrification, human society is approaching a new automation and intelligent stage. In the main industrialized countries of the world, industrialization has been completed, and the society is being in the post-industrialization or information stage. In an information society, the economy is frequently called “knowledge economy”. The fast-developing network technology and computer software are icons of the knowledge economy.

9.4.2.4 Changes in Way of Life and Work

Along with the advance of technology, the daily life of people has been changed in almost every aspect, including the way of thinking, behavior, life style etc.

With the wide application of computers, automation in production, office and home, the so-called 3A, becomes a reality. The modern communication technology greatly shortened the distance between people around the world. On the other hand, space and ocean exploration extended the scope of human activity. Humans are becoming “residents not only of the earth.”

9.5 Progress in Mathematics and Mechanics

9.5.1 Numerical Algorithms

Many mathematic problems have no closed form solutions; thus, numerical methods have to be relied on. This fact was realized very early and alternative methods were sought. In China, Qin Jiushao proposed a numerical method solving polynomial equations early in the 13th century (Libbrecht 1973). Newton proposed the base of the Newton-Raphson method which uses the tangent to find an approximate root of an equation. J-L Lagrange, C. Hermite also proposed different interpolation methods in the 18th and 19th century, respectively.

However, the real development of numerical methods happened only after WWII, mainly because of the following two reasons (Chen 2007):

(1) Numerical methods were needed by large projects, such as passenger planes, large dams, nuclear fission, oil and gas deposit simulation and weather forecast. In these problems, the variables might reach millions or even tens of millions, and high efficiency, high accuracy, and auto-meshing were required. These created a real need for efficient and large scale numerical methods.

(2) Computers provided the technical base for large scale numerical calculation. The computation power of computers completely changed the traditional thought of computation.

In the past several decades, numerical computation technologies have been developed very fast. The efficiency of these numerical methods has also been dramatically increased with the increase of computation power of computers.

As Shi Zhongci, an academician of Chinese Academy of Sciences, put (Shi 2000, 8–14):

> Computation does not only serve to validate theoretical models, but also has become an important tool in scientific discovery as demonstrated by many examples. Scientific computation along with experiments and theory have become the three cornerstones in scientific activities.

Some numerical methods related to mechanical engineering are outlined below.

9.5.1.1 Numerical Solution of ODE

Many dynamic problems are mathematically represented by ordinary differential equations (ODE) with known initial conditions. Numerical solution of ODE, thus, constitutes the foundation of dynamics. Linear ODE can be solved analytically; however, most real dynamics problems are nonlinear in nature. Numerical methods some times are the only option.

The initial value problem of ODE was first proposed by L. Euler in 1768. During the 19th century, the famous Runge-Kutta method was formulated. Since then it has been widely used by engineers and scientists.

After WWII, the responses of complicated engineering systems to dynamic loads attracted much attention. For example, for the safe operation of nuclear power plants, the structure response to earthquake has to be checked. Similarly, offshore platforms are subjected to very harsh operational and environmental loads, such as ocean wave, storms and earthquake etc.; therefore, the safety of the platform and the people working on it has to be the primary consideration in design. On the other hand, the dimension (or size) of the system and components have to be limited for economical reason. The dynamics of such systems is generally with the following features: huge number of DOF, very complicated dynamic loads, and nonlinearity. The numerical methods for solving initial value ODE was developed primarily for the need of dynamics study on these large engineering structures.

A Swedish mathematician, Germund Dahlquist, investigated the stability and error of numerical solutions of ODE in 1958. Several important numerical integration methods were proposed between the 1950s and the 1970s (Hall and Watt 1976). One interesting thing is that almost all the numerical methods for solving ODE were formulated by experts working on specific fields, not dedicated mathematicians.

Some dynamic systems of multiple DOF, such as open-chain mechanical systems and systems with clearances, contain both fast-changing and slow-changing variables. The ODE of this type are called stiff. For stiff equations, small integration time step should be chosen. However, the requirement for small time step can’t be released even after the fast-changing components approached stable. Otherwise errors will be sharply increased. In 1968, Charles Gear developed a multi-step method based on backward difference formulas, solving the problem with much higher stability. Software packages have been developed to implement Gear’s method, making it probably the most widely used method for solving stiff systems (Li 1997).

9.5.1.2 Finite Element and Boundary Element

Elastic mechanics is an old subject which is characterized by a set of PDE relating force (or stress) to deformation (or strain) within elastic objects. However, analytic solutions are available only for a few of special cases with very simple geometry. For the general cases, there is no closed form solution available. Finite element method was developed initially for solving problems of elastic mechanics.

During the 1940s, the aeronautic industry experienced fast growth. The design of plane structures faced two conflicting requirements, light weight and adequate strength (or rigidity). Thus the strength and rigidity had to be carefully computed and evaluated in the design.

Ray Clough, an American scholar, made special contribution to the development of finite element method (FEM) and its engineering application. In the analysis of vibration of a plane wing of triangle shape (the Delta wing), he first used the traditional beam theory, but got disappointed results. Then he tried to formulate the stiffness properties by assembling plane stress plates of triangular shapes. With this method good agreement was obtained between the calculated deformation and the measured result. The method was formally published as a paper in 1956, but with a name of direct stiffness method (Clough and Wilson 1999). In 1960, Clough used the name of FEM the first time. Initially some scholars were skeptical to the FEM because the strain assumption of FEM was coincident with a very earlier concept. A well-known journal in applied mechanics even refused to publish papers of FEM for several years. On the other hand, engineers were well aware its potential in practical application, but not equipped with proper computer programs. One of Clough's graduate students started to develop an automated finite element program in 1958, which greatly pushed the application of FEM in engineering.

A Chinese scholar, Feng Kang, developed independently the finite difference method based on variation principles in computation of dam constructions in the 1960s when China was actually isolated from the western world. Feng was credited as one of the pioneers in FEM to the end of 1970s (Yu 2001).

Elastic mechanics, combined with computers and FEM, gained great power in application. The application of FEM has been widely expanded since its birth, specifically as below:

- From structural statics to dynamics and reliability analysis;
- From two-dimensional problems to 3-dimensional problems and plate and shell problems;
- From linear elastic materials to plastic, viscoelastic, viscoplastic, thermal viscoelastic, thermal viscoplastic and composite materials;
- From small deformation (linear) to large deformation (nonlinear) problems;
- From analysis to optimization;
- From solid mechanics to fluid mechanics.

FEM now can solve almost any problems of continuum mechanics and continuous field, including problems of stress, strain, vibration, temperature field, and electromagnetic field etc.

The boundary element method (BEM), similar to FEM, is another numerical computational method which is mathematically based on the theory of integral equations of partial differential equations (PDE). Study was initiated in the 1970s at the University of Southampton, England. To the 1980s, research focus was shifted from theory and methods to application. BEM has been very successful in dealing with some problems, such as wave propagation, fracture mechanics, and vibration etc. (Brebbia 1991). BEM only meshes the surface; thus, the number of elements in BEM is much smaller than that in FEM for problems, and the computation intensity could be greatly reduced. In addition, BEM can also solve the infinite field problem which FEM is not capable.

9.5.1.3 Mathematical Programming

The unconstrained function optimization is originated from the maximum-minimum problem in calculus. Methods for unconstrained optimization include gradient, Newton's and Lagrange multiplier's methods. However, these old methods were not able to solve the optimization problems encountered in the latter-half of the 20th century.

Operations research originated from military-planning in the effort to optimize the logistic and supportive activities. Linear programming is a branch of operations research dealing with the management of production, transportation and stock. Similar to the operations research, linear programming also originated from military, but later expanded to economical fields. During WWII, a research group was formed on the request of the US Army Air Force. The well-known simplex method was first proposed by a scientist in this group, which is still widely used nowadays for solving linear programming problems. Now thanks to powerful computers, problems of linear programming with dozens of thousands variables and constrains can be solved easily (Gass 2010).

In many fields of engineering, however, the optimization problems are nonlinear. Thus, nonlinear programming became a research topic (Bertsekas 1999).

The search methods for mathematical programming can be outlined as below:

- Conjugate gradient method:It is a method first proposed by an American mathematician utilizing the derivative of the objective function.
- Quasi-Newton methods: they are a group of methods based on the Newton's method, and also called variable metric methods. This type of methods need the second derivative information, being generally faster than the conjugate graduate method.
- BFGS method: It belongs to the quasi-Newton methods and was named after four scholars.
- Direct search methods: They are a group of methods, and also called Monte Carlo methods in which no derivative information is needed. These methods have lower efficiency, but have more chances to find the global optimization solution.

Optimum design is the application of mathematical programming in engineering design. More details will be given in Sect. 11.4.

9.5.2 Progress in Vibration Theory

Three achievements in mechanics occurred during the 3rd Technological Revolution are closely related to mechanical engineering. They are the progress in vibration theory, the creation of multibody dynamics, and the development of fracture mechanics.

In this section we discuss the vibration theory and multibody dynamics, leaving the fracture mechanics to Sect. 13.5.2.

In the 20th century, vibration became an outstanding problem for many engineering systems, such as risers of offshore systems, oil and gas pipeline, cranes, automotive vehicles, airplanes, rockets, turbines, pressure containers, boilers, heat exchangers, and nuclear reactors etc. Thus, intensive research has been conducted toward these problems. In addition, research on vibration of continuum, including string, beam, plate and shell etc., was actively continued. To the time of 1950s–1960s, the linear vibration theory approached maturity and a systematic theoretical frame was formed.

After WWII, the classical vibration theory continued to develop. To the 1970s, some new and emerging technologies, such as automatic control, computer, FEM and measurement technologies, were absorbed into the classical vibration theory.

The classical vibration theory achieved great success in dealing with discrete systems. However, for continuum systems the governing equations are in the form of partial differential equations. For very simple shapes, the governing equation can be derived with the classical vibration theory. For objects with complicated geometry, however, the classical vibration theory is incapable in both deriving the governing equation and finding the solution.

9.5.2.1 Inverse Problems

Traditionally vibration focuses on direct problems in which the response is predicted with known system parameters and excitation. After WWII, however, research on inverse vibration problems grew fast. There are actually two types of inverse vibration problems. The first type is also called experimental modeling in which the model is obtained through experiments. This is very useful when some system parameters, such as damping, friction, clearance, and time-lag in control, can't be determined through analysis; thus, it is regarded as an aid to the usual theoretical modeling (direct problems). The other type is called load identification from which a new subject, fault diagnosis, is in fast growing. The direct and inverse vibration problems are schematically shown in (Fig. 9.22).

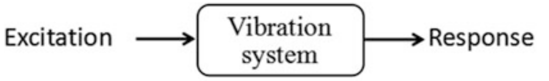


Fig. 9.22 Three problems in vibration

Exc.	Sys.	Res.	
known	known	?	Direct problem
known	?	known	Reverse problem 1
?	known	known	Reverse problem 2

9.5.2.2 Random Vibration

The classical vibration theory deals with systems with deterministic excitation. The deterministic means that the excitation at any time instant is fully known, or predictable. However, in some engineering fields, the excitation is random and could not be represented by a deterministic function. Typical cases include: plane's vibration under air turbulence, automobile vibration under the unevenness of road surface, and offshore platform's vibration under ocean waves. Random vibration, as a branch of vibration theory, deals with deterministic systems subjected to random excitation.

The mathematic basis of random vibration includes probability and random processes which deal with random variables and processes. Theory about random variables was already mature in the 19th century; while theory of random processes started to develop in the early 20th century (see Sect. 6.1).

A. Einstein was regarded as a pioneer in random vibration; he built the 1st theoretical model on Brownian motion in 1905. J. Rayleigh was the first to use the word, random vibration, in 1919 (Zhu 1998).

After WWII, investigations into accidents and failures of some engineering systems directed some researcher's attention toward the randomness in vibration. These systems include offshore platforms, rocket launching vehicles, and airplane on-board instruments etc.

In the mid. 1950s, some new vibration issues from the aerospace and military industry caught the attention of researchers. Three typical such vibrations observed at that time included: (1) the vibration of airplane under atmospheric turbulence; (2) the vibration of airplane fuselage panel in the neighborhood of jet engines, which was so severe that the fatigue cracks rapidly developed due to the acoustic excitation from the jet exhausts; and (3) missile vibrations during launching process (Paez 2011; Roberts and Spanos 2003). A common feature in these vibrations was that the excitation was random, thus, could not be represented as a deterministic function of time. Therefore, a new theory was called for to deal with these new problems. In the random vibration theory, effort is focused on obtaining the relationship between the response and the excitation in probabilistic or statistic sense. The individual excitation and response time history, which are the core in the classical deterministic vibration theory, become insignificant. In fact, the relevant theory had already existed then in some other engineering fields, such as statistical mechanics, communication and turbulence theory. Thus, the initial theoretical framework of random vibration was formed by directly grabbing the existing theories from those fields.

A symposium was held in 1958 at MIT and the publication of the collected papers under the title Random Vibration, edited by Stephen Crandall, marked the birth of a new subject (Crandall 1958).

Most researchers of random vibration started from time-invariant linear systems; however, after several years research effort was quickly shifted to nonlinear random vibration problems.

9.5.2.3 Nonlinear Vibration Theory

As stated in Chap. 6, nonlinear dynamics can be analyzed qualitatively and quantitatively. The qualitative research is the 1st stage, and the methods in this stage were mainly developed before the end of the 19th century. The quantitative research is the 2nd stage. Quantitative methods were developed later, and the theoretical framework was formed around the 1960s. The monograph *Nonlinear Oscillations* by Nayfeh and Mook (1995) summarized the work on the 2nd stage, being regarded as the most representative book in nonlinear vibration.

The discovery of chaos can be regarded as the 3rd stage in nonlinear dynamics (Chen 1993; Zhang et al. 2002). During this stage, the research focused on some complex nonlinear phenomena, such as bifurcation and chaos.

In the past 40 years, researchers analyzed many types of bifurcations, the route to chaos and chaos structure etc. At the same time, applications of bifurcation and chaos were also found. These theoretical and application work make up a very broad system of nonlinear dynamics.

The theory of nonlinear dynamics has been applied broadly in machine dynamics (Chen et al. 2007; Zhang et al. 2002). To name a few:

(1) nonlinear vibration of the flexible robotic arms in aerospace craft and stations, antennas of satellites, tether satellites, and solar arrays;
(2) vibration of flexible robots and flexible mechanisms;
(3) vibration of the crank-shaft and valve-train in internal combustion engines;
(4) vibration of the rotor in large generators;
(5) oil whiling of journal bearings, vibration of gear trains and viscos-elastic belts;
(6) chattering in machining process;
(7) stability and hunting oscillation of high speed trains;
(8) vibration of solid-fluid coupling systems, such as hydropower units, and its structures under the action of the fluid.

It is worth to mention that research on bifurcation and chaos now is limited to low-dimensional systems. However, it is moving upward and the scale and difficult level of problems which nonlinear dynamics theory can handle are expected to increase.

9.5.3 Multibody Dynamics

During the 1960s, a new branch, multibody dynamics, speared out of the classical mechanics. Two important factors contributed to the birth of this new mechanics branch.

(1) More complex objects

With the development of science and technology, many complex systems, such as automobiles, space craft, robotics, mechanisms and even human body, became the object of investigation in dynamics. These systems are composed of multi-individual objects either rigid or flexible.

(2) Computer in dynamics

Computers gained wide applications in almost every aspect of science and technology. Computer's power was increased dramatically in both numerical and symbolic computation, making it possible to derive equations automatically.

9.5.3.1 Rigid Multibody Dynamics

Technically, the governing equations of a rigid multibody system can be derived with the classical methods in analytical mechanics, such as the Newton-Euler method and Lagrange method. However, the constrained forces in the Newton-Euler method and the terms in the energy functions (kinetic and potential energy) will be dramatically increased with the increase of the body number in the system. Then the derivation may quickly become unmanageable.

A straight forward idea is to let computers do the tedious job. For this purpose, the methods in mechanics should be made suitable for the computers. This created the multibody dynamics, which was targeted at complex systems and took advantage of computer's, power in modeling and solution.

The two pioneers in multibody dynamics included an American scholar, Thomas Kane, and a German scholar, Jens Wittenburg.

In 1965, Kane and Wang proposed a method for dynamics analysis of complex systems (Kane and Wang 1965). In this method, the motions of bodies were represented by generalized velocities, instead of generalized coordinates. Then the generalized active forces and inertial forces in vector form were projected along the unit vectors to eliminate the constraint forces. The Kane method combined the advantages of vector mechanics and analytic mechanics; thus, wide application was found in dynamics of robots. The Kane, Newton-Euler and Lagrange methods became the main three methods of dynamics modeling.

In 1966, Roberson and Wittenburg adopted the graph theory to represent connected rigid bodies. The graph theory, along with other mathematic tools including matrix, symbolic vector and tensor notation etc., gives a general presentation of kinematic relationships, nonlinear equations of motion, energy expressions and other relevant quantities, making it very suitable for computers (Roberson and Wittenburg 1966; McPhee et al. 1996).

Literally, rigid multibody dynamics did not have any new contents beyond the classical vector mechanics and analytic mechanics. However, it creates new representation of the system and makes it suitable for computer to work. In view of this fact, the work by Roberson and Wittenburg was regarded as the landmark signaling the birth of rigid multibody dynamics. Wittenburg also wrote the earliest monograph which for the first time made a complete and systematic iteration of this topic (Wittenburg 1977).

Multibody dynamics, similar to the analytic mechanics, became a branch of classical mechanics through generalizing the formulism of representation to the system. The rigid multibody dynamics has been maturely developed in theory, modeling and analysis, and dozens of commercial software packages are widely used. For these packages, the user is only required to give input of the parameters and description of the system structure, all other works, modeling and derivation, are left to the computer.

Broadly speaking, Newton, Euler, Lagrange, Wittenburg and Kane all looked at the dynamics involving multibody. In view of this, some scholars put all these scholar's work under the umbrella of "multibody dynamics". However, the multibody dynamics in strict sense generally means the methods developed after the 1960s which are especially suitable for computers.

9.5.3.2 Flexible Multibody Dynamics

Flexible multibody dynamics deals with modeling and analysis of flexible multibody systems which are generally constrained and move in large space. The large displacement contains both rigid motion and elastic deformation. The subject was formed in the early 1970s, being a natural extension of the rigid multibody dynamics.

One typical object in flexible multibody dynamics is various space crafts, which are designed more and more complicated in structure due to the many supposed tasks. For example, solar panels and slender antenna are installed in many satellites. These flexible structures experience significant elastic deformation in operation that may affect the attitude control accuracy. The robotic manipulators in space stations are also subject to elastic deformation which negatively influence the accuracy of positioning and trajectory. In the 1950s, there were reports that American satellites went out of control. These needs and accident cases led to the realization that rigid multibody dynamics was not capable of dealing with the dynamics of space crafts.

In some robots and high-speed mechanisms, the flexibility of parts is also nonnegligible. In the past, they might be designed conservatively with over-size; thus, their dynamics can be analyzed based on the rigid body theory. However, with the increase of operation speed and the adoption of light-weight design, the elastic deformation of parts become significant, and more accurate methods taking into consideration of the elastic deformations are required.

Starting from space crafts, the theory of flexible multibody dynamics started to develop in the 1970s. Edward Haug and Ahmed Shabana were two pioneers (Shabana 1997; Song and Haug 1980; Yu and Hong 1999).

In a roughly parallel time line, another method called Kineto-Elastodynamics (KED), which considers the elastic deformations of links, was developed in high-speed mechanism dynamics (Zhang et al. 1997). However, the flexible multibody dynamics in strict sense does not include the KED.

The main challenge in flexible multibody dynamics is the coupling of the large rigid motion and the relatively small elastic deformation. This makes it differentiating from structure dynamics and rigid multibody dynamics. The coupling of the two types of motion leads to strongly nonlinear equations in flexible multibody dynamics, and brings some difficulties to modeling and simulation.

Although flexible multibody dynamics has been developed for many years, progress focuses on theory. Application in real engineering is still in a much lower level compared with its rigid counterpart.

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Chapter 10
Summary of Mechanical Engineering in New Era

> *The First Industrial Revolution used water and steam power to mechanize production. The Second used electric power to create mass production. The Third used electronics and information technology to automate production.*
> —Klaus Schwab (German engineer and economist, 1938–): *The Fourth Industrial Revolution*, 2016

10.1 Introduction

After WWII, a new Technological Revolution took place, and fundamentally influenced almost every aspect of human society. Meanwhile, the world was remained in peace overall, growing fast in economy. Globalization formed a world market. On the other hand, competition became tougher, forcing manufacturers to continuously improve product quality, and develop innovative products in order to keep their competitiveness.

Mechanical technology and the machine building industry were advancing forward in all aspects during this period.

10.1.1 Four Driving Forces Behind Mechanical Engineering

Behind the progress in mechanical engineering were the following important driving forces.

10.1.1.1 Change in Market Requirements

In the new era, market requirement on mechanical products became higher and more comprehensive. Many machines, on the one hand, tended to be of high speed

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and heavy duty. On the other hand, the requirements on machine products became higher and tougher; these requirements in general include lighter weight, higher reliability, higher precision and accuracy, more cost-effectiveness, more environmentally friendly, and higher safety and comfortability standards etc.

10.1.1.2 Changes in Production Mode

The production mode changed fundamentally. Ford Motor invented the mass production mode in 1914. Mass production of coincident products was achieved through moving assembly lines. Mass production was dominant until the 1960s–1970s with the primary objective to increase productivity. However, two changes came during the 1960s–1970s. First, the improvement of living standard led to diversified requirements on products; thus, the large quantities of coincident products could not meet the requirement any longer. Second, with the intensive market competition, the seller's market was changed to a buyer's market. To respond to the changing market, the traditional mass production gave place to mode of medium and low quantities, but with more variation in the products.

10.1.1.3 Relationship Between Technological Revolution and Mechanical Engineering

The relationship between the new Technological Revolution and mechanical engineering is illustrated in Fig. 10.1. Obviously there are interactions between the Technological Revolution and mechanical engineering. On the one hand, the new technologies created during the Technological Revolution, such as the technologies of information, space, new energy, new material, marine, and biology etc., provided either technological support or theoretical input to the mechanical engineering. On the other hand, advance of these new technologies also needed support from mechanical engineering, for example, to provide production equipment. In either way, supporting or being supported, a driving force was applied to the mechanical engineering.

As shown in Fig. 10.1, information technology provides the mechanical engineering with new control strategy; application of computers makes CAD and CAM a reality. At the same time, manufacturing systems of IC need the mechanical engineering to provide precision manufacturing equipment. Similarly, exploration in space, deep-ocean and micro world needs specially designed robots. On the other hand, these exploration activities may create new materials which in turn support the mechanical engineering, and also put forward new challenges to the mechanical engineering for machining these new materials.

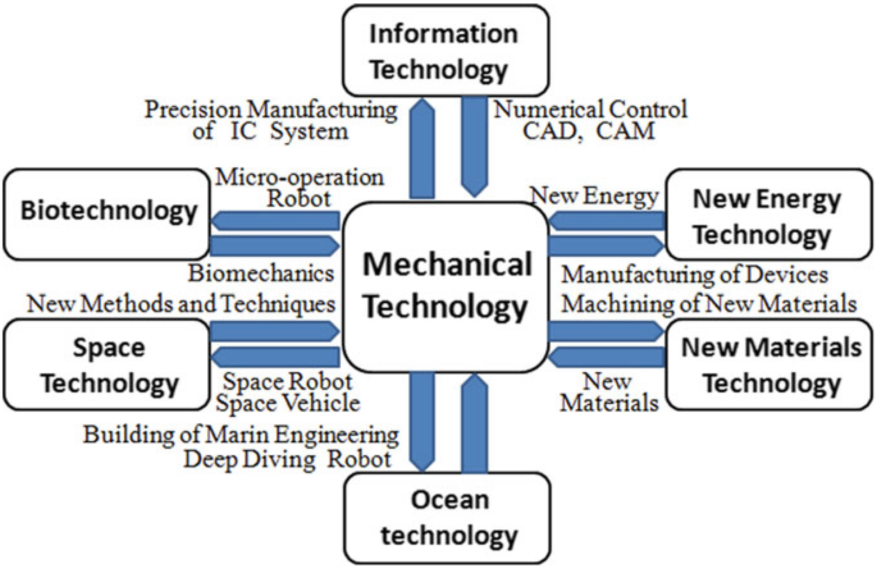


Fig. 10.1 Relationship between mechanical engineering and other fields of third technological revolution

10.1.1.4 Relationship Between Basic Science and Mechanical Engineering

Mathematics and mechanics have made great progress since the 19th century, providing new theoretical base and computational methods to mechanical engineering. For example, in machinery dynamics, complicated nonlinear ordinary differential equations (ODE) need to be solved; it would be impossible without various numerical methods. Also the theory of multibody dynamics has already been widely accepted by mechanical engineering as a powerful modeling tool for various machines.

Physics contributed to the invention of computers. The discovery of laser quickly led to the birth of laser machining. Likewise, system science offered philosophical guidelines to analysis and control of mechanical systems.

The above four factors are coincident with the important relationships discussed in the preface. The 1st and 2nd reflect the relation of technology and society shown in Fig. 1.2, while the 3rd and 4th show the relation between mechanical engineering, basic science and other technological disciplines shown in Fig. 1.3.

10.1.2 Booming of Mechanical Engineering

The higher and tougher market requirements on machine products and the changes in production mode brought every aspect of mechanical engineering, from design to manufacturing, to a historical high level.

10.1.2.1 Advanced Design Methods

The term of advanced design methods is a general umbrella under which there are several specific methods, including design methodology, concurrent design, CAD, optimum design, reliability design, dynamic design, creative design, and green design etc.

The advanced design methods mainly target at two fundamental objectives: to design high quality, diversified and personalized products, and to accomplish the design as quickly as possible. The two key words can be summarized as "good" and "fast".

During this new era, machine design advanced from traditional empirical and semi-empirical design methods toward more advanced ones characterized with faster speed, partially automated and intelligent, as well as visualization supported. Computers have been providing a powerful support to machine design, fundamentally changing the picture of machine design.

10.1.2.2 Advanced Manufacturing Technologies

Advanced manufacturing technologies involve the use of computers to improve products and/or processes in quality, accuracy and process automation level. In mass production, rigid automation is commonly used in which machines and manipulators designed for specific and highly repetitive tasks are the main equipment. While in the multi-specification and small-batch production, programmable or soft automation is preferred in which the machines and robots are designed as 'programmable' to accommodate the changes in product. Common equipment and technologies involved in production mode include programmable NC machine tools and robots, group technology, computer-aided process planning (CAPP), CAD/CAM and flexible manufacturing systems etc. Some other notable progress in manufacturing include the continuous increase of machining speed and accuracy, special machining techniques for new materials of poor-machinability, and 3-D printing etc. The 3-D printing, in particular, may overturn the traditional material-removing manufacturing technologies.

The 1st and 2nd Technological Revolutions are featured with mechanization and electrification, respectively. While in the 3rd one, automation and intelligentization are the main features. A new discipline, mechatronics, was born on the basis of control theory, computer technology and mechanical engineering. Many mechatronic products already appeared in market.

Some very complicated machines were developed after WWII; examples include automobiles, high-speed trains, airplanes, spacecraft, large generators, IC manufacturing facilities, and tunnel boring machines (TBM) etc. Some scholars referred these types of systems as "complex electromechanical systems" or "large systems". These systems are featured with complicated structure and composition, complicated and intricate dynamic behavior, and very high level of automation. In addition, these systems normally contain subsystems of different fields, such as mechanical, electric, electronic and fluid. Due to the highly complex and complicated nature, challenges exist in both design and manufacturing of such systems. New analytic tools, new design methods, and new manufacturing technologies are often created first for these systems and then are spread to other general fields.

10.1.2.3 Development of Basic Theories in ME

MMS, strength theory, mechanical transmission and machine dynamics were already established, and gained certain development during the 1st and 2nd Industrial Revolution. These basic theories in mechanical engineering kept fast development during the 3rd Technological Revolution. At the same time some new subjects, such as robotics and MEMS, appeared. The progresses in basic theories and mechanical engineering interacted with each other. For example, machine design called for new theories in design methodologies. On the other hand, fracture mechanics, multibody dynamics and numerical methods added more powerful tools to the arsenal of mechanical engineering.

This chapter covers the trend of mechanical products, and important and representative technological innovations in mechanical engineering. Some iconic developments in several special fields are also briefly introduced.

10.2 Trends of Mechanical Products in New Era

In the new era, society's requirements on mechanical products became higher, tougher and more comprehensive. These requirements trickled down to the market, pushing the upgrading and improvement of machine products. In the past 200 years, the common tendency of requirement of machines existed all the time include higher speed, more powerful, higher level of automation, higher precision and accuracy, and lighter weight etc. This tendency became even more urgent in the recent 60 years. In addition, continuous improvement of living standard called for higher standards in safety, comfortability and aesthetics. Also wide awareness of environmental and ecological concerns created new requirements on energy efficiency and environment friendliness.

Given that automation will be discussed in later chapters involving robotics, NC machine tools and mechatronics, this chapter will not touch this topic here.

10.2.1 Higher Speed and More Powerful

The Concorde, a British-French turbojet-powered supersonic passenger airplane, reached a maximum speed over twice the speed of sound. The Airbus A380 has a power of 230 MW.

Nowadays high speed trains run generally at a speed above 300 km/h. In 2007, TGV Est, made by Alstom Co., set the world speed record for rail vehicles of 574.8 km/h (Associated Press 2007).

Before WWII, the largest steam powered turbo-generator in the world had a capacity of 100 MW. When it came to the 1970s, the largest became 1300 MW (Wang 2004).

When machining steels with Carbide tools, the cutting speed reaches 200 m/min. When ceramic tools were first used in production in the 1950s, the cutting speed was as high as 500 m/min (Bei 2004).

In 1978, the German company, ThyssenKrupp AG, made the then largest excavator, Krupp-288 (shown in Fig. 10.2), which was 215 m in length and 95 m in height. The machine weighted 45,500 tons and the cost exceeded 1 billion US dollars. The excavating head itself was 21 m in diameter (Malone 2007).

Taisun, made in China in 2008, holds the world record for “heaviest weight lifted by crane“ and has a safe working load of 20,000 metric tons (CIMC 2010).

Early in the 1980s, jaw crushers with a processing capacity as large as 800 tons/h already existed. The average size of the ore the machine could handle was 1.8 m in diameter. The large gyratory crushers made then could treat ores of 500 tons/h, and the maximum processed ore size reached 2 m (Chen 2004).

The web-fed printing press manufactured by the American company, GOSS, reached an unimaginable high speed of 100,000 copies per hour (GOSS International 2016).

Fig. 10.2 World’s largest excavator, Krupp-288 (https://en.wikipedia.org/wiki/Bagger_288)

The overlock machine made in Japan in 1995 works at a speed of 10,000 stitches/min (Deng and Sun 2004).

Powerful and high speed machines need more accurate analysis and careful design because accidents of these machines could be more disastrous. Thus, strength theory and machine dynamics have to meet the higher level requirements.

10.2.2 Higher Level of Accuracy

Space technology and mechatronic products greatly increased the requirement on accuracy and precision. IC manufacturing (Sect. 10.4) is a typical example. Many parts needed in the information industry, such as chips, storage disks and spindles and heads, laser head, inkjet printing head etc., are manufactured with the ultra-precision machining and microfabrication technology.

The gyroscope in a missile guidance system has critical influence on the targeting precision of the missile. It is reported that for a gyroscopic rotor of 1 kg, a 0.005 μm offset of the mass center would lead to a 100 and 50 m error in shooting range and trajectory respectively (Wang and Yuan 2002). In a satellite, the bearing in the attitude control system needs a machining accuracy in nanoscale. Otherwise, the performance of the satellite would be unsatisfied.

The gene manipulation machinery used in genetic engineering can move in a distance of nanoscale with an accuracy of 0.1 nm (Zhu 2001).

Since the 20th century, the level and concept of accuracy have been fundamentally changed; two characteristics can be summarized below: (1) the level of linear accuracy has been uplifted from 10^{-4} m to 10^{-8--9} m; (2) accuracy requirement have been expanded from individual parts to assemblies and the whole system (Jin 2005).

10.2.3 Higher Level of Reliability

It is reported that during WWII the airplanes of the U.S. Air Force that were crashed due to accidents were one and a half times that shot down by the enemy force. Systematic study on reliability first started during the 1960s in the U.S. for the need of space technology.

On January 28, 1986, *Challenger*, a space shuttle of NASA, exploded during its tenth mission (Fig. 10.3). Three month later, the most disastrous nuclear accident in world history, the Chernobyl disaster, happened in the Soviet Union, resulting in wide spread of radioactive pollution in Europe. After the accident, many people were forced to leave the land where they had lived for generations (CFEGE 2006).

Two general trends in various machines and space vehicles have been higher speed, and larger size. These made the reliability of the systems more critical, and

Fig. 10.3 Challenger disaster

design for reliability (DFR) received more attention. The requirement on reliability upgraded the strength theory to the level of fracture mechanics.

Design for reliability now has found wide application in many fields from space crafts to home appliances, and has become an icon of modern machine design.

10.2.4 Urgent Need for Lighter Weight

In the recent decades, a common realization has been gradually reached that the natural resources available on this planet is limited. This directly led to the need for machine to be more energy-efficient, more material-efficient and more environment friendly. All these pointed to the design and manufacturing of lighter machines.

An illustrating example comes from the auto-industry. In the past, heavy and large vehicles were dominant in the market because comfortability consideration was prioritised. However, heavy vehicles consume more gas, thus, emit more pollution to the air. It is estimated that a 10% reduction in the vehicle weight can decrease 6–8% fuel consumption (Xiao and Yang 2004). The oil crisis happened in the 1970s greatly shifted the direction of the auto-industry. Japanese-made vehicles featured with lighter-weight and higher fuel efficiency quickly displaced the American vehicles, which were larger and heavier in general, from the market. Since then light-weight has become a trend in this industry, making light-weight design of automotive an active research topic. In the main automotive production countries, government provided guidance and support to the light weight design of automotive.

For spacecraft, it is easy to understand that the weight should be kept as light as possible because of the technological and cost considerations.

The light-weight requirement also influenced the course of development of many other machines.

FEM and optimal design provided the methodological and theoretical tools to support light-weight design and analysis. Progress in material science created many lighter materials, such as high strength aluminum alloy, titanium alloy, and composite, laying the foundation for light-weight design.

To reduce the weight, the strength and rigidity of a machine component should be carefully calculated and checked. In addition, less rigid components are more prone to vibration. Thus, machine dynamics faces new challenges.

10.2.5 Higher Performance to Cost Ratio

The "performance" and "cost" here are both in broad sense. The performance includes the functional performance, aesthetics and service; while the cost includes all the cost in the life cycle of the product, including the purchasing price, maintenance cost, and operational cost etc. For example, the fuel consumption of a vehicle, energy-consumption of a home appliance, and the cost of wearable and auxiliary parts, all should be included in the cost calculation. The consumer makes his/her decision after comparing the performance to cost ratio.

To achieve success in the market, manufacturers should strive to increase the performance/cost ratio of products. One good example of the improvement of performance/cost ratio is electronic products. On one hand, performance upgrades very fast. On the other hand the price decreases fast as well. Normally improving the performance/cost ratio of mechanical products is not as fast as that of electronic products.

For any product, economy is an important consideration; thus value engineering came into birth (see Sect. 11.6.1).

10.2.6 Higher Level of Environmental-Friendliness

It is estimated that about 70% of the total pollutant emissions comes from the manufacturing industry all over the world.

In 1972, the United Nations Conference on the Human Environment was convened under United Nations auspices held in Stockholm, Sweden. This was the UN's first major conference on international environmental issues. In the report of this conference included the famous "Declaration of the United Nations Conference on the Human Environment", marking a turning point in the development of international environmental politics.

Automotive vehicles have enormous impact on the environment. The emission contains 150–200 different types of chemicals which are all hazardous to human health. In most developed countries, government regulations or laws were established during the 1960s–1970s on auto-emission.

The environment issues inspired the concepts of green product design and green manufacturing (see Sect. 12.7).

Fig. 10.4 Diversification and personalization

10.2.7 Higher Level of Safety and Comfortability

Machines should be safe and have high comfortability. These requirements are particularly important for automotive, airplanes, bicycles, household machines and machine tools.

Safety is the primary requirement for any machines. Radiation in the nuclear industry, pollution from the chemical industry, hypoxia at high altitude, high pressure in deep sea, and absence of weight in space are typical hazards to operator's safety.

Safety of machines involves different subjects, including strength theory, machine dynamics, and human factors and ergonomics etc. The higher requirements on safety pushed the development of these subjects.

10.2.8 Diversification and Personalization

When a new product is put in the market, customers may not care much about styles and appearance at the beginning. In the status of scarcity, "have" or "haven't" is the first concern. The world has remained a long period of peace in general after WWII, leading to the overall improvement in living standard all over the world. The needs, thus, tended to be more diversified and more personalized, for example the diversified requirements on product's appearance, style and color etc. Moreover, these requirements change all the time.

Taking the auto-industry in Japan as an example, there are thousands of variations combination in engine power, body style, color and audio equipment (Xu et al. 2001).

During the 1960s, China was in scarcity of almost any commodities, and customers had very little option. Taking bicycles as an example, there were only 3 brands then available in the market. After the "reform and opening-up", numerous brands and styles, such as mountain bicycles, racing bicycles and lady bicycles, appeared in the market (Fig. 10.4). There are also luxury and common types in option for some brands.

The diversified requirements on appearance and aesthetics of products promote the development of industrial design.

The diversified market needs also drove the shift of production mode from mass production of coincident products to medium or low production with more variation. In some fields, products can even be designed and manufactured according to individual customer's requirement. Customized design and manufacturing require a fast, visual and interactive design tool.

These higher and tougher requirements to mechanical products are important driving forces to the development of machine design, manufacturing technology and basic theories of ME.

10.3 Important Inventions and Innovations in New Era

During the 1st and 2nd Industrial Revolutions, many machines were invented in almost all sectors of industry. In the 3rd Technological Revolution, however, inventions and innovations in machines far exceeded the total of the past hundreds of years.

During the 3rd Technological Revolution, progress in machines was mainly made in two forms.

(1) New inventions: Many completely new machines and complex electro-mechanical systems were created; these include space crafts, robots, IC manufacturing equipment, MEMS, and many mechatronic products.

(2) Fundamental improvements to existing machines: All existing machines experienced continuous improvements, some of which are fundamentally reborn. For example, the high-speed train, automotive and airplane nowadays, are fundamentally different from the G. Stephenson steam locomotive, K. Benz car and Wright brothers airplane respectively. Other examples of this kind include tunnel boring machines (TBM), rolling mills, steam turbine units, and high precision NC machine tools, to name a few. In the evolution of these machines, numerous patents, innovations and improvements have been happened. To distinguish from the new inventions, we refer this group as "fundamental improvements".

In the following two Sects. 10.3 and 10.4, we will briefly introduce some of the most representative new inventions and fundamental improvements happened in the 3rd Technological Revolution. Some of the improvements were already mentioned in Sect. 10.2.

10.3.1 Mechatronic Products

A traditional machine consists of a power source, a system of mechanisms and, an interface to operators. Most modern machines contain a control system; thus, are also referred as automated machines. To the middle of the 19th century, automated machine tools appeared; however, the control (automation) at that time was achieved through mechanical devices, mainly cams. During the middle of the 20th century, control through hydraulic systems and relay controllers were invented.

With the fast advance in control theory, electronics and sensor technology, and computer technology in particular, automation entered the modern stage on the basis of analog and digital control theory. The modern automation fundamentally differs from its predecessors based on mechanical devices.

Mechatronics has went through 3 stages in development.

Attempts were already made before the 1960s in using electronic technologies to improve machine performance. During WWII and after, many technologies combining mechanical and electronic components were invented and first applied in military. Later, these technologies were gradually trickled down to civil applications. This is regarded as the 1st stage in the development of mechatronics. Examples of products developed in this stage include radar servo systems, NC machine tools, and robots etc. The 1st stage laid the concept foundation of mechatronics.

In 1969 an engineer in Yaskawa Electric Corporation, Japan, created a new word, *mechatronics*, to register as a trademark (Hehenberger and Bradley 2016). This word later spread all over the world and became an essential word in nowadays industry and technology.

Microprocessors were successfully made through the LSI technology in 1971, pushing the computer technology to the level of the 4th generation. In the period of 1970s and 1980s, mechatronic technologies entered a booming period with wide applications in many fields. This period is regarded as the 2nd stage in mechatronics development. Japan played an active and leading role in this development stage. In 1971 government regulations were launched to encourage business to upgrade machines through computers and other electronic devices. In several years, Japanese economy saw miraculous growth.

Some iconic progresses made in the 2nd stage include: (1) NC machine tools found wide application in the industry, (2) machining centers were invented and (3) robots were commercialized. At the same time many mechatronic products entered market, such as airbags, anti-lock braking system (ABS), copying machines, CD players, driving simulators, CNC construction machine, CNC packaging machines, automatic warehouse (Fig. 10.5), and vending machines etc. Technically, any traditional machines could be upgraded through incorporation of electronic technologies. Electronic technologies can greatly simplify the structure and composition of machines. For example, a chip of integrated circuit could replace about 350 mechanical parts in a sewing machine (Wang et al. 2010).

Fig. 10.5 Automatic warehouse

Mechatronics entered the 3rd stage, also called the intelligent stage, around the end of the 20th century. AI and network technologies in this stage greatly expanded the territory of mechatronics. The concept of machines was changed fundamentally. Some machines nowadays became "intelligent", being able to collect, store, manage, process and utilize information. Information is processed to obtain features and knowledge, which are utilized to make decision and give instruction to the machines. Unmanned vehicles and intelligent robots which are still under development are two examples of this stage.

Robots and CNC machine tools are typical mechatronic products. The development of CNC machine tools will be discussed in Sect. 12.2 with more detail along with machine-building technology.

10.3.2 Robots

Robots, as a mechatronic product, are an important invention in the 3rd Technological Revolution.

Back to the Ancient times, humans already built automata resembling animals and humans for entertainment. These can be regarded as the ancestors of modern robots (see Chap. 2).

In 1920 a Czech writer, Karel Čapek (1890–1938), created a new word, robot, in a play, meaning forced labors or servitudes who could work tirelessly. This was a reflection of a long-standing dream in human society to create a machine to do hard labor for human. The play was later showed in many countries, helping spread the word robot. However, nobody at that time really expected this word becoming a widely-accepted term in technology.

In 1950, Isaac Asimov, an American writer, proposed the famous Three Laws of Robotics (Asimov 1950).

10.3.2.1 Serial Robots

In 1948, the Argonne National Laboratory under the United States Department of Energy successfully developed the first master-slave manipulator in the world for the purpose of moving nuclear fuels (Holl et al. 1997).

An American, George Devol, was granted the first patent in 1954 on industrial robots, in which the concepts of servo-control, programmable and teaching/playback were already contained. Then, Devol set up a company, called Unimation, aiming at development of the patent into a physical machine. In 1961 the first Unimate robot was installed in General Motors for die casting handling (Rosen 2011) (Fig. 10.6). In 1962, AMF, an American company, developed the VERSTRAN robot installed in a Ford's factory.

In 1970 the first international conference on robots was held in the U.S., following which research and development entered a fast track.

The first generation of industrial robots are most teaching/playback type, which is capable of repeating the motion pre-taught with very high accuracy. To the time of 1970s, wide applications in material handling, welding and painting were found in the industry. However, one shortcoming of this type of industrial robots is that they can only repeat the motion of pre-set without the ability to sense and interact with the working surrounding.

America was the earliest to develop industrial robots. Japan purchased some robot patents from the U.S. and made great effort in further development. Application was first made in its auto-industry. To the 1970s, commercialized production of the teaching/playback robots was started in Japan. Since the early 1980s, application of industrial robots has been dramatically expanded in several countries, especially in Japan. In view of this fact, some scholars credited the 1980 as the "first year of robots". This may not be right from the viewpoint of history; however, it is reasonable from the standpoint of application. Japan exceeded the U. S. becoming the world leader in production and application of industrial robots. According to a statistics in 2000, Japan manufactured about 70% of the total number of robots of the world that year.

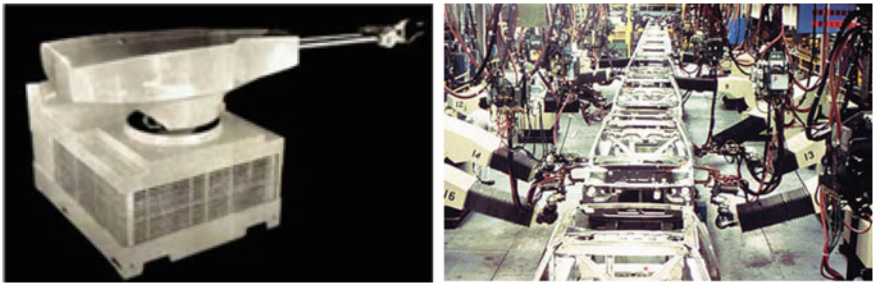


Fig. 10.6 UNIMATE and its application in General Motors (https://www.robotics.org/joseph-engelberger/unimate.cfm)

Fig. 10.7 Original ASIMO (https://en.wikipedia.org/wiki/ASIMO)

After the 1st generation, research was continued toward the 2nd generation robots which, equipped with sensors, have the ability to see, feel and hear the surrounding environment.

At the same time, the application of robots was expanded to ocean and outer space exploration, medical service and household work.

Honda displayed its humanoid robot in 2000, ASIMO (Fig. 10.7), which amazed almost every audience seeing it (Hanlon 2011).

The 3rd generation robots, also called intelligent robots, are still under development. The operators only need tell this type of robots what to do. The robot itself can sense the environment, and make the decision as for how to do the assigned job. Research on this type of robots reached a high tide in the 1990s. So far only partial intelligence has been achieved; real and complete intelligent robots are still an objective yet to be achieved.

There is a fundamental difference between a mechanical manipulator and a robot. A manipulator can only move in a pre-set path which can't be changed; thus, it is suitable for fixed automation of mass production. However, a robot's motion is programmable so that it is good for production of mixed products. The wide application of industrial robots in painting, material handling and welding was mainly driven by two opposite trends: the increase of labor cost and the decrease of robot's price. The change of the two factors since the 1990s is shown in Fig. 10.8 (Craig 2004).

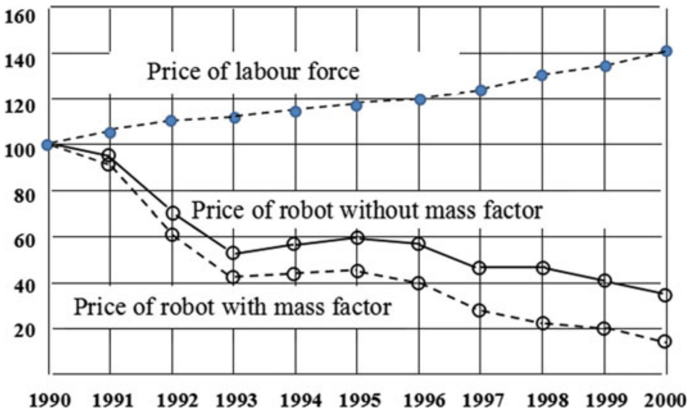


Fig. 10.8 Comparison of price and cost of robot in 1990s

10.3.2.2 Parallel Robots

The origin of parallel robots is generally credited to the Steward Platform, as shown in Fig. 10.9, proposed by an English engineer, D. Stewart in 1965 (Stewart 1965) for the purpose of flight simulator. In fact, A Romanian-English scholar, V. Eric Gough, developed the same mechanism much earlier in 1956 for automotive tire tests (Gough 1956). Thus, in later literature, this mechanism was termed as Gough-Stewart Platform.

Kenneth Hunt, an Australian scientist, started constructing robots on the basis of the Steward platform (Hunt 1990). To the mid. 1980s, theoretical investigations on the Steward platform started.

Two American machine tool companies, Giddings & Lewis and Ingersoll, independently displayed a new type of machine tools based on the Hexapod, at

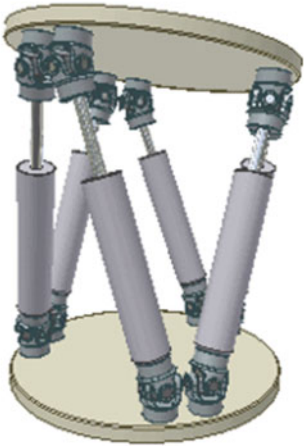


Fig. 10.9 Gough-Stewart platform (https://en.wikipedia.org/wiki/Stewart_platform)

Chicago Trade Fair in 1994. This new type of machine tools are based on the parallel kinematic structure, completely overturning the traditional serial kinematic architecture of machine tools. It was expected to become a model for machine tools in the 21st century (Zhang and Heisel 2003). The parallel kinematic machine (PKM) thereafter became a hot research topic. Later study revealed that PKM had shortcomings in rigidity, cooling down a bit on research activities.

During the second half of the 1990s, NASA developed the low impact docking system (LIDS) based on the Steward mechanism for the purpose of mating spacecrafts (Chambers 2013). PKM also found application in material handling and force sensors. The Steward platform is one of the most commonly used PKM.

Parallel robots in many applications only have 2–5 degrees of freedom (DOF). Machines with less than 6 DOF are referred to as lower mobility parallel robots. Lower mobility robots have a series of advantages over 6 DOF machines, such as simpler structure, lower cost, larger workspace, and easier to control etc. Due to these unique advantages, lower mobility robots demonstrate great potential in application, among which the most well-known are the Delta and Tricept. Since the 1980s much research has been conducted to lower mobility robots.

The Delta robot, as shown in Fig. 10.10, was invented in the early 1980s by a Swiss scientist, Clavel (1991). This robot has 3 DOF with the end effector being able to translate along 3 dimensions. It has very light moving parts; thus, a high acceleration of 12 g was achieved. It is reported that on a variation of the Delta an acceleration as high as 20 g was reached. It has been widely applied in packaging operation in the food, medical, pharmaceutical, and electronic industry (Fig. 10.11).

In 1985, Karl-Erik Neumann at Neos Robotic, Sweden, patented the Tricept parallel robot as shown in Figs. 10.12 and 10.13 (Zhang and Heisel 2003). This robot has very high load capacity and motion accuracy. It has found application in Boeing for milling aluminum and composite parts, in GM and Volkswagen for machining large stamping molds, laser cutting and assembling operation.

Parallel and serial robots have different characteristics; thus, they found applications in different fields. Combination of the two types expanded the scope of application of robots in general.

Fig. 10.10 Delta robot

Fig. 10.11 Delta Robot on an assembly line (http://www.parallemic.org/Reviews/Review002.html)

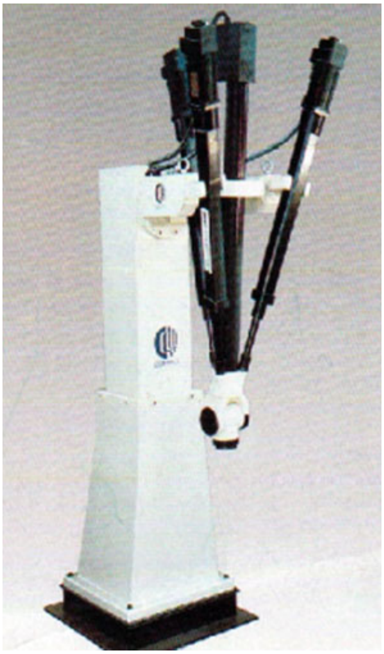


Fig. 10.12 Tricept robot

To improve the speed, working space and adoptability, flexible robots, redundant robots, bipedal walking robots, and multi-robot systems (MRS) were developed later (see Sect. 13.3).

According to the World Robotics Report 2016 issued by the International Federation of Robotics (IFR), there were about 1,631,600 industrial robots in operation by the end of 2015. This number was estimated to reach 2,589,000 by the end of 2019.

Fig. 10.13 A machine tool made up of Tricept robots

The biggest customer of industrial robots is the automotive industry with 38% market share, and the second is the electrical/electronics industry with a market share of 25%.

10.3.3 High Speed Rail Systems

Under the competition of highway and water transportation, rail transportation once dropped behind. With the appearance of high speed trains, rail transportation gained new momentum.

10.3.3.1 High Speed Trains

Trains operating at a speed over 200 km/h are referred to as high speed trains. In the early 1950s, France began to study and test high-speed trains. In 1964, the Japanese Shinkansen connecting Tokyo and Osaka was put in operation. The bullet trains built for the Shinkansen reached a speed of 230 km/h. The Shinkansen soon became well known in the world for its excellent performance in safety, punctuality, energy efficiency, environmental friendliness and cost effective etc. (Hood 2007).

Fig. 10.14 CRH (China Railway High-speed)

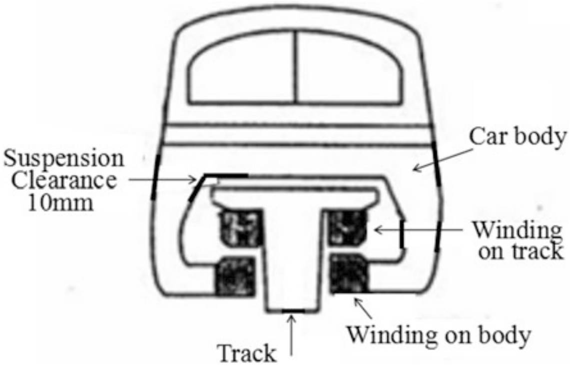
In 1976, diesel-electric trains were put in operation in UK, reaching a speed of 201 km/h.

In 1981 the train, named TVG, developed in France started to run between Paris and Lyon. This train adopted streamlined shape, reducing the aerodynamic drag by 1/3. In addition, the driving car was designed so powerful that the train could climb up an inclination of 35% without compromise in speed. It can also start from inclined rails. The TGV test train set the world speed record of wheeled train and kept it for many years.

Germany, Italy and China also made effort in developing high speed rail technology. China first imported relevant technologies from Europe, and then focused on development of its own unique technologies. Despite starting later, China quickly came to the leading position in both high speed rail construction and train manufacturing. It is reported that China had 22,000 km of high speed rail in operation as of the end of 2016, making up two-thirds of the world's total (ANON 2016). A high speed train developed in China, CRH, is as shown in (Fig. 10.14).

The aerodynamic drag on a train in operation is proportional to the square of its speed. When the speed is increased from 120 to 240 km/h, the driving force to overcome the drag would be 4 times the original. The dramatic increase of in driving power with the speed posts a great challenge in dynamic study of the trains. High speed trains have kept an excellent safety record so far, with very few fatal accidents since it was invented. However, the reliability of high speed trains needs to be scrutinized with great attention given the extremely fatal consequence of accidents at high speed.

Fig. 10.15 Schematic diagram of maglev train



10.3.3.2 Maglev Train

The high speed rail is based on diesel electric trains and traditional rail systems. Through upgrading and innovating the propulsion system, the train shape and the rail, the operation speed is significantly increased. However, the basic structure of the traditional rail and train system remains unchanged.

Differing from the traditional wheeled trains, Maglev trains use two sets of magnets, one set to repel and push the train up off the track and the other set to move the floating train ahead at great speed (Fig. 10.15). Due to the fact that the train is floated in the air, friction disappears; therefore, the aerodynamic drag becomes the only resistance. Maglev trains can run at a speed above 500 km/h.

A German engineer, Hermann Kemper, proposed the mechanism of magnetic levitation in 1922, and filed a patent application in 1934 (ANON 2014).

In the late 1980s, a maglev line was built in Berlin, Germany. In 2001, China constructed a line connecting Pudong International Airport and the Longyang Road Metro Station with the technology of Transrapid. This line is 30 km long and was put in operation in 2002. The highest speed reached 430 km/h (Michael 2014).

Maglev trains obviously have super speed, consume less energy, and are more environment friendly. However, Maglev lines are not widely adopted; the following two concerns may be responsible for this situation:

(1) The train may have fatal accidents in the case of power disruption if no preventive measures are taken.
(2) The strong magnetic field may have detrimental effect on passenger's health and the local eco-system. Also it may interfere with the operation of on board electronics.

All these concerns are still under study, waiting for clear conclusion and concrete technical solutions.

10.3.4 Large Scale Construction Machinery

10.3.4.1 Large Scale Tunnel Boring Machine

The first tunnel boring machine (TBM) was invented during the 1st Industrial Revolution in Britain. However, the TBM nowadays is different from the ancestor in many ways.

In a TBM a circular cross-section steel shield is moved along the axis of the tunnel, protecting the operation and temporally supporting the walls before lining. All the operations, including excavating, mucking and lining, are conducted under the shield protection (Bao et al. 2012) (Fig. 10.16).

The TBM has been widely used in railway, subway, highway and other tunneling construction in urbanized areas. In 2013, Hitachi Zosen Corporation produced a TBM known as Bertha with a bore diameter of 17.45 m (Newcomb 2014).

The machine is made up of subsystems of mechanical, electrical, hydraulic and optical etc., being a typical complex electromechanical system. Thus the design and construction of the machine involve knowledge from many subjects, including geology, civil engineering, mechanical engineering, mechanics, hydraulic power transmission, electrical engineering and measurement technology etc.

Due to the very high manufacturing requirements, very few companies in the world, mainly in Japan, Europe and the U.S., have the capacity and ability to manufacture TBM.

10.3.4.2 Other Construction Machines

Since the 1950s, construction machines started to develop with two trends, hydraulic power and large capacity.

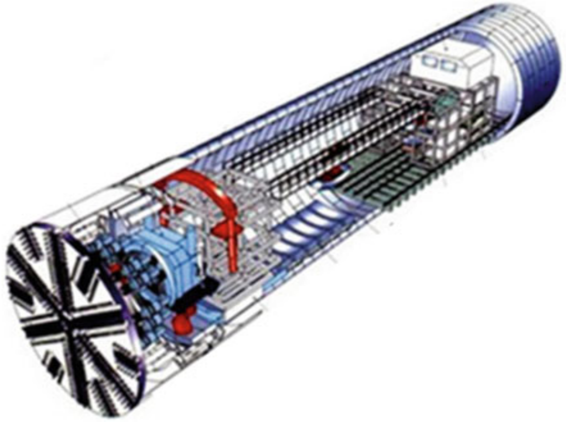


Fig. 10.16 Tunnel boring machine

Around the mid. 1950s, hydraulic powered excavators being able to swing 360° were made in West Germany and France, marking a new stage in the history of excavators of single bucket.

To 1958, the capacity of multibucket excavators reached 3.6 m^3 for each bucket. Bucket-wheel excavators manufactured in the Soviet Union in 1973 and West Germany in 1977 had a capacity of 5000 m^3/h and 40,000 m^3/day respectively (Yang 2004).

10.3.5 *Information Machines*

10.3.5.1 Printing Machines

Before the 1950s, the relief printing technology was dominant in the industry. The types in this technology are made from an alloy of lead; thus, intensive labor work is required to handle them. Other shortcomings include long production time and pollution to the environment. In the 1960s, the faster and more efficient offset printing technology was invented, gradually displacing the old relief printing. At the same time, some other new printing technologies, such as gravure printing, electrostatic printing and inkjet printing, were in fast development and found application in packaging and commercial brochures.

10.3.5.2 Digital Camera

A digital camera captures photographs in digital memory through electronic sensors. It was invented by an American engineer, Steven Sasson, at Eastman Kodak in 1975. He was only at the age of 25 then with his newly-obtained Master degree (Estrin 2015). Digital cameras are a typical invention of “fundamental innovation”.

10.3.5.3 CT Scanner

X-ray can penetrate human body. Shortly after it was discovered, it found application in medical diagnosis to create images of body interior. However, the two-dimensional representations of conventional X-ray plates were often unable to distinguish between normal and pathological tissues because the images of different cross-sections were overlapped. During 1963–1964, Allan Cormack, a South African-American physicist, laid the theoretical foundation for the modern CT scanning technology in which images of different cross-sections (slices) are created through computer calculation and used to construct a 3-D image of the tissue. In 1972, Godfrey Hounsfield, an English electric engineer, invented the first commercial CT scanner without knowing the Cormack's work. Cormack and Hounsfield were awarded the 1979 Nobel Prize in Physiology or Medicine for their independent work.

10.3.6 Power Machines

Steam engines, as the dominant power source of the 1st Industrial Revolution, began to decline in the 20th century as other power sources became available. From the 1950s, steam turbines started to replace steam engines in large ships with power above 8 MW. Also steam turbines became the only option in almost all power plants (see Sect. 10.4.3).

10.3.6.1 Generators

If the armature and conductor coils of a generator are made from superconducting materials, the resistive losses of the coils would be almost zero. Thus, the generator can be much more efficient and much smaller in size. It is reported that 43 sets of superconducting systems have been developed in the world. The capacity of a single superconducting generator is estimated to be possibly as high as 3500 MW in future. However, the high cost is a hurdle to application at present (Bumby 1983).

Steam and gas turbines in power plants have only an efficiency of 30–40%. Since the 1950s, research has been undertaken on magneto-hydrodynamic (MHD) generators in some countries, such as the U.S. and USSR. In an MHD generator, fossil fuel is first transformed into an electrically conducting gas which is then directed through a strong magnetic field. The kinetic energy of the gas is converted directly to electric energy. An MHD generator has the potential of an ultimate efficiency in the range of 60 to 65% which is much better than the 30–40% of the steam and gas turbines in traditional power plants (Brogan 1964).

10.3.6.2 Internal Combustion Engines

The speed of internal combustion engines in the 1970s was already several times of that made in the early century. Nowadays the engine speed in race cars reached 10,000 and 5000 rpm for gas and diesel engines respectively.

A German engineer, John Wankel, invented rotary engine in 1957 (Hege 2006) (Fig. 10.17). This type of engines are simple, compact and light-weight. However, they have several shortcomings, including poor fuel efficiency, no diesel option, and relatively high position of output shaft, making it difficult to fit into an automotive vehicle. Moreover, the poor manufacturability and high cost also prevented its application. It seems that it was installed only on some Mazda vehicles.

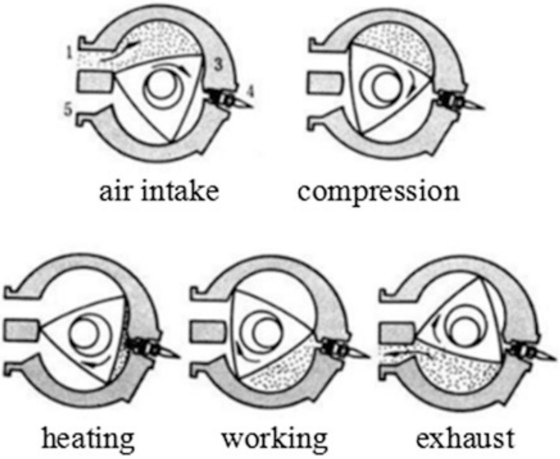


Fig. 10.17 Work cycle of Wankel rotary engine

10.3.7 Textile Machines

A ring spinner was invented in the U.S. in 1828. After continuous improvement, ring spinners almost replaced self-acting mule during the 1960s. Through increasing speed and efficiency, the productivity of ring spinners, the end spinners in particular which work without using a spindle, was significantly improved. In 1965 the rotor spinning machine was developed. The working procedures of this type of machines include: (1) a sliver is fed into a rapidly rotating opening roller, (2) the sliver is combed out into individual fibers by the teeth of the roller, (3) the individual fibers are directed to inside wall of the rotor through centrifugal force and air flow (vacuum), and (4) yarn is formed through twisting the fibers then the yarn is wound directly.

After the 1950s various shuttleless looms appeared; all contributed to the improvement of productivity. Shuttle and shuttleless looms operate with intermittent output, limiting the further increase of speed and productivity. Thus, the idea of continuous weft insertion was proposed later. In the 1970s, more efficient fabric forming machines were developed; examples included ripple-shedding looms, triaxial looms, and fabric knitting machines which combined weaving and knitting together (Pan and Wang 2005).

10.3.8 Agricultural Machines

Mechanized agriculture grew rapidly in the early 20th century. After WWII, large tractors were popularized, bring the agricultural mechanization into a new level. In the U.S., tractor's power and speed reached 330 kW and 10–15 km/h in the 1970s. New technologies, such as hydraulic power, electronic monitor, automatic control, and laser positioning etc., were adopted. These new technologies help the driver to quickly complete operations of the attached tools, switch working fields, monitor working process and fix potential problems.

Some inventions of the early 20th century in agricultural machines were implemented during and after WWII. In the 1920s, harvesters were combined to tractors. Later on harvesters incorporated the function of threshers. Self-propelled combine harvesters were first marketed in 1944. Cotton picking machines were not developed until after WWII, although the concept was proposed in 1927.

In the U.S. mechanization of agriculture was completed in the 1940s. In some other countries, include U.K, France, Germany, Japan, Denmark, and the Soviet Union, it was a little latter between the 1950s and 1960s. Now in these countries almost all farming work is conducted by machines (GSHCAS 1985), such as plowing, seeding, spreading fertilizer and pesticide, irrigating, harvesting, transporting, drying, storing and processing etc. Mechanization in animal husbandry developed fast as well. For some work in livestock production, such as feed manufacturing, feeding and cleaning, mechanization has been already a reality since the 1950s. Specialized machines were designed and manufactured for the work. Mechanization of aquaculture started in the 1970s (Pan and Wang 2005).

10.4 Important Developments in Manufacturing

Machines were not in the center of the 3rd Technology Revolution, the machine industry, however, remains a pillar sector in the world economy. With the mechanization of many other industrial sectors, the machine industry has grown unprecedentedly, developing many specialized branches. After WWII, the industry has achieved much more than that in the past centuries.

Automotive and airplane manufacturing links to many other industries, such as the metallurgical, petroleum, rubber, electronic, plastic industries etc. Thus, it has great influence to the whole economy.

Manufacturing was once regarded as a sunset industry in the U.S. in the 1970s, creating widely-felt negative effect on its economy. This was noticed by the U.S. government around the late 1980s, and corrective measures were taken to revitalize the manufacturing industry. Focus was placed on high-tech product manufacturing, including pharmaceuticals, electronics, luxury automotive and aerospace. It is estimated that to the year of 2025 the United States manufacturing would boost almost $530 billion annually (Ramaswamy et al. 2017).

China became the largest manufacturing country in the world in 2010. According to a report issued by the Chinese Academy of Social Sciences (IEI 2011), the manufacturing industry in China covered a whole spectrum, ranging from traditional low-tech to the most advanced, high-tech products. The country, as a whole, has no “sunset industry”, all sectors have great potential for further growth.

In the discussion of the machine industry, this book focuses on design and manufacturing. In the following section, we will introduce the important development in several areas. These areas are thought to have significant influence on the whole machine industry and machine science, including automotive manufacturing, aerospace manufacturing, large power generating facility manufacturing, IC manufacturing and machine tool manufacturing.

10.4.1 Automotive Manufacturing

The automotive industry has existed almost 130 years. Nowadays family cars have been very popular in many countries. According to a statistics (PS 2015), about 90.78 million automotive vehicles were produced in 2015 around the world. The automotive manufacturing is a very comprehensive industry, having considerable influence on many other industries. In several countries it is a pillar sector in the national economy.

In China, the automotive manufacturing industry consumes 40% of the machine tools produced in the country in terms of value. It is also the largest customer of the forging industry, consuming 60–70% of its die-forging products. It is also one of the largest consumers of new materials and new production equipment. New process and technologies are often used in the automotive manufacturing first.

Historically automotive was the first large-size product of mass production. The automotive manufacturing industry was the first to adopt industrial robots, and is still being the largest consumer of robots presently.

Japan made a miracle in the automotive industry. The oil crisis happened in the 1970s hit the automotive industry in the U.S. very hard, but gave Japanese auto-makers an opportunity. Japan was then good at making smaller-size, more fuel efficient vehicles. In 1980 Japan displaced the U.S. from the position of the largest automotive producer in the world.

China started manufacturing trucks in 1958, marking the birth of the nation's automotive manufacturing industry. After several decades, China became the largest automotive producer of the world in 2009, and has been keeping in the position ever since. According to a statistics, China produced 28.11 million vehicles in 2016. Despite the outstanding achievement in production capacity, China, however, is obviously short of innovation in the automotive industry. This fact has been acknowledged by both the government and the main automakers in China, and measures have been taken to catch up in technology development.

With the increase of living standard, the market demand for luxury and race vehicles grows fast. These types of vehicles require much higher in speed and ride comfortability. After WWII, the U.S. first applied the theory of aerodynamics to the design of automotive body. Since then lower center of gravity, rounded shape of exterior and longer vehicle body have been adopted to achieve higher speed.

The rapid growth of the industry during the second half of the 20th century caused intensive market competition. Most auto-makers realized that ride comfortability, handling smoothness, and fuel efficiency were the most important performances for a vehicle to stand out in the competition.

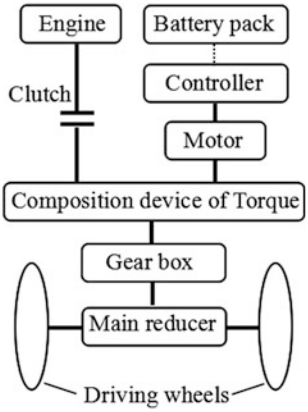


Fig. 10.18 A transmission scheme for hybrid car

Automotive causes two concerns, namely pollution and consumption of energy, despite the immense positive changes it brings to human society.

The primary concern comes from the pollution caused by automotive. It is estimated that transportation contributed 42% of total pollutants to the air, and 70% to the noisy pollution in city. To tackle the pollution problem, Europe launched its first emission standard in 1992 (Euro 1).

Another concern with the automotive is the availability of energy. It is predicted that the proven reserves of crude oil would be exhausted in decades. This crisis makes electric vehicles regain momentum (Wakefield 1994). The first electric car in history was built only 4 years after Benz invention. However, the greater range, quicker refueling times and lower cost of gas cars lessened the advantages of the electric vehicles. To the year of 1935, electric vehicles were actually knocked out of the market by their gas counterparts. During the 1960s and 1970s, the interest in electric cars resumed a little bit, but not becoming the main stream. Hybrid cars are the other option in dealing with environmental and energy resource concerns. A typical transmission layout for a hybrid car is as shown in Fig. 10.18. However, the debate between pure electric and hybrid is far from settling down.

10.4.2 Aerospace Industry

The Wright brothers made the first flight of airplane in 1903 (see Sect. 5.2). The military potential of airplanes caught the attention first in 1909. Then specialized research institutions were created in several countries. The WWI served as a test field of airplanes for military use. Following WWI, the airplane technology and industry continued to grow.

The half a century after WWII saw a booming period in the aerospace industry. Adoption of new technologies, such as new materials, electronic technologies, radio and radar technologies, greatly enhanced the performance of various airplanes. Now jet engines are the most popular propulsion for both military and civil airplanes (Jiang 2010).

The U.S. and some countries in West Europe started the development of supersonic airplanes around 1950. To the 1970s, the speed of military airplanes reached 3 times of sound speed. NASA predicts that in the future the military airplanes may fly at 5 times of the sound speed.

Airplanes in the civil aviation industry, on the other hand, have developed along two directions, large size and heavy duty. From the 1960s, the U.S., USSR, UK and France have started development of large passenger airliners propelled by turbojets. The Concorde, a supersonic passenger plane jointly developed by UK and France, made the first flight in 1969; its maximum speed was over twice the speed of sound. The Airbus A380 plane was launched for commercial service in 2007. As the largest airplane in the world, A380 has a power of 230 MW, a length of 73 m and a wingspan of 80 m. It has the capacity to carry 853 passengers (Goddard 2010).

The Soviet Union launched the first man-made satellite to circle the earth in 1957, marking the age of space industry.

The aerospace industry, including aeronautics and space, has the following features: (1) being knowledge and technology intensive, (2) requiring very high in manufacturing accuracy and precision, being very comprehensive in manufacturing technologies and processes, (3) serving both military and civil sectors, and (4) requiring broad collaborations, long development time and high investment.

About 30 countries in the world have an aerospace industry, among which the U.S., Russia, China and France take the lead.

The aerospace industry demands for huge investment and comprehensive technological support. It is, thus, regarded as an indicator of a country's economic and technological power, or of comprehensive national power (CNP). In addition, it has significant influence on many other industrial sectors.

Aerospace vehicles, as a top-level high-tech system, are obviously much more complicated than general machines. For example, a Boeing 777 plane consists of more than 3 million parts (including fasteners). Requirements on reliability and light-weight of any aerospace vehicles are extremely high. To achieve these two requirements, many new theories and technologies are first developed for the aerospace industry, and then spread to other fields. Examples include FEM, active vibration control, fault diagnosis, NC machining, CIMS and concurrent engineering etc.

Aerospace vehicles are also complex mechanical-electronic-fluid systems. For example, the solar panel on a satellite, and the manipulator for capturing a satellite are both mechanical-electronic systems. The dynamics of aerospace systems is generally nonlinear in nature; elasticity, clearance as well as the coupling effect between solid and fluid systems have to be considered.

10.4.3 Large Power Generating Systems

To the early 20th century, water turbines, steam turbines, and internal combustion engines were all approaching maturity in structure. Later developments mainly went along two directions, increasing power and increasing efficiency.

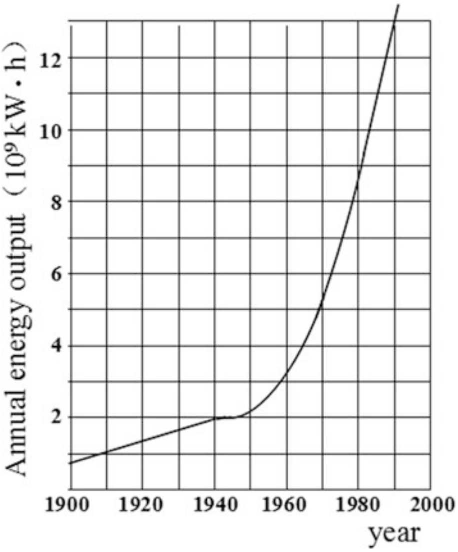
During the 3rd Technology Revolution, electricity was the dominant power although some alternatives were available. Thus, the electricity generating capacity was frequently used as an indicator of economical growth. The change of annual electricity output of the world between 1900 and 2000 is shown in Fig. 10.19. Two observations can be made with this figure. First, the increase for the years before WWII is almost linear. Second, the rate of increase becomes much faster after WWII (Shi 1990).

Steam turbines generated almost 80% of the electricity in the world. To reduce operational cost and improve efficiency, a tendency has been kept since the 1980s to make the unit larger and larger. For example, the largest unit of the world in the 1970s was 1300 MW; while nowadays a capacity of 1000 MW is common, and most are super-critical units.

The U.S., Russia, Japan and Germany are the world leaders in the manufacturing of large-scale power generating units. China started later, however, caught up very fast. In 2013, China came to the first place of the world in terms of electricity generating capacity.

Since the 1980s, some new developments have taken shape, including improving efficiency, control of pollution, reduction of cost and automation.

Fig. 10.19 Growth of World power generation



The rotor in the system experiences very complicated vibration. To deal with rotor vibration problems, a dedicated subject, rotor dynamics was formed (see Sect. 7.4.2).

Accidents in a power station would cause immense economical and life loss. Thus, power generating units are one of the areas in which fault diagnosis technology was applied very early.

10.4.4 IC Fabrication

Computers advanced the development of the electronic industry. The core of modern electronic industry lies in the technology of integrated circuit (IC) which was established in the early 1960s. Gordon Moor predicted in 1965 that the number of transistors per square inch on an IC doubled every year. In the years following, the pace slowed down a little with data density doubled approximately every 18 month; this is the so-called Moor's Law. In the Intel Pentium 4 chips, more than 42 million transistors were integrated on an area of 116 mm^2. The smallest wire width was only 0.13 µm. Several decades ago, the number of transistors integrated was only in dozens. Presently the number reaches hundreds of millions with the technology of large scale integration (LSI). The progress is dramatic.

One technology stemming from the IC is micro-electro-mechanical systems (MEMS). One feature of the MEMS is that it contains moving parts. It can be anticipated that MEMS will create innovative new products and change human's life as the IC is doing.

A statistics indicated that the revenue created by the MEMS in the world reached more than $11 billion in 2014. The prediction for 2024 even reaches $29 billion (Grand View Research 2018).

IC fabrication involves very complicated process with many steps, such as wafer, deposition, lithography and packaging etc. Every step is important, but packaging is more critical. It is a special challenge to the IC industry.

IC packaging equipment typically requires very high precision. An important step in the packaging process is wire bonding which connect the chips and the package lead using small diameter wires of copper, aluminum or gold as shown in Fig. 10.20. For clarity purpose, this figure has been greatly exaggerated. The real width of the picture actually is only around 700 µm. Bonding is generally made by ultrasonic, thermos-compression or thermos-sonic means depending on the wire materials. In the process, the wire is guided to move along a complicated path in space at high speed to form the required packaging shape. The bonding is conducted very fast; generally 8–10 wires/s in early equipment, and 16–18 wires/s in contemporary equipment. Also frequent start-stop is required, leading to acceleration of the working table as high as 27–30 g. In addition to the high acceleration, very high accuracy for trajectory and position, very small wire size, and distance between wires are all challenges to the design and manufacturing of the machines.

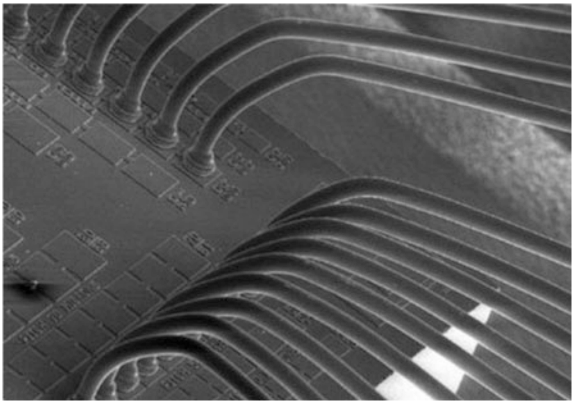


Fig. 10.20 Wire bonding (https://www.ntc.upv.es/encapsulado_tech.html)

It is reported that the wire diameter for pure gold wire has decreased from about 0.1 μm to 0.03–0.04 μm, and the distance between wires from 80–100 to 20 μm (He 2004).

The manipulator on IC packaging equipment is generally slender and flexible, working under very harsh condition of extremely high speed, high acceleration, and high accuracy requirement. Thus, dynamics study and control strategy are critical to the design of the machine. On the other hand, IC fabrication requires super cleanness in environment, super purity in material and super accuracy and precision in work. All these are challenging topics to the manufacturing technology.

The U.S., Japan, France, Holland and South Korea are the leading countries in IC manufacturing technology.

10.4.5 Machine Tools

In the second half of the 20th century, numerical control (NC) and automation technologies started to be used in manufacturing. Representative technologies include NC machine tools, machining center, group control of machine tools, flexible manufacturing system (FMS), as well as computer integrated manufacturing system (CIMS). Further discussion with more detail will be presented in Chap. 12 on these technologies.

In the past half a century, traditional machine tools have mainly developed along three directions, large size, high precision and high-technology. Some dedicated machine tools were also developed for special machining requirements. Some illustrating facts of the above trends are as below: (1) the largest lathe: 6 m in diameter of work piece, (2) the largest vertical lathe: 26 m in diameter of work piece, (3) the largest boring machine: 0.36 m in diameter of boring bar, (4) the largest planer: 8 m in the width of work piece, (5) the largest hobbing machine: 15 m in the diameter of the gear under cutting (GSHCAS 1985).

The demand for precision machining led to the creation of precision and ultra-precision machine tools (see Sect. 12.3.7). Besides, Non-traditional machine tools were developed for special machining operations, such as electric discharge machining and laser beam machining.

Computer numerical control (CNC) technology has been widely adopted in various machine tools. Now the NC rate of machine tools produced in the main industrialized countries reached 60–70 and 80–90% in terms of units and value respectively.

Now the center of machine tool production and consumption is shifting to Eastern Asia. The annual output revenue of the machining tool industry in this area in 2005 was more than doubled that in 2002. In 2005, Japan, Germany, China, Italy, Taiwan, the U.S. and South Korea are the leading countries in terms of revenue of the industry (SEC 2007).

10.5 Complex Electromechanical System

Some complex systems nowadays contain multi-components, including mechanical, electrical, electronic, and hydraulic etc., and consist of multi-subsystems. These subsystems embed in the machine work in collaboration to conduct a complicated task. This type of systems is referred to as complex electromechanical systems (Zhong et al. 2007). Examples of such systems include airplanes, space crafts, high-speed trains, automotive vehicles, NC machining centers, turbine generator units, IC manufacturing equipment, large tunneling boring (TBD) machines etc. (Fig. 10.21).

In the above-mentioned examples, only a few are new inventions, such as space crafts and IC manufacturing equipment. The others, such as airplanes, trains and automotive vehicles, have been in use for dozens, even hundreds, of years. During the New Era, these old inventions, on the one hand, developed toward high power, high speed and high performance. On the other hand, through adoption of new technologies, such as the hydraulic power and control technology available after the 1930s, and the mechatronic technology available after the 1950s, they became complex containing multiple subsystems, forming the so called complex electromechanical systems.

The performance improvement of various machines has been mainly made though two routes, the advance within the mechanical engineering, and the adoption of new components from other disciplines. These may include electric, electronic, hydraulic and pneumatic systems with which the level of automation could be greatly improved. However, before the 1960s, most machines contained only mechanical and electrical parts.

After 1970, LSI, microelectronics, and computer technologies have developed on fast track. These technologies, microprocessor in particular, made it a reality to embed computers into traditional machines so that the performance of machines can be dramatically improved.

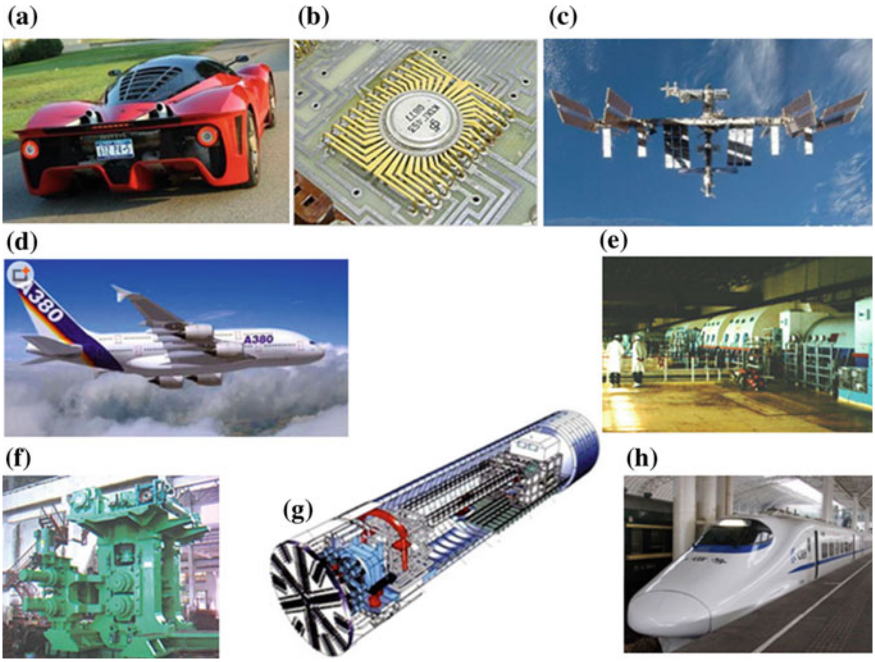


Fig. 10.21 Complex electronic-mechanical systems

The complex electromechanical systems are a representative example of high-tech mechanical systems.

The higher and higher requirements on speed, power, accuracy, reliability and lightweight of such complex systems became a strong driving force to the development of mechanical science and technology. Most new methods in analysis and design were first developed for such systems, and later spread out to other mechanical fields. The following gives an incomplete list of examples.

(1) Accidents in the aerospace industry led to the creation of fault diagnosis and design for reliability. The knowledge in these two subjects were quickly adopted by large-scale turbine generators, and then trickled down to many other fields.
(2) Many new technologies were first used in the aircraft manufacturing industry; these include NC machining and machine tools, group control of NC machine tools, CIMS and collaborative design network.
(3) FEM and active vibration control were also first developed for solving problems in the airplane industry.
(4) large scale turbine generators, a typical complex electromechanical system, demonstrate the most complex dynamic behavior, their vibration modeling involves the interaction between steam, liquid and solid, being nonlinear in essence.

(5) In high speed trains, dynamic stability, vibration and noise control are critical. In addition, the interaction between the train and track, track and bridge as well as the aerodynamic effect have to be accounted for carefully.

(6) Boeing 777 was the first commercial airplane designed entirely by computer. All the design, analysis and simulation were conducted through a CATIA CAD system. Thus, virtual prototype and concurrent engineering methods were adopted.

(7) Application of industrial robots started from the auto-industry.

Two clear trends have been observed from the complex electromechanical system (CNSF 2010).

(1) The frontiers of knowledge and technologies are pushed farther outwards all the time. For example, the modern rolling mill has the capacity to control the error within 1 mm for 1 km material. The frame of A380 plane has a diameter of 5.5 m, which requires a press of 75,000 t capacity for manufacturing. Some CNC machine tools have a repetitive positioning accuracy of 1 μm.

(2) Multi-disciplinary and adoption of new technologies are common. Taking the high speed train and TBM as examples, the design and manufacturing involve mechanical engineering, civil engineering, mechanics, control theory, hydraulic power, electrical engineering, material and information etc.

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Chapter 11
Mechanical Design in New Era

> *Engineering, medicine, business, architecture and painting are concerned not with the necessary but with the contingent - not with how things are but with how they might be, in short, with design.*
>
> —Herbert Simon (one of founders of design science, 1916–2001)

Design is the first step in building a machine. The direct cost of design is insignificant in general; however, design is the most determinative factor to the overall cost of a machine. According to VDI-2225, a survey completed by the Association of German Engineers, about 75–80% of the total cost of a product is determined by design (Huang 1989). More importantly, the performance of a machine is determined to a large extent by design. Design has become a cornerstone in an industrialized society, being a main activity for innovation.

Machine design experienced fundamental changes during the 3rd Technological Revolution, showing a series of new and unique features. These changes mainly came from two factors. First, tough market competition and the changes in production technologies put forward higher requirements to machine design. Second, the advance in computer technologies provided powerful tools to machine design.

11.1 Introduction

As stated in Chap. 7, historically design has gone through 4 stages, namely intuitive design, empirical design,semi-empirical design, and semi-automatic design. The semi-automatic design started from the 1950s.

C. Zhang and J. Yang, *A History of Mechanical Engineering*,
https://doi.org/10.1007/978-981-15-0833-2_11

11.1.1 Development of Machine Design

11.1.1.1 Background

After WWII, the improvement of living standard worldwide created needs for machines of higher performance, better quality and lower cost, making the market competition more intensive. In some cases, machines needed to be specially designed according to customer's requirements. Design for targeted customers or specific environments became common practice. At the same time, products were upgraded faster and faster. In response to these changes, the way of production also took changes, gradually shifting from mass production of coincident products to medium or small quantity production of products with certain variation.

Machine design involves several scientific and engineering subjects. For example, cybernetics, information theory, and systems theory provide general and philosophical guidance to machine design; multibody dynamics and FEM provide new modeling and simulation tools to dynamics; computers provide powerful technical support to machine design and analysis. On the basis of all these available scientific and technological supports, a new term, Advanced Design Methods, was formed under which many special methods, such as CAD, optimized design, design for reliability, dynamic design, creative design, and green design etc., are included.

11.1.1.2 Two Key Words

The Advanced Design Methods are built around two fundamental key words. The first word is "good", meaning to design high quality products; the other is "fast" which means that design has to be conducted quickly in response to market changes.

Tough market competition requires manufacturers to produce machines of super performance meeting or even exceeding the customer's expectation. The "performance" here is in broad sense. It may mean any specific criteria, such as high speed, high accuracy, light weight, reliability, automation, comfortability, cost, and appearance etc. Obviously it is impossible to meet these requirements without careful design and insightful analysis.

To meet the needs of the new production mode, customized production in particular, products have to be developed and produced as quickly as possible, calling for the development of automation, intelligence and visualization techniques in design. Examples include using animation to show a machine's movement, using 3D solid model to show how the product looks like, using color-coded images to show the stress level within a part, and using curves to demonstrate the dynamic response in time and frequency domains.

The 3-D model, response curves, animation, color coded images etc. are different ways of visualization. Visualization is the technology to display data on computer screens through appropriate forms; thus, an interactive interface between the

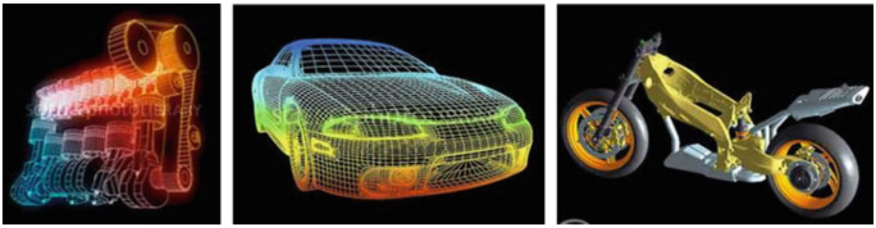


Fig. 11.1 Visualization of design

operator and computers is formed. As a complex technology, it involves multi-subjects and technologies, including computer graphics, image processing, computer vision, CAD. Various visualization technologies have been widely adopted in CAD, dynamic design and FEM software (as shown Fig. 11.1).

Traditionally, products were developed within a factory or at one location. However, this fashion is proven to be unable to meet the fast changing market. Distributed collaborative design is an alternative technology in which experts in different fields and locations are incorporated into one design project. This new design technology is built based on the internet technology, and able to combine the strength of experts and stakeholders with different background, thus, great economic benefit can be expected. Details about this design method can be found in Sect. 12.8.

The Advanced Design Methods are all relevant to fast design, visualization, design automation and intelligent design.

11.1.1.3 Three Characters

The semi-automated design method, which has been developed since the 1950s, has the following characteristics.

(1) Popularization of computers

Computers were first used in mechanical CAD in 1960s. After the 1970s, personal computers became popular in many applications. Computers are the critical technical support for dynamic design, optimum design and FEM, making the rapidness, visualization and automation in design a reality. Computers have been widely used in almost every steps of machine design and manufacturing. The impact of computer technology on machine design can never be overvalued. As Angeles (1997), a former IFToMM president, stated "*It is impossible nowadays to design and manufacture machines without the intervention of the computer. The "computer-aided" qualifier that gained so much popularity in the seventies is thus rapidly becoming an obsolescence*".

(2) Design Theory

Design theory becomes a scientific subject. It provides philosophical guidance to design activities. Concurrent engineering (CE) combines the design and manufacturing process together, which are used to be separated from each other. CE also changes the working sequences from sequential to concurrent. Different design philosophies and methods along with powerful supporting technologies constitute a complex system for modern design theory.

(3) Team Work

As stated in Chap. 9, the development of a new machine now relies more often on team effort. Sometimes, the team may be pretty large involving experts from many different departments of a company, or even from many different companies. For example, the development of Boeing 777 required 8 super computers and more than 2000 terminals. One can imagine how many people were involved in the design. This example represents the highest level of semi-automated design; more discussion will be given in a later chapter.

Undoubtedly, the next step of development will be from the semi-automated design to the fully automated design. However, consensus is not yet reached in the academic community. Some think the fully automated design has not yet achieved. Some others think the computer integrated manufacturing system (CIMS) appeared during the 1990s marked the realization of fully automated design. In this book, we tend to adopt the first.

11.1.2 Design Theory and Methodology

11.1.2.1 Design Methodology

Machine design was split from applied mechanics around the early 19 century, becoming an independent subject. To the first half of the 20th century (see Chap. 7), the frame was formed as a modern scientific subject. However, the modern machine design has crucial limitations; specifically it contains too much empirical, approximate and uncertain knowledge.

Machine design started to develop toward a science after WWII. Computers and system engineering played a critical role in driving this development. In addition, the tougher market competition called for more innovative products to be designed. Design methodology appeared in response to these changes (Feng 2003).

Design methodology deals with design process, design strategies and tactics, design evaluation as well as decision making in each steps of the design process.

Starting in Germany around the 1950s, design methodology developed into a subject having systematic contents, and spread all over the world to the 1970s. In the 20 years following it evolved along two lines (Hubak and Eder 1996). One is represented by Germany that placed emphasis on streamlining the design process and design methods; while the other, represented by the U.S., focused on the creativity of design and application of computers.

11.2 Concurrent Engineering

Concurrent engineering, also called concurrent design, is a systematic approach of designing and developing products, in which the different stages run simultaneously, rather than consecutively (Prasad 1996; Xiong 2001).

All the elements in concurrent engineering already existed more than eighty years ago. For example, the famous Model T car was developed on a teamwork basis. Henry Ford himself sketched his ideas; while his colleagues developed them into engineering specifications, checked the manufacturing feasibility, and solved the problems about new material and casting of block (Chelsom 1994).

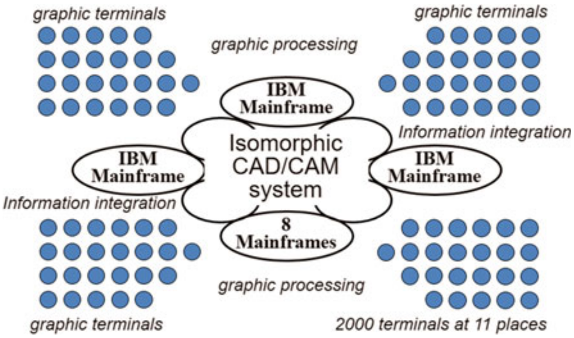
During WWII, both the U.S. and Germany made great effort to speed up new weapon development. In this case, the concurrent design method demonstrated its benefit and potential in weapon development.

In 1988, the Institute for Defense Analyses, IDA, looked into the role of concurrent engineering in weapon system acquisition. This was the first time the term of concurrent engineering was used.

The aim of concurrent engineering include to improve quality, reduce cost and shorten delivery time.

Concurrent engineering was successfully adopted in the development of Boeing 777 airplane during the 1990s (Abarbanel 1996; Sharma and Bowonder 2004) (Fig. 11.2). The design was implemented with a 3D CAD software CATIA on 8 IBM ES/900-720 mainframe computers. About 2000 graphic terminals were distributed at 11 different locations among which the largest distance was about 80 km. This was the first commercial airplane designed entirely with CAD technology; all drawings were created by computers. The traditional, costly physical mock-up was replaced by a virtual computer model, with which the engineers could

Fig. 11.2 Concurrent engineering in development of Boeing 777



simulate the performance, and check for interference between parts. With the help of visualization system, collaborative design was achieved. The adoption of concurrent engineering made it possible to take many downstream factors, such as manufacturing and materials, into consideration during the design stage; thus, the time of development was greatly reduced and design quality was improved.

11.3 Creative Design

Now the competition between countries and enterprises become more and more intensive. Products are seemingly the center of the competition; however, essentially the competition lies more in human skills and the creativity of design.

Creative design in mechanical engineering means to design innovative and practical mechanisms and machines. The innovation might be in function, working principle or mechanical structure. To this end, the existing knowledge and the creative potential of the designer should fully cultivated.

In fact, any invention of new mechanisms or machines, from ancient water mills to modern robots, are creative. However, traditionally the creativity in design was achieved mainly relying on the individual inventor's intuition and inspiration. Some scholars, thus, made effort to develop systematic methods to inspire human's creative thinking. The effort led to the creation of a new subject, "creatology" dealing with various creative theories, techniques and empirical facts. The creative design in this book limits to the methods based on the creatology theory.

11.3.1 Birth of Creatology in U.S.

Creatology was originated from the U.S. primarily for the purpose of training people for creative thinking. Early effort was made during the period between 1930s and 1950s (Yuan and Xu 2010).

The General Electric (GE) started training of its employee with creative courses in 1936. Surprisingly positive effects were created; the number of patent applications of the company in 1937 tripled that in 1936.

In 1938, an advertising agency, called BBDO, run into a crisis in business, losing many clients and key personnel. Alex Osborn (Fig. 11.3), the BBDO's executive vice president then, was frustrated by the employee's inability to creative ideas individually. He tried to explore group thinking techniques. *Brainstorming* was first presented in his book, *How to Think up* (Osborn 1942). With the increasing activity in creative thinking, his writing career soon overtook his work in advertising. His another book, *Applied Imagination* (Osborn 1952), was translated into more than 20 languages and printed more than 120 million copies.

Joy Guilford, the 3rd president of Psychometric Society of the U.S., urged physiologists to work on promoting creativity in a public speech of 1950. In the

Fig. 11.3 A. Osborn

same year, George Prince and William Gordon developed the synectics (Gordon 1961). After a few years, Osborn set up the Creative Education Foundation in 1954.

The above cited events marked the first wave of creatology in the U.S. Osborn's book, *How to Think Up*, was generally accepted as the landmark of the birth of creatology.

MIT started to deliver courses in creativity in 1948, and was followed by many other American institutions. Large companies also started training employee in creativity. Creatology played an important role in keeping the U.S. leading position in science and technology.

During the 1950s, the Soviet Union launched the first earth satellite of the world. This event greatly shocked the U.S. In response, the U.S. governments and the society invested heavily on the study of creativity, and hundreds of creative techniques were proposed, forming the 2nd wave in creatology development.

Japan basically followed the step of the U.S. and Europe in science and technology development after WWII. In the mid. 1950s, creativity study in engineering and management was introduced to Japan. Research centers and institutes focusing on creativity research were set up at some universities. In 1979, the national society, Japan Creativity Society, was formed. It is widely accepted that the education and application of creatology was a key factor for Japan's quick rising in science, technology and economy after WWII.

To the 1980s, the competition in the world market became even tougher. As a result, the competition was extended from product's quantity and quality to the product's peculiarity and uniqueness. To design and manufacture unique and superior products, the creativity of the human resource is essential. All these pushed the spread of the creatology and relevant techniques all over the world.

11.3.2 TRIZ in USSR

Creativity study in the Soviet Union started a little later than the U.S. and developed in a different route (Tan 2002). An iconic example of creativity achievement in Soviet is the TRIZ which is the Russian acronym for “Теория Решения Изобретательских Задач”, meaning “theory of inventive problem solving” in English. It was developed by G. Altshuller (Ге́нрих Альтшуллер) (Fig. 11.4), a Soviet inventor, and his colleagues starting in 1946. After analysis on over 2.5 million patents, they found that creative innovation followed universal principles which, if identified and codified properly, could be followed to find new solutions or improving ones. Based on their finding, Altshuller developed a practical, yet systematic, toolkit, the TRIZ, which could be used for inventive work.

In December of 1948, Altshuller wrote a letter to Joseph Stalin, the dictator of Soviet Union, stating the lack of creativity in Soviet after the war, and proposing the tools they were developing. Unexpectedly he was arrested due to this letter and sentenced to 25 years in the Vorkuta Gulag labor camps. He was freed in 1953 after the death of Stalin (Liu et al. 2011).

He published his first book on TRIZ in 1961, *How to Learn Invention* (Альтшуллер 1961). In his second book, titled “*Algorithm of Invention*” published in 1969, he summarized 40 principles of invention which could be followed in solving complex inventive problems. This was a landmark in the creativity study (Альтшуллер 1973).

The 1960s saw a booming of creativity training in Soviet. Various schools and organizations for creativity were fast developed. An incomplete statistics stated that more than 100 Soviet universities at that time offered courses on TRIZ.

Fig. 11.4 G. Altshuller

The collapse of Soviet created a wave of emigrants, bring the TRIZ to the attention of the outside world (Webb 2002). Since then examples of successful applications have been reported. For example, Boeing successfully solved a difficult problem in developing a new air-to-air refueling system, beating its competitor and increasing extra sales of billions of US dollars (Masingale 2002). In Germany almost all the large enterprises in the Fortune 500, including Siemens, Benz and BMW, set up dedicated departments for training and application of TRIZ.

Samsung, a giant electronic company of South Korea, is another example of success in application of TRIZ. It officially stated in 2004 that the use of TRIZ generated the company economic benefits of more than Euro 1.5 billion (Souchkov 2002).

Creatology has developed in three representative routes in the U.S., Japan and Soviet Union. Each has its unique pros and cons. In the United State, methods by Osborn and Gordon are representative. In these methods invention is regarded as natural consequence of imagination, intuition and inspiration; thus, emphasis is placed on removing mental barriers. Japan stresses on practice, focusing on collecting and digesting information. While in the Soviet Union, creativity study concentrates finding universal principles in inventive work.

Historically invention was mainly driven by individual's intuition and inspiration. Although creativity is under systematic study and various techniques are proposed nowadays, intuition and inspiration, in the author's opinion, still play an important role in inventive activities.

11.3.3 Creative Design

Creative design is the application of creatology theory in engineering design, with the aim of designing creative and innovative engineering systems. In the field of mechanical engineering, creative design can be conducted generally in three levels, namely creative conceptual design, creative mechanism design and creative structural design.

Devising proper mechanism concepts to a given task is always the core in machine design. In some books, creative mechanism design means to generate new mechanisms through basic techniques covered in typical undergraduate texts, such as kinematic reconfiguration, transformation and inversion.

Yan (1998) at National Cheng Kung University, developed a set of systematic techniques for creative mechanism design. The elegance of these techniques lays in that starting with an existing mechanism all the mechanisms which can achieve the same function can be enumerated. Thus, infringement of patent to the existing mechanism could be avoided.

Other methods of creative machine design include reverse engineering and bionic design.

11.3.4 Reverse Engineering

Reverse engineering, or reverse design, is the process to develop a product through disassembling, and analyzing an existing similar product.

Reverse engineering found very successful application in Japan. Japan's economy was completely demolished in WWII. Its GDP in 1950 was only 1/29 of the UK's. After the War, reverse engineering was taken as an important tool to resume its economy. During the period between 1945 and 1970, Japan spent 6 billion USD on importing foreign technologies. However, the investment on analysis and absorbing these technologies reached 15 billion USD. In average the time to obtain a technology was 2–3 years with reverse engineering. It was estimated that if all these technologies to be developed by Japan in the traditional way it would cost 180–200 billion USD and take 12–15 years for each individual technology. It was common then in Japan to import first, manufacture domestically then, and export to the world market in the last (Liu and Huang 1992).

Reverse engineering is not simply copying. The embedded patent, copyright and trademark in the original product have to be respected. Thus, systematic and careful study on both the hard and soft aspects of the original product, including physical models, catalogue, technical documents, manuals as well as technique drawings, is needed.

The above discussion on reverse engineering is made in broad sense. In mechanical engineering, reverse engineering means to obtain the CAD model of a machine through 3D scanning technologies.

11.3.5 Bionic Design (Biomimicry)

Life has existed on earth for millions of years, and has developed skills to adapt well to the nature throughout history. Primitive human beings started to learn from the nature early in the prehistoric times. Many ancient tools were actually resulted from inspiration of the nature. For example, making needles from animal bones might be inspired by fishbones. Wood canoes were made in the shape of fish and the double paddle and single paddle were likely a direct imitation of the pectoral fins and tail fin of fish. These examples, as the origin of bionic design, were not bionic design yet, but simply consequence of bio-inspiration.

Intentionally looking for inspiration in nature to provide solutions for design problems started from the 1950s. The combination of biology and engineering created an interdisciplinary field—bionics. Bionics has achieved great success in many technical fields, such as automatic control, aerospace, marine and military.

Fig. 11.5 Wall-climbing robot (www.yankodesign.com)

Fig. 11.6 Shadow Dexterous Hand (www.shadowrobot.com/)

Fig. 11.7 Artificial leg (http://wonderfulengineering.com)

The word, biomimetics was first used in 1950 by Otto Schmitt, an American biophysicist and inventor (Vincent 2009), in the development of a device that replicated the biological system of nerve propagation. In 1958 Jack Steele created a similar word, bionics, when he worked at Wright-Patterson Air Force Base in Dayton, Ohio. At the same air base the 1st symposium on bionics was held in September 1960 with the motto of "living prototypes—the key to new technology". This symposium marked the birth of bionics (Robinette 1960).

Bionics gained fast growth and wide application thereafter. Its application in design is termed bionic design which has also experienced fast development. A series of products are the results of bionic design (Figs. 11.5, 11.6 and 11.7), examples include robots, radar, sonar, automatic controller as well as navigators.

11.4 Computer Graphics and Computer-Aided Design

Before the 1950s, computers were mainly used for scientific computation. Around the end of the 1950s, two milestone computers, TX0 and its successor TX2, were built in MIT with the feature of direct interaction between the operator and the computer through a Cathode Ray Tube (CRT) screen and a light pen (Newman and Sproull 1973). This early interest in display technology eventually led to the development of more advanced graphics terminals. After the 1960s, computers started to be widely used in mechanical engineering. The fast development of computer technology and the appearance of some peripheral equipment made two new subjects, computer graphics and computer-aided design (CAD), born in MIT. These two inter-linked subjects laid the foundation of visualization in mechanical design.

11.4.1 Computer Graphics

11.4.1.1 The Birth of Computer Graphics

In January 1963, Ivan Sutherland (Fig. 11.8) completed his Ph.D. thesis at the MIT Lincoln Laboratory titled as "SKETCHPAD: A Man-Machine Graphical Communication System". Sketchpad, the project Sutherland developed using Lincoln Laboratory's TX-2 computer, launched the use of interactive graphics for engineering design and drafting. Another key feature of Sketchpad was that the data structure initially formulated by Doug Ross, a then staff at MIT, for CAD systems was extended by Sutherland into ring structure (Weisberg 2008). Several other important concepts and techniques in computer graphics were also adopted in this project the first time.

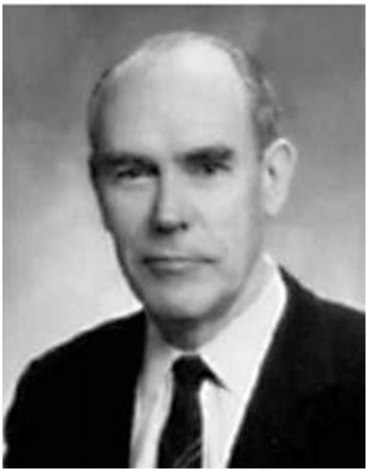


Fig. 11.8 I. Sutherland

Sketchpad was regarded as the origin of not only computer graphics, but also modern computer-aided design. Through Sketchpad Sutherland showed the world the potential that interactive computer graphics was used in artic work as well as technical fields.

11.4.1.2 Development of Computer Graphics

The scope of computer graphics is very broad, covering interactive graphics, curve and surface modeling, solids modeling as well as images with rendering, shading and texture mapping effect.

During the 1970s, raster display technology was invented, followed by a booming period in raster graphics. At the same time, computer graphics made great advance in realistic graphics and solid modeling. Computer graphics began its application in CAD systems, process control and management as well as education (Fu 2005).

After the mid. 1980s, the power of computer was improved significantly due to the progress in LSI technology. In 1979, ray tracing algorithm made breakthrough. In 1984 researchers at Cornell University developed a method for the interaction of light between reflecting surfaces, in which the object-to-object reflection was accounted based on methods in thermal engineering. These progress laid the foundation for computers to generate realistic images on the screens.

In the period of 1980s–1990s, applications in animation, scientific visualization, CAD/CAM, movies and video games as well as visual reality put forward higher requirements on computer graphics (Fu 2005).

A large conference on computer graphics, SIGGRAPH (Special Interest Group on GRAPHics and Interactive Techniques), has been organized every year since 1974. The conference attracted tens of thousands of attendees in engineering, computer graphics, computer animation and video games. Hundreds of companies set up elaborate booths to compete for attention and recruit new talents. SIGGRAPH is widely regarded as the most prestigious forum for the publication of computer graphics research. Some highlights of this conference include its Animation Theater and Electronic Theater presentations, where films recently created with computer graphics are played.

11.4.1.3 Applications of Computer Graphics

Computer graphics has found application in CAD, scientific visualization, VR, computer animation and computer art. Given the special importance of CAD in mechanical engineering, a dedicated later section is put aside to cover the detailed discussion.

(1) Scientific visualization

The first conference on scientific visualization was held in Washington D.C., the U. S. A consensus was reached in this conference that scientists need analyze data as well as understand the change of data in the process. To this end the data need to be displayed in the form of graphics and images which could be edited by the operators through interactive techniques. It predicted that scientific visualization would be a powerful tool for scientists (Nielson et al. 1997).

Scientific visualization now has found application in many fields. Representative examples include: (1) the distributed virtual wind tunnel of NASA, (2) visualization of the Joplin tornadic storm at the National Center for Supercomputing Applications (NCSA), and (3) visualizing human embryonic development with the software developed by University of Illinois at Chicago.

In the U.S. the scientific visualization technology has developed very fast by combining the power of supercomputers, fibre-optical high-speed internet, powerful work stations and visual reality.

(2) Visual reality

It is inappropriate to think visual reality (VR) is only one application of computer graphics. According to Burdea and Coffet (2003, 3), *Virtual reality (VR) is a high-end human-computer interface allowing user interaction with simulated environments in real time and through multiple sensorial channels. Such sensorial communication with the simulation is done through vision, sound, touch, even smell and taste.*

VR is not a new invention; however, the exact origins are disputed. The development before 1973 can be regarded as early stage of this technology. The following are some examples of that period. The experience theater, proposed by Morton Heilig, could encompass all the senses in an effective manner, thus drawing the viewer into the onscreen activity. The first head-mounted display (HMD) system created by Sutherland in 1968 for use in immersive simulation applications (Burton 2012). It should be noted that Sutherland was a pioneer in three interlinked fields, computer graphics, CAD and VR.

To the 1980s, some representative VR systems were developed (An 2014). Examples include the SIMNET developed by the Defense Advanced Research Projects Agency (DARPA), which was used for military training and was able to simulate and display tanks, helicopters and airplanes in a virtual battlefield; and the View (Virtual Interface Environment Workstation) developed by NASA. Some other systems for automotive driver and airplane pilot training were also developed in this period.

The word, "virtual reality", was first used in 1987.

VR entered a fast track of development in the 1990s (An 2014). In 1986, Jesse Eichenlaub proposed to get rid of the then popular stereo glasses and heavy head mounted display units, and develop more advanced 3-D display systems. In 1996, 2D/3D switchable stereoscopic display was invented.

Japan, UK and some other European countries also conducted research work on VR.

(3) Computer graphics in art

Computer graphics are also used in artistic work, mainly including architecture design, auto-design, packaging design and product industrial design.

11.4.2 Computer-Aided Design

11.4.2.1 Birth of Computer-Aided Design

Computer-aided design came into birth at MIT during the 1960s. Then there were two groups in MIT working on computer graphics simultaneously, the Mechanical Engineering Department' design division and the Electronics Systems Laboratory (ESL, the new name of Servomechanism lab).

The two groups held an informal meeting in 1959 at MIT. During this meeting one consensus was reached that there was a significant opportunity for computers to be used in engineering design. Following this meeting, a series of seminars were organized in the same year, and the term of Computer-Aided Design (CAD) was coined the first time during these seminars.

The implementation of CAD was generally credited to I. Sutherland. His doctoral dissertation on "Sketchpad" was considered the origin of modern CAD programs. He reported the Sketchpad in the Joint Computer Conference in the spring of 1963, attracting huge interest in interactive design. Due to his pioneering contribution in Sketchpad, he was awarded the "Turing Award" in 1988 by the Association of Computing Machinery (Weisberg 2008).

11.4.2.2 Application of CAD

General Motors showed great interest in computer graphics in order to improve automotive design. Early in 1950 the company started to develop the DAC-1 system (DAC stands for Design Augmented by Computers) which was released for production in 1963. This system was initially developed on the IBM 704 computer for the purpose to use simple cubic polynomials to describe the outlines of components such as automobile hoods. This was widely credited as the earliest application of CAD in engineering (Krull 1994).

The latter half of the 1960s saw significant progress in the development of computer graphics devices. The introduction of microcomputers after the 1970s greatly accelerated the pace of commercialization of CAD technology. Application was expanded to many fields, from creating simple circuit diagrams to designing very complicated airplanes and automobiles (Fig. 11.9). At the same time, many commercialized CAD systems were put in the market.

During the 1980s, the Very-Large-Scale Integration (VLSI) technology made the micro-processor and computer memory more powerful and much cheaper.

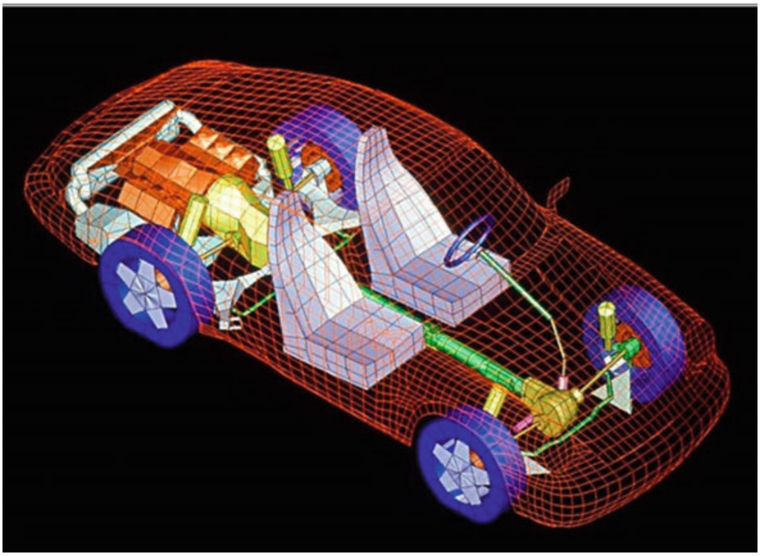


Fig. 11.9 Computer-aided design of a car

Workstations appeared and CAD became popularized in mid and small-sized businesses.

Autodesk Inc. released the AutoCAD in 1982, a landmark in the course of CAD technology.

The 1990s saw rapid popularization of CAD in almost every industry. One important driving force behind was the tougher market competition. In addition, the change to production of small quantity but more product variation, or even customized products, also called for faster design with visualization technology.

The fast growth of CAD technologies caused the development in both hardware and software. Various input and output devices, such as graphic terminals, digitizers, light pens, plotters and photo scanners, were invented. With regard to software, many specialized programs, including graphic, analytic, optimization and finite element packages, were launched to the market.

11.5 Advanced Design Methods for Improving Quality

There are dozens of advanced design methods, several of which, such as optimum design, design for reliability, design for quality and dynamic design, are mainly for improving design quality. We introduce three of these methods in this section, and leave the dynamic design to be discussed in Sect. 11.5.

11.5.1 Optimum Design

Starting from the 1960s, a new subject, optimum design, grew out of the nonlinear programming theory (see Sect. 9.5). Initially optimum design was mainly used by scientists, but quickly accepted by engineers. In mechanical engineering, probably the earliest application was in the field of MMS.

During the 1970s, commercial software packages on optimum design became available in the market, in which multiple algorithms were generally available for the user to choose. With these packages the designers can directly use the optimum algorithms without the need to know the detail of them.

The algorithms described in Chap. 9 are generally called traditional optimum algorithms. This group of algorithms require a starting point to start the optimization process. Due to this reason, the converging speed toward the optima is limited. In addition, the quality of the final solution in these algorithms is highly dependent upon the starting point. If a starting point is not chosen properly, the search may be trapped in a local optimum. The global optimal solution would be never found.

In contrary, the evolutional algorithms use mechanisms inspired by the biological evolution, such as reproduction, mutation, recombination, and selection etc., to find the optimum solutions (Fogel 1994). The best-known one in this group is the genetic algorithm (GA), which was first introduced in 1960 by an American scholar, John Holland, under the inspiration of Darwin's theory of evolution.

To the end of 1960s, the development of the Schema Theorem placed the GA on firm theoretical framework (Holland 1975). GA usually starts from a population of randomly generated individuals. The population in each iteration is called a generation and in each generation the fitness (objective function) of each individual in the population is evaluated. GA overcomes the drawback of being trapped in local optimum, thus, is more likely to find the global optimum solution. After the 1980s, GA began to be applied in many fields. Another evolutionary algorithm commonly used in mechanical engineering is the simulated annealing algorithm which was first developed by N. Metropolis in 1953 (Metropolis et al. 1953). This algorithm simulates the cooling of materials in annealing process to find the feasible solutions. It has the advantage to converge to a global optimal solution. In 1983, S. Kirkpatrick et al. successfully introduced Metropolis' annealing into the field of combinatorial optimization (Kirkpatrick et al. 1983).

11.5.2 Design for Reliability

Electronic systems were extensively used in military equipment during WWII. However, the reliability of these electronic systems was a critical concern. It was reported that the US Navy supplied a million replacement parts a year to support 160,000 pieces of equipment (Coppola 1984). To address the reliability issue, an Ad Hoc group on reliability of electronic equipment, named Advisory Group on Reliability of Electronic Equipment (AGREE), was established in 1950 under the leadership of the US Department of Defense. A formal report was issued by AGREE in 1957 with the title of "Reliability of military electronic equipment", in which the definition of reliability was first given and the evaluation of reliability was recommended as well (AGREE 1957).

In 1961, H. A. Watson at Bell Laboratory created the method of fault tree analysis (FTA), as shown in Fig. 11.10, which maps the relationship between faults, subsystems, and redundant safety design elements by a logic diagram of the overall system (Watson 1961). In this method, the undesired outcome is taken as the root ('top event') of a tree of logic. With FTA the weak points in the system could be easily identified; thus, it is especially suitable for analyzing complex systems. FTA has gained wide application since its invention. The Boeing Company, for example, started to advocate FTA in as early as 1963 (Ericson 1999).

A conference on reliability was hold in 1974 at the University of California, Berkeley. In this conference, FTA and the reliability theory were listed as two equally important progresses. The FTA was mainly used by engineers; while the reliability theory was favorited by mathematicians and statisticians. The two are the same in essence.

In January 1986, the Challenger, the space shuttle of NASA, exploded tragically after launch. Shortly after, the Chernobyl disaster happened to the Soviet Union in

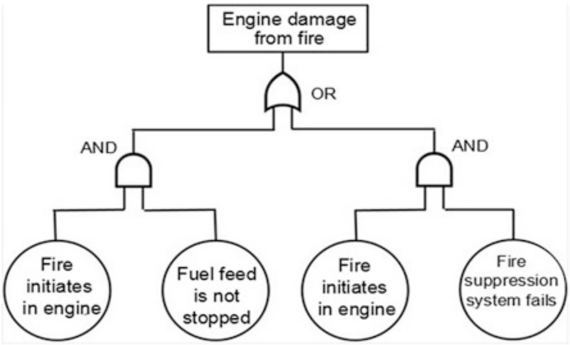


Fig. 11.10 An example of fault tree analysis: engine damage from fire

April of the same year. These two catastrophic tragedies clearly awakened the world the importance of reliability of engineering systems. Since then, the reliability theory has been applied in many engineering fields, ranging from space shuttles to home appliances.

The reliability of a product is mainly determined by the decisions made during the design stage. Thus, the design process has to be organized to ensure that the desired reliability criteria are met and any deviation from the criteria is identified and fixed. Such a design method is called design for reliability (O'Connor and Kleyner 2012).

11.5.3 Design for Quality

Design for quality (DFQ) is the application of rules, guidelines and methodologies during the product development with the purpose of impacting its value while meeting the product design requirements (Feng 2003). Traditionally product quality was thought only relying on machining, assembly and installation. In the reality, product quality is affected by much more factors, including the whole life cycle, starting from planning, through design, production, service to end of life.

Genichi Taguchi, a Japanese engineer, proposed the so-called Taguchi's method early in the 1950s to assure product quality. This method consists of the so-called three designs, namely system design, parameter design and tolerance design. With the three designs, the robustness of a product can be improved through optimization with the quality as the objective function. The Taguchi's method is essential a specific form of design for quality (Logothetis and Wynn 1989).

On the April 17, 1979 issue of the Japanese newspaper, "the Asahi Shimbun", the quality of TV sets made by Sony-U.S.A and Sony-Japan was reported. The color density was taken as the quality characteristic and the tolerance limits for the two factories were set the same (Dehnad 2012). The distributions in color density of the TV sets made by the Sony-U.S.A and Sony-Japan's are as shown in Fig. 11.11.

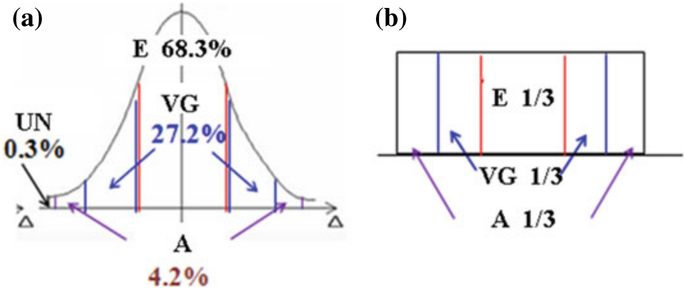


Fig. 11.11 Different distribution of quality. **a** Normal distribution, **b** uniform distribution. E—Excellent, VG—Very good, A—Acceptable, UN—Unacceptable

The Japan made TV sets followed the Normal distribution with 68.3% excellent, 27.2% very good, 4.2% acceptable and 0.3% unacceptable. While the U.S.A products ended up with uniform distribution. Although the Sony-U.S.A did not produce any unacceptable TV, the fact was obvious that Sony-Japan made high quality products.

System design is the first step of conceptual level. The parameter design is the second step in which design of experiments and tolerance analysis are used to find the optimum combination of parameters. The tolerance design, as the third step, determines the tolerance limits of the parameters so that a quality-cost balance could be achieved.

The Taguchi methods found application first in Japan in many industries, including electronics, chemical, automotive, and iron and steel making etc. The methods were soon adopted in Europe and North America when the significant economical benefit was noticed.

11.6 Dynamic Design and Vibration Control

11.6.1 Dynamic Design

11.6.1.1 From Test-Analysis-and Fix to Dynamic Design

Traditionally, machine design was primarily performed on the basis of strength or rigidity without considering dynamics. The dynamic characteristics were tested and analyzed after the physical product was manufactured. In this case, modification to the design has to be made to fix the problems identified in the dynamic test and analysis. This design concept is called the "test-analysis-and fix" (TAAF). However, the TAAF method is not applicable or the cost for the design modification is too high in some cases. It is reported that a fighter plane was burned at its maiden voyage due to severe vibration.

In this case, the dynamic characteristics were thought necessary to be considered during the design stage. This design concept was referred to as dynamic design, which along with condition monitoring, fault diagnosis and proper maintenance are all important for the safe operation of a machine system.

In the early years, the structure rigidity of airplanes was designed without consideration of the aerodynamic effect. There were several records of airplane crashes caused by severe vibration in the literature. For example, a twin-engined bomber went into trouble caused by the tail flutter at the beginning of WWI (Bisplinghoff et al. 1996). During the 1930s, several fighters of the U.S. Air Force broke apart during flight. These accidents led to the study on flutter vibration. Probably airplanes were the earliest examples which were designed with consideration of dynamics. Clear understanding of flutter along with vibration control measures, including passive and active, significantly reduced the accidents caused by flutter.

For automobiles, vibration and noise have detrimental effects on both ride quality and environment. Thus, it has become common practice to consider the dynamic characteristics in design stage.

11.6.1.2 Inverse and Direct Problem

(1) Inverse dynamics

If the desired dynamic characteristics are given and the system parameters are to be determined, the problem is termed as inverse dynamics. Inverse dynamics is applicable to relatively simpler systems, in which the relationship between dynamic characteristics and system parameters can be easily obtained. In the mechanical engineering, high-speed cam systems are a typical example for which inverse dynamics can be used in design. In structural dynamics, the inverse eigenvalue problem also belongs to inverse dynamics.

(2) Direct dynamics

If system parameters are given and the dynamic characteristics are to be determined, the problem is called direct dynamics. Direct dynamics is used more commonly than the inverse dynamics. It includes structural dynamic modification and optimization.

The early development of structural modification and optimization was closely related to the aero-industry.

There are many “structures” in machines, such as the fuselage and wings in airplanes, the blades in turbines as well as the columns in a machine tool. Dynamics of structures developed much earlier than that of machines. For example, optimization of plane trusses traced back about 100 years. Most concepts of machine dynamics, thus, are directly borrowed from structural dynamics (Zhang 2009).

11.6.1.3 Structure Dynamic Modification

In 1958, S. Gravitz proposed to construct the flexibility matrix of airplanes based on the test data. This was the first effort in the application of dynamic modification of structures (Rong et al. 2002). Following this work, many structural dynamic modification methods were developed. Structural dynamic modification is especially applicable to problems with well separated natural frequencies, and has been successfully applied in the design of airplanes and machine tools.

To model a real system generally requires both theoretical and experimental method, and could be very complicated. Figure 11.12 shows the procedure used in the design and analysis of the Viking Orbiter, an interplanetary spacecraft developed during the 1970s in the U.S. (Garba et al. 1976).

11.6.1.4 Structural Dynamic Optimization

The objective function of the optimization could be mass, natural frequencies, stress or responses. However, frequencies are more often be used (Zhang 2009).

Frithiof Niordson published a paper in this field in 1965 (Niordson 1965). In his work, the problem of finding the best possible tapering of a simply supported beam was studied with the primary natural frequency as the objective function. His work belongs to the inverse dynamic problems, and was a pioneer in structural optimization.

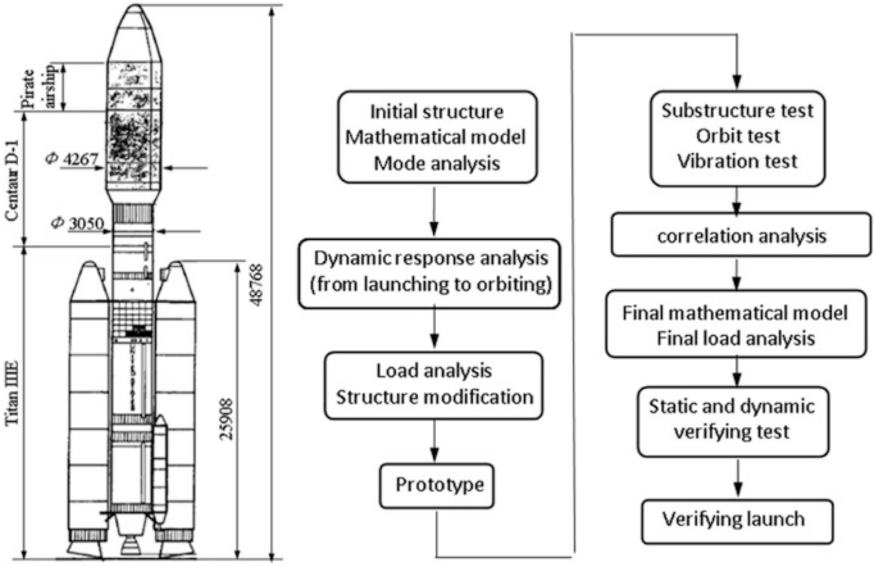


Fig. 11.12 Sketch of Titan IIIE/Centaur D1/pirate airship system

Mehdi Zarghamee, an Iranian scholar, examined a problem to find the optimal primary natural frequency the first time by combining a finite element model and the nonlinear programming technique. His work belongs to the direct dynamics (Zarghamee 1968).

Mathematical programming and optimization criterion method are the main two algorithms used in structural optimization. However, the optimization criterion method became more and more accepted due to some unique features, such as fast convergence and less reanalysis etc. (Zhang 2009).

NASA and some airplane manufacturers developed their own structural optimization programs. Almost all took the natural frequency as the objective function.

11.6.1.5 Sensitivity Analysis and Reanalysis

Calculation of the eigenvalue of large, complicated engineering structures requires intensive computation. Structural optimization needs many iterations, to converge to an optimized solution. Thus, the computation intensity required is surprisingly high. For this reason, some simplified methods for reanalysis have been developed in order to release the tough requirement on computation.

Matrix-perturbation is one of these reanalysis methods. In this method, the change of eigenvalue and eigenvector caused by small change of parameters, called perturbation, can be predicted; thus, the time consuming repeated computation of the eigenvalue could be avoided. The foundation of this method was laid by J. Rayleigh more than 100 years ago.

After the 1960s, many attempts have been made to simplify the reanalysis and several new matrix-perturbation techniques were proposed (Chen 2007).

11.6.2 Vibration Control

11.6.2.1 Methods of Vibration Control

Vibration in machines need to be controlled for different purpose. The study of vibration control has had a history of more than 200 years. With the ever-stopping tendency of increasing in machine speed, many techniques have been developed in vibration control. In the recent half a century, the traditional passive vibration control techniques gained fast development and application. At the same time, active vibration control techniques have appeared and attracted more and more attention.

Vibration control in the past was focused on suppression after it happened. Nowadays, the tendency is to take vibration into consideration in the design stage. Thus, vibration control becomes a part of dynamic design.

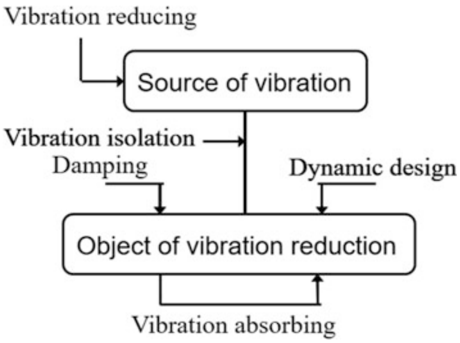


Fig. 11.13 Vibration reduction

Methods of vibration control can be briefly summarized with Fig. 11.13 (Ding 1988).

The most straightforward method in vibration control is to alter the excitation source so that it produces less vibration. For example, vibration of a rotor (or shaft) can be controlled by properly balancing to reduce the unbalance mass (see Sects. 7.4, 13.1 and 13.4). However, this method may not always be effective. Some vibration sources can not be altered, examples include earthquake excitation, wind turbulence, and road roughness.

Another method to control the vibration is to insert an isolator in between the vibration source and the machine (see Sect. 7.3). This method is called vibration isolation; it gained wide application in modern automotive vehicles.

The other method is to focus on the object for which the vibration needs to be controlled. This method is classified into three types.

(1) Vibration absorption

A dynamic vibration absorber, often shortened as vibration absorber, uses another mass-spring system attached to the main (or original) mass whose vibration needs to be controlled. Since the invention it has found applications in many fields, including single and Multi DOF systems, linear and nonlinear systems, and passive and active systems (Pan et al. 2002).

(2) Dynamic design

In this method the vibration is controlled through shifting the natural frequency of the member from the excitation frequency by way of modifying the parameter, shape dimension or materials of the structure member. However, this method is not feasible in the case of broad band excitation, such as the airplane engines.

(3) Damping

Damping dissipates vibration energy; thus, introduction of damping can achieve vibration control. Although this is a traditional vibration control method which have been used for many years, the systematic theory was not established until the 1960s.

In the recent half a century, this technique developed very fast, and it has become an inherent part of dynamic design.

11.6.2.2 Various Dampers

Many different types of damping elements have been developed in the recent decade (Dai 1991).

(1) Hydraulic damper

Shock absorbers have been widely used in automobile since the 1960s. A shock absorber takes advantage of the damping created when hydraulic oil passes through a small orifice to absorb vibration.

(2) Viscoelastic materials

Viscoelastic materials exhibit both viscous and elastic characteristics when undergoing deformation, and have larger values of internal damping. They were first developed in the 1960s for the space and military purpose. The earliest application was for reducing the noise of submarines. Since the 1980s they have been successfully used for control the noise of automobiles in some European countries. However, these materials generally are pretty expensive.

(3) Dry friction

Dry friction dampers are relatively cheaper; thus, applications are found in many fields. For example, installation of friction dampers on turbine blades could effectively control the vibration of airplane engines (Griffin 1990). The multi-layer steel damper and the so called "metal rubber", first developed in the Soviet Union during the 1970s, also falls in this group. Metal rubber is made with metal helixes. It combines the rubber-like elasticity with porosity, and possesses very high damping to vibration due to the friction between the metal helixes. Dampers made of metal rubber can work in wide ranges of temperature and pressure, erosion as well as severe vibration environment (Jiang et al. 2002).

(4) Electrorheological (ER) fluid damper

Electrorheological (ER) fluid is a type of smart fluid whose rheological characteristics can be altered upon the application of an electric field. The first patent on ER fluid was issued to Willis Winslow in 1947 (Winslow 1949). Due to the electrorheological effect, dampers made of ER fluid have a series of very attractive features, such as quick response, ease of control, simplicity in structure, and excellent vibration absorption etc. It has shown great potential in vibration control and was already successfully used in the Cadillac sedans.

(5) Magneto-Rheological fluid Dampers

Magneto-Rheological (MR) fluid is also a type of smart fluid whose properties could be changed by applying magnetic field. It was first found by an American, Jacob Rabinow, in 1948 (Rabinow 1948) and was made with small magnetic dipoles suspended in a non-magnetic fluid. Although MR fluid has been known for decades, it did not attract much interest until 1996. The most developed MR fluids today are those whose viscosity increases when a magnetic field is applied. MR fluid has found application in the automotive industry, being used in the suspension of the Cadillac SRX and Chevrolet Corvette (Szary 2004).

Traditional vibration control methods have no external energy input, thus, are called passive vibration control. Many patents have been filed around the world on vibration control devices based on the passive methods. Dynamics, sometimes nonlinear dynamics, is the basis for design and analysis of these devices.

11.6.2.3 Active Vibration Control

Contrary to the above passive vibration control technologies, active vibration control suppresses vibration by superimposing a secondary vibration source which is equal and opposites to the primary one. Thus, a minimum residual vibration could be achieved. Such a system generally consists of a sensor to detect the vibration, an electronic controller to manipulate the signal from the detector, and an actuator to apply the secondary vibration source (Fuller et al. 1996).

Active vibration control has gained fast development in the recent 4 decades (Preumont 2011), initially to meet the needs of military and the aerospace industry. In 1959, the well-known B-52 bomber was installed with accelerometers on the rear part of the fuselage to pick up the vibration signal which was fed back to the rudder for vibration control purpose. To the year of 1971, control systems for suppressing the low frequency vibration of fuselage were expanded to airplanes of several models.

Active vibration control technology achieved particular success in the following two areas during the 1960s. (1) Through using a magnetic bearing on the top of the shaft in a centrifuge along with the damping vibration technology, new process of isotope separation was created. (2) super quiet manufacturing environment was achieved through active vibration control technology, which is critical to the accuracy of the inertial navigation system in submarines and intercontinental ballistic missiles (Ding 1994).

Later on, active vibration control technology began to be applied to other fields.

During the 1970s and 1980s, some very flexible structures, such as large solar panels, space stations and space manipulators, were built in the United States. Some solar panels are as long as dozens of meters. In addition, the material's internal damping was very small, and usually no external damper was included. Thus, the structure vibration, if not controlled, would be hard to die out, and created several issues for the system, such as affecting the accuracy of the tracking system and causing fatigue to the parts. In all these flexible structures, active vibration control found successful application (Ding 1994).

After the 1980s, piezoelectric materials were used as the sensor and actuator in suppression of the vibration of flexible manipulators and linkages with active control (Zhang 2009).

For small rotors, active vibration control technology, along with controllable oil-lubricated bearings and ER fluid dampers, was successfully applied to suppress the vibration when passing the critical speed. However, there are still hurdles to overcome for application in large rotors (Ding 1994).

For some large structures and machines, the force level, frequency response and deflection magnitude requirements in active vibration control may render an actuator design totally impractical or lead to very high cost. In this case, an alternative solution is to use semi-active control technology which suppress the vibration by modulating the characteristics of essentially passive elements such as springs and dampers. Semi-active vibration control technology found particularly successful application in automotive and rail vehicles, greatly improving the vehicle's performance (Gao et al. 2003).

After the 1970s, automotive active and semi-active suspensions appeared. In 1974, Dean Karnopp et al. invented a damper which could be opened and closed automatically. With this damper, a semi-active suspension was constructed (Karnopp et al. 1974).

A semi-active automotive suspension contains sensors to detect bumps on the road, and a controller to control the damper on the wheels through automatically adjusting the stiffness. In this concept, sensors are used to collect data of the road condition which are sent to a computer for control purpose. In addition to automotive vehicles, semi-active suspensions have been also applied in rail vehicles. For example, the Shinkansen trains are equipped with semi-active dampers in which accelerometers are used to pick up acceleration signal. The acceleration signal first is filtered and then integrated to obtain the velocity. Based on the velocity the actuator generates a proper level of damping. For the challenge to control lateral hunting oscillation, Germany and Japan both developed semi-active hydraulic dampers installed on their high-speed train systems respectively.

Almost all modern control methods, such as adaptive control, optimal control and robust control, have found application in the active vibration control. The focus in vibration control has been shifted from linear vibration to nonlinear vibrations.

Smart structures represent the most outstanding progress in active control of vibration. They integrate the actions of sensors, actuators and control circuit elements into a single system that can respond adaptively to environmental changes in a useful manner (Hu et al. 2007; Meng et al. 2007). Now smart structures have found applications in active control of the vibrations in some flexible structures, such as the solar panels and space deployable antennas.

Most modern machines contain a control system. Thus, dynamics of machinery nowadays has to include the control system. For some important machines, it has become common practise that the machine parameters are determined in the design stage through dynamic analysis. In the following operation stage the machine is controlled with active control technology so that the machine works as expected. In short, design of the control system has become an integrated part of the dynamic design.

In fact, active vibration control technology has advanced to systems with nonlinear components and time delay. Hu Haiyan, a Chinese scholar, noticed that vibration control differs from the control of general industrial process in that time delay is inevitable in the feedback (or feedforward) of vibration control. This time delay is the source of self-excited vibration. Hu systematically investigated the control of dynamic systems with time delay and developed the stability criteria for such systems (Hu and Wang 2002).

11.7 Other Advanced Design Methods

11.7.1 Value Engineering

Value engineering is a systematic method to improve the "value" of goods, products or services by using an examination of function. It can help reduce costs and increase profit margins if properly applied (Wang et al. 2006).

Value engineering began at General Electric (G.E.) during WWII which caused shortage of skilled workers, raw materials, and component parts. Several engineers at G.E., including Lawrence Miles, Jerry Leftow, and Harry Erlicher, tried to look for acceptable substitutes, and found that these substitutions often reduced costs, improved the product, or both. What started out as an accident of necessity was turned into a systematic process. They called their technique "value analysis". In 1947, Miles summarized these techniques and created the basic structure of "value engineering." G.E. invested around $800,000 on value engineering in a period of 17 years between the 1950s and 1960s. The gain, however, exceeded more than $200 millions.

Value engineering combines technical knowledge and project management techniques to identify the function of a product or service, to establish a worth for that function and to generate alternatives through the use of creative thinking. It has the following features: (1) Value engineering does not intend to simply reduce cost, instead it defines the product value as the ratio of function/cost. (2) Unnecessary expenditure is identified through analysis of function, and removed; thus, the value of a product or service could be increased. (3) Cost is related to the whole life cycle, including the cost in production, design, maintenance, and replacement. In some cases the maintenance cost may be much higher than production cost.

Value engineering has been widely adopted in the U.S. After the 1960s it was exported to Japan, West Europe and the Soviet Union. In some countries, national standards have been established. In China value engineering also found application in many businesses.

11.7.2 Industrial Design and Ergonomics

Industrial design (ID), according to the definition of the Industrial Designers Society of America, is the professional service of creating and developing concepts and specifications that optimize the function, value and appearance of products and systems for the mutual benefit of both user and manufacturer (Fig. 11.14).

The birth of ID is closely linked to industrialization. In 1907 Deutscher Werkbund (German Association of Craftsmen), was established with the aim to improve the competitiveness of German industry in global markets (Schwartz 1996). This state-sponsored association was a mixture of art and industry, and attracted the top artists, greatest architects as well as industrialists and manufacturers. Deutscher Werkbund was a landmark in the development of architecture and industrial design, directly leading to the creation of the Staatliches Bauhaus.

The Staatliches Bauhaus, the first school of design in the world founded by Walter Gropius in 1919 at Weimar, was widely regarded as the landmark of the birth of modern industrial design (Pevsner 1999). Bauhaus, coined by Gropius, was derived by inverting the German word, “hausbau”, literally meaning “building house”. The school was forced to a close by the Nazi in 1933 because of the left-wing political views in students and staff. The Bauhaus, although existing in very short time, had significant influence on later industrial design education.

The International Council of Societies of Industrial Design (ICSID), latterly changed to the World Design Organization (WDO), was founded in 1957 to promote the profession of industrial design.

After WWII, ID gained fast development and great achievement. Many design philosophies appeared after the 1960s. The popularization of Internet and the idea of sustainability in the 21st century brought fundamental changes to the ID. The iPhone from Apple Inc., for example, opened a new era of design centered around service (He 2004).

More and more products manufactured through mass-production become more appealing in appearance with the help of ID. Among the many applications of ID in the mechanical engineering, one representative example is the concept design of automotive vehicles (Fig. 11.15).

Fig. 11.14 Industrial design: a bicycle foldable into an umbrella size

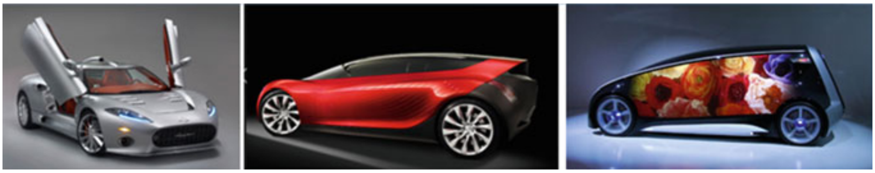


Fig. 11.15 Industrial design: concept car

Along with societal and technical progresses are shorter life-cycle of product and faster pace of life. The abundance in material life makes people pay more attention to unique features of a product other than quantity, such as ease of use, comfortability, reliability, value, safety and efficiency. This is the so-called personalized design which is often mentioned in product-design.

To design personalized products, human engineering has to be used.

Human engineering is an inter-disciplinary study (Meister 1999) originating from Europe, but mainly getting developed in the U.S. Human engineering and ergonomics are considered interchangeable, human engineering being used in the U.S. and ergonomics being more commonly used in European countries and Japan. The term Ergonomics was derived from the Greek words: Ergon—work; Nomos—natural law. It was first used by a Polish Professor, Wojciech Jastrzebowski, in 1857.

According to the International Ergonomics Association Executive Council (IEAEC 2000), "ergonomics" (or human factors) is defined as the scientific discipline concerned with the understanding of the interactions among human and other

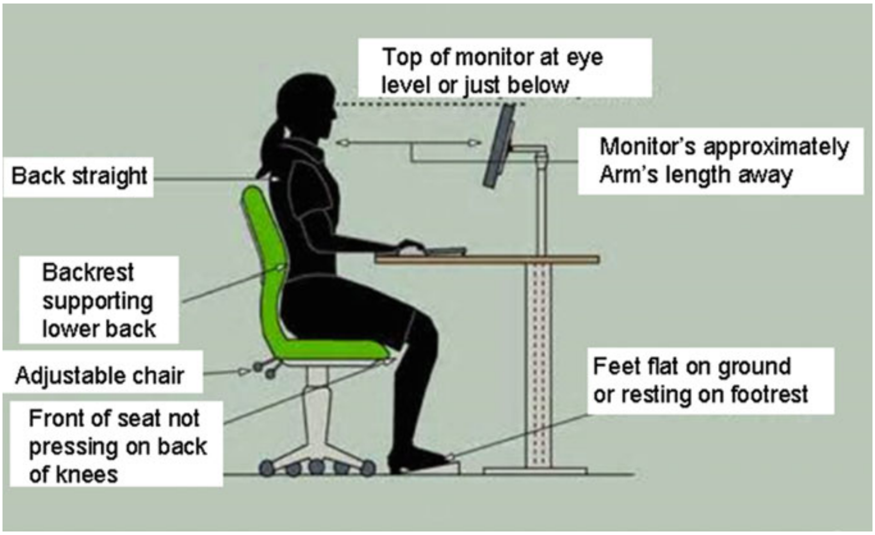


Fig. 11.16 An example of ergonomics research

elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance (Fig. 11.16).

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Chapter 12
Manufacturing Technology During New Era

> *Manufacturing industry is the "never fall sun", one of the pillars of contemporary civilization. It is both the basis and also the frontier, both an old craftsman and also a young scholar. It is the foundation of sustainable development of national economy.*
>
> —Yang Shuzi (Chinese academician, 1933–)

We first make a comparison of the typical manufacturing technologies in the 2nd Industrial Revolution against that in the New Era (Table 12.1).

Without further explanation, the great progress made during the 3rd Technological Revolution is clearly seen.

12.1 Introduction

12.1.1 Challenges in New Era

12.1.1.1 Higher Productivity

After WWII, the world was in peace again and the economy around the world resumed quickly. The desire for higher living standard drove up the demand for almost all products. Taking automobiles as an example, Table 12.2 shows statistics of the number of vehicles per 1000 inhabitants in several counties (ANON 2017). In the U.S. every 1000 people owned 797 motor vehicles in 2014; however, this number was only about 143 in 1924.

To meet the dramatically increased demand for motors, more machine tools along with other types of production machines, such as stamping presses, were needed. Also, productivity of these machines needed to be improved, driving the development of new technologies, including high-speed machining, computer-aided process planning (CAPP), group technology, as well as digital manufacturing.

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https://doi.org/10.1007/978-981-15-0833-2_12

Table 12.1 Comparison of manufacturing technologies between the 2nd industrial revolution and new era

	Traditional technology (in the second industrial revolution)	Contemporary technology (in the new technological revolution)
New machine tools	Grinding machine, gear cutting machine, etc.	CNC machine, machining center, ultra precision and ultra high speed machine tools
Tool material	High-speed steel, carbide	Carbide, ceramic tools
Cutting speed	100 m/min or more	The highest speed is more than 1000 m/min
Automation	Mechanical and electrical automation, single machine automation, rigid automation	Flexible automation, towards to intelligent automation
Production mode	Mass production	Multi-variety and small-batch production, customized production
Processing	Machining	Machining, non-traditional processing, additive manufacturing
Environment	Less considered	Green manufacturing
Management	Taylor's management	Computer integrated manufacturing system, network manufacturing, virtual property
Distribution of resources	Labor intensive, equipment intensive	Information intensive, knowledge intensive

Table 12.2 Number of road motor vehicles per 1000 inhabitants

Australia	The U.S.	Italy	Poland	Japan	S. Korea	Russia	China	Vietnam
736	797	679	537	591	459	293	205	23
(2016)	(2014)						(2015)	(2013)

12.1.1.2 Higher Accuracy

Newly emerged technologies and large complicated engineering systems, such as space shuttles, airplanes, and mechatronic products, greatly lifted the requirement on machining accuracy. For example, the micro-robots used in gene manipulation have a motion range in the scale of nanometre, requiring the accuracy as high as 0.1 nm (Zhu 2001).

To meet the high requirement in accuracy, ultraprecision machining technologies appeared, which have a precision level to the atomic scale in the order of 0.2–0.4 nm. For this reason, the ultraprecision machining is also called nanomachining (Joshi 2012).

12.1.1.3 Change in Manufacturing

Machine building became an industrial sector in Britain during the 1st Industrial Revolution. Since then manufacturing has experienced fundamental changes.

Initially, machines were built by craftsmen in workshops. In this case, products were with very little variation, and production quantity was small. The year 1914 saw a fundamental change when H. Ford introduced an assembly line to his factory (Hounshell 1984). With this assembly line, large number of coincident cars were manufactured efficiently. This new way of production is termed as high production or mass production. Mass production uses dedicated machines and various automated equipment; thus, automation of this type is called rigid automation or Detroit type automation. Mass production and rigid automation dominated the manufacturing in about half a century, being a symbolic achievement in mechanical engineering in the 20th century.

Changes came again during the 1960s and 1970s. Mass production met the common demand of most people. However, personal preferences and special requirements on products stood out after the basic demand was met, leading to the change of market need from large number, but coincident products to smaller number, but more variant products. To meet this changed market requirement, manufacturers changed the mass production back to a job shop style in which a variety of products could be made. It was reported that job shop production has been the dominant in the U.S. where 90% of the products in the market was manufactured with less than 50 items (Xu et al. 2001).

This also caused changes to the manufacturing system. Mass production was implemented through rigid automation in which automated machines and manipulators are the main players. In the job shop production, however, flexible manufacturing systems are needed to make smaller number of, but more variation in, the products. Programmable machines and robots are the center in such a production style.

12.1.1.4 Crisis of Natural Resources and Energy

The crisis of energy and natural resources was already discussed in 9.2.2. The manufacturing industry has been the largest consumer of energy and natural resources for a long time. In the New Era, market needs dramatically increased while product life was generally shortened, putting an ever high need for energy and almost all natural resources. The United States Department of Energy predicted in its International Energy Outlook 2001 that the consumption of energy would increase by 60% in 20 years.

To address the challenge, Kenneth Boulding, an American economist, proposed the concept of circular economy in 1966. The Club of Rome published a report in 1972 titled as “The limits to growth”, warning that the global system of nature, which we all live in, could not support the rates of economic and population growth beyond the year 2100 (Meadows et al. 1972). In 1987 the United Nations World Commission on Environment and Development released the Brundtland Report, in which the concept of sustainable development was defined the first time (Brundtland Commission 1987). In 1992, the Agenda 21 was issued on the UN Conference on Environment and Development as an action plan for sustainable development, calling all the nations to draw their own plans in national and local level in order to achieve global sustainable development.

The crisis in energy and natural resources significantly affected every aspect of mechanical engineering. To reduce energy consumption, light-weight design became a trend. Lighter materials, such as ceramics, started to replace metals in making some mechanical components. The introduction of new materials brought challenges to both design and manufacturing. Also, for light-weight purpose, thin-walled parts were used more often, which might be an issue for machining. These manufacturing challenges, in turn, led to the invention of non-traditional machining technologies.

12.1.1.5 Environmental Crisis

It is reported that more than 70% of the total pollutant discharge all over the world comes from the manufacturing industry. Thus, it is an urgent challenge faced by the world to find greener and more sustainable manufacturing technologies (Eccleston and March 2010).

The challenges from natural resources and energy crisis, as well as ecosystem and environmental degradation directly inspired the development of green manufacturing.

12.1.1.6 New Materials

New materials have been continuously developed and applied in mechanical engineering. Structural ceramics have been used to make many mechanical parts, such as bearings and cylinders of internal combustion engines. Compared with metals, ceramics are harder, and more brittle; thus, more difficult to machine. On the other hand, however, the requirement on accuracy of manufacturing was not compromised.

Titanium alloys, super-alloys and various reinforced plastics are widely used as materials for fuselage and wings of airplanes. These materials are all hard to machine.

To address the machining problems of these new materials, one effort was to adopt traditional machining methods to these materials. The other route was to

Fig. 12.1 Installation of generator rotor in Three Gorges Hydropower Station, China

develop specialized technologies for the hard to machine materials, the so called non-traditional machining technologies.

12.1.1.7 Extreme Dimension

During this period, machines developed toward two extremes in terms of size, very large and very small.

Three Gorges Dam, for example, is the largest hydro-power complex project all over the world. Its power generating units are so large that the outer and inner diameter of the generator are 22 and 20 m, respectively (Fig. 12.1). Despite the huge size, the requirement on accuracy of manufacturing is very tight; the dimension deviation of the inner diameter is within 1 mm.

The other extreme is the manufacturing and fabrication of integrated circuit, micro-scale machines, as well nano-machines. As their names imply, these machines are extremely small. The micro-scale machines normally range from 1 to 100 μm in size. The nano-machines are even smaller, being measured in nanometers (Wang 2013). Some details of manufacturing this types of objects are given in Sect. 10.4.4.

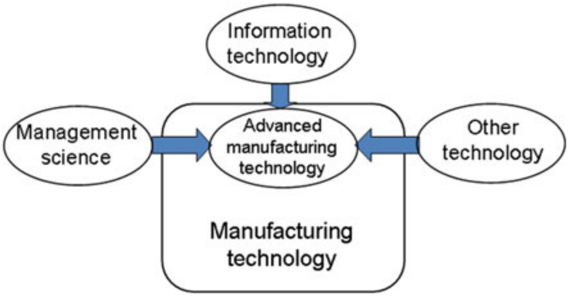


Fig. 12.2 Advanced manufacture technologies

12.1.2 Developments of Manufacturing Technologies in New Era

Along with the change in production from large quantity, less variation to small quantity, more variation, flexible and intelligent manufacturing systems were gradually replacing the traditional rigid ones.

GT, CAD/CAM, CAPP, NC machining, machining centers, and FMS, which are all based on information technology, make up the main contents of the so-called advanced manufacturing technologies. These technologies played a big role in reducing labor working intensity, lifting productivity and improving machining accuracy.

In addition, progresses were also made in this period in ultra-high-speed machining, ultra- high-precision machining, non-traditional manufacturing as well as additive manufacturing technologies.

With the advent of the knowledge economy era, the manufacturing industry changed from labor and machine intensive to information and knowledge intensive (Wang 2004).

The advanced manufacturing technologies were a result of incorporation of information technologies, management and several other disciplines (Yang and Wu 2003) (Fig. 12.2).

In 1951 the Foundation of the International Institution for Production Engineering was established, which later changed to the International Academy for Production Engineering Research (shortened as CIRP).

12.2 Automation: Backbone of Advanced Manufacturing

Automation is the backbone of the advanced manufacturing technologies. Given that CIMS covers a wider scope including the whole system in a manufacturing enterprise, CIMS is introduced in a dedicated section in this chapter.

12.2.1 NC Machining and NC Machine Tools

Since Christopher Spencer invented the first fully automatic turret lathe of the world in 1873, interest in automated machining has never stopped. Before the WWII, automation was mainly achieved through cams, hydraulic transmission and relay control. However, real automation in machining was not accomplished until the advent of computers.

12.2.1.1 Birth of NC Machine Tool

Parsons Corp., an American manufacturing company, and MIT were widely credited as the pioneers in developing NC machine tools. John Parsons first used a "computer" in manufacturing in 1946 (Olexa 2001); however, the computer he used was not more than a punched card calculator. In 1948, Parsons got a contract from the U.S. Air Force to develop a machine for construction of jet-plane wings. However, he quickly realized in the process of building this machine he and his staff did not have the necessary knowledge and resources. Thus Parsons subcontracted part of the machine to the Servomechanisms Laboratory at MIT. In 1950, the Servomechanisms Laboratory bought a surplus "Hydro-Tel" mill from Cincinnati Milling Machine Company for development, and signed a new contract directly with the Air Force without Parsons. The MIT's machine was widely credited as the first generation of NC machine tools, and was publicly demonstrated in 1952. Nevertheless, Parsons already filed a patent earlier. The control system of the MIT machine consisted of vacuum tubes and relays.

12.2.1.2 Further Development of NC Machine Tools

During 1952–1958, the collaboration between MIT and the U.S. Air Force continued. The initial NC system was programmed by hand and it was very time consuming. John Runyon at the MIT attempted to automatize the process. In 1956, D. Ross, a researcher at the Servo-lab, made main improvement to the programming solution, which eventually evolved to the Automatically Programmed Tool (APT). At this time, NC became CNC (computer numerical control). Besides the milling machines, NC technology was expanded to other types of machine tools, including boring machines, drilling machines and lathes. Obviously, MIT made ground-breaking contribution to the development of CAM, computer-aided manufacturing (Reintjes 1991).

To 1959, the second generation of numerical control (NC) technology, characterized with transistors and printed circuit boards, became dominant. To 1965, The third generation of NC technology was adopted, represented by the much smaller, more reliable and energy-efficient integrated circuits. On the International Machine Tool Show 1970, at Chicago NC systems with general minicomputers were demonstrated for the first time. This system is referred as the fourth generation of NC system or CNC system. With the appearance of microprocessors, NC technology advanced to the 5th generation, featured with much cheaper and more reliable large scale integrated circuit technology.

Now CNC has been a mature technology. Allen-Bradley, FANUC and Siemens are the largest three CNC providers of the world (Wang 2004).

The first commercial machining center of the world, Milwaukee-Matic II as shown in Fig. 12.3, was successfully developed at Kearney & Trecker Corp., the U. S., in 1958 (Makely 2005). It added automatic tool changer and automatic work positioning to a NC milling machine; thus, multiple operations, such as milling, drilling, reaming and broaching etc., could be performed with one setup. A machining center is normally equipped with multiple tool options. Machining centers greatly improved the productivity due to the automation of work and the reduction of non-productive time. In the 1966 Chicago Machine Tool Show machining centers were displayed the first time and immediately attracted wide interest from various industries. Following that was a rapid development.

The first effort of using one computer to control multiple machine tools, group control, was made in 1966 as the direct numerical control (DNC) technology. With the number of CNC machine installation grew during the 1970s and 1980s, DNC evolved into a new form as distributed numerical control (DNC).

Military aircrafts are normally produced with low quantity, but high quality requirements. The U.S. Air Force and its aircraft providers paid great attention to the development of NC machine tools. Manufacturing of aircrafts was always faced

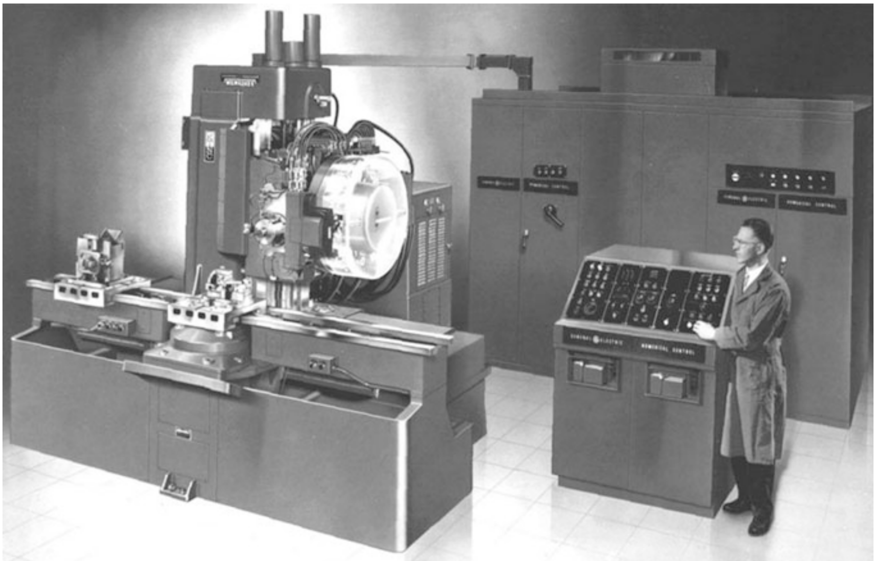


Fig. 12.3 Milwaukee-Matic II, the first machining center

with new challenges; to addresses the challenges often inspired the creation of new technologies. The Air Force collaborated widely with universities, and provided abundant research funding to support fundamental research as well as technical development with regard to NC machining. Correspondingly, many innovations in this field were tied, directly or indirectly, to the U.S. Air Force. This fact combined with the America's leading position in electronic and computer technology made the U.S. one of the top NC machine producers.

Now NC technology has been applied to lathes, milling machines, EDM machines, and various gear cutting machines. Compared with conventional machine tools, NC machine tools have a series of advantages, such as flexibility of operation, ability to produce complex shapes, high productivity, as well as high product quality. Due to these features, they have been widely accepted by the manufacturing industry.

12.2.2 Process Planning

12.2.2.1 Group Technology

With the batch production becoming dominant, two needs came forward. One was to improve the productivity, and the other to integrate design and manufacturing into a higher level. Group technology (GP) is a methodology that takes advantage of the design and processing similarities among the parts to be produced. It is especially beneficial to the above two needs. Machines may vary in types and functions; however, the individual components within the machines can be grouped into several part families. Individual parts within each part family bear great similarity in design or manufacturing. A gearbox, for example, can be divided into a housing, shafts, gears, and seals etc. Improvement in productivity is achieved by arranging the manufacturing equipment into machine groups or cells and each cell specializes in the production of a part family.

The origin of GT is traced back to a paper by R. Flanders, an American engineer, in 1925 in which he proposed a way to organize manufacturing. In 1937, A. Sokolovsky (А. Соколовский), a scholar from Soviet Union, described the essential features of GT. S. Mitrofanov (Сергей Митрофанов), also a Soviet Union scholar, published a book in 1959 entitled *Scientific Principles of Group Technology*. H. Opitz in Germany developed the well-known part classification and coding system, the Opitz Classification System (Groover 2001). After these developments, application of GT also significantly expanded in many countries, including UK, Japan, China and the U.S.

GT, combined with computer technology, is critical in many design and manufacturing activities nowadays, such as CAD, CAM, CAPP and FMS. In the U.S. Air Force project, Integrated Computer Aided Manufacturing (ICAM) (see Sect. 12.8.1), the design, manufacturing and management were connected through the GT technology.

12.2.2.2 Computer-Aided Process Planning

Computer-aided process planning (CAPP) is the use of computer technology to aid in the process planning of a part or product to be manufactured.

Process planning involves determining the most appropriate manufacturing processes and the sequences for producing a given part or product according to the specification set forth in the design documentation. It used to be accomplished by engineers who were familiar with the manufacturing process, equipment and machining tools required. Process planning was time consuming, and the quality of the planning heavily relied on the knowledge level and experience of the planner. CAPP is a more efficient and reliable alternative way of the above process planning.

The earliest research on CAPP was in 1965 (Niebel 1965). The earliest CAPP system, AUTOPROS, was developed in Norway in 1969 and was available in market in 1973 (Sun 2004). Among the many CAPP systems, the CAM-1 Automated Process Planning, developed by CAM-1, is a landmark.

CAPP stands as a bridge in the integration between CAD and CAM.

12.2.3 Integration of CAD/CAPP/CAM

The three computer-aided technologies significantly improved the efficiency in design and manufacturing. However, they were developed following the conventional engineering practice in which engineering drawings were prepared by designers and draftsman and later used by manufacturing engineers to implement the design. The design and manufacturing were separated from each other in this practice, creating duplication of work by design and manufacturing personnel and being of low efficiency. Thus, during the 1970s and early 1980s, effort was made to integrate the three into one CAD/CAPP/CAM system, in which the design and manufacturing were directly linked. The goal was to automate not only design and manufacturing, but also the transition between the two. In an ideal system, the design specifications of a product embedded in the CAD data base can be directly accessed by the CAPP to convert into process plan and by the CAM to generate the NC part program.

It is worth mention that the GT was also integrated into the system in some cases.

The integration of the three technologies laid the foundation for computer integrated manufacturing systems (CIMS).

12.2.4 Flexible Manufacturing Systems

Flexible manufacturing systems (FMS) was a technology developed starting from the 1960s (Toni and Tonchia 1998).

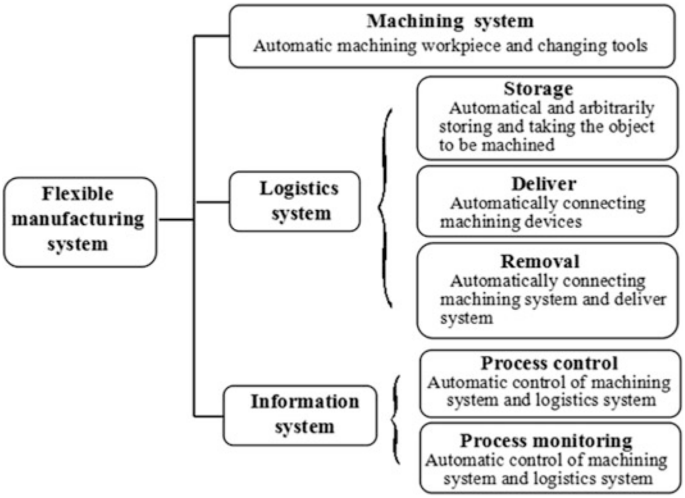


Fig. 12.4 Flexible manufacturing system

Mass production relies on dedicated equipment and production lines, featuring high efficiency and low manufacturing cost. However, mass production systems tolerate very little, or not at all, product variation. Traditional production of low and medium quantity had certain capacity to deal with product flexibility through using general purpose machine tools and equipment. The drawback was low productivity and high production cost.

A flexible manufacturing system (FMS) consists of processing workstations, usually CNC machine tools or machining centers, interconnected by automated material handling and storage systems and is controlled by distributed computer systems. It has high productivity, and a certain level of flexibility at the same time (Fig. 12.4).

The first FMS concept was proposed for machining by David Williamson, an engineer at Molins, UK. He was granted the patent in 1965 (Maleki 1991). His concept was named system 24, because the system was expected to work 24 h/day, 16 h of which unattended by human workers.

One of the first FMS installation in the U.S. was the Omniline I system at Ingersoll-Rand Company in Roanoke, Virginia, in 1967. This system was installed by Sunstrand, and consisted of two five-axis machining centers, two four-axis machining centers and two four-axis drilling machines. In 1976, Japan's Fanuc Ltd. exhibited the flexible manufacturing cell (FMC) consisting of machining centers and industrial robots. West Germany and Soviet Union also installed FMS shortly after in 1969 and 1973 respectively.

FMS approached technical maturity around the late 1970s, and gained increased acceptance all over the world. By 1990, about 1500 FMS were installed throughout the world.

Benefits of FMS include reduction of overall product cost, labor and machines required, shortening of lead time as well as possibility of unattended production.

12.2.5 Robots in Manufacturing

The beginning of robotics in the U.S. was closely related to the auto-industry. The Unimate, the first commercialized product of Unimation, was installed in an assembly line of GM (see Sect. 10.3).

By the late 1960s, robots were widely applied in Japan for automotive production. After 1980, industrial robots gained further popularity. Now all the main auto-makers of the world have adopted robots in their production systems.

Assembly was the first operation to use robots (Fig. 12.5). Other operations in which robots are applied include conveying, welding and painting.

In the first half of the 20th century, manipulators were used in fixed production systems for moving work parts between machine tools. A manipulator differs from a robot essentially. A manipulator is an automated machine which has fixed moving sequences. It does not contain a computer. While a robot contains computers in its control system and its moving sequences can be changed through programming. Thus, a robot can accomplish multi-tasks, and is particularly good at medium and low quantity production dealing with certain level of product variations.

Industrial robots have become an integrated part of FMC.

Parallel robots are the basis of parallel machine tools, details of which are given in Sect. 10.3.2.

Fig. 12.5 ABB robots work at an automobile manufacturing facility in Tianjin (http://usa.chinadaily.com.cn/weekly/2012-10/05/)

12.3 Progress of Machining Technology

In the New Era, machining technologies also progressed fast. The demand for high productivity, and high machining precision as well as the advent of various new materials are among the main driving forces to the progress.

12.3.1 Tool Materials

To meet the requirement of high-speed machining and machining difficult-to-machine materials, many innovations were made in tool materials, amongst which the development of hard coating technology and ceramic materials was the most representative (Kane 1982; GSHCAS 1985).

During the 1970s, the chemical vapor deposition (CVP) and physical vapor deposition (PVP) technology were used to engineering tool surface. Through applying coating of TiC, TiN, HfC, Al_2O_3 on surface of high-speed steel and cemented carbide, the tool's performance and durability were greatly improved.

Market needs pushed the development of new tool materials, also improved the existing ones. These needs mainly include improving productivity, improving machine tool structure and NC machine tools performance, and machining of difficult-to-machine materials etc. It is estimated that difficult-to-machine materials now make up above 50% of total materials requiring machining. Cemented carbides are not satisfactory in machining some of the difficult-to-machine materials. In addition, the current market demand for cemented carbides is already very large, consuming huge amount of tungsten, cobalt, tantalum and niobium. It is estimated that the resources of these precious elements on earth will run out in several decades if the current consumption rates continue.

Ceramics tools were developed as an alternative solution to the above challenge (Kane 1982; Ai and Xiao 1988; GSHCAS 1985).

The effort of making tools from ceramics first happened in UK and Germany during the early 20th century. However, the high brittleness prevented its application. In 1922, ceramic tools were used to cut plastics and nonferrous metals in the Soviet Union. The U.S. also conducted study on ceramic tools during the 1930s and 1940s. However, the real breakthrough did not occur until the mid-1950s. Due to the lower strength and toughness, ceramic tools were only used for uninterrupted finishing or semi-finishing operations. In 1950, the 2nd generation ceramic, Al_2O_3-TiC, was developed in the U.S., which significantly improved the strength and toughness on the basis of aluminum oxide. Tools made of the 2nd generation aluminum-based ceramics were developed in 1968, which greatly expanded the scope of application of ceramic tools. Silicon nitride tools were developed around the end of the 1970s. Silicon nitride has better toughness and hot strength than aluminum oxide, and is categorized as the 3rd generation of ceramic tool material. Its application is fast growing in the main industrialized countries.

12.3.2 High-Speed Machining (HSM)

High speed machining (HSM) means using cutting speed that are significantly higher than those used in conventional machining. There is not a consistent definition of HSM so far. One definition is based on the DN ratio, the bearing bore diameter (mm) multiplied by the maximum spindle speed (rev/min) (Groover 2007). According to this definition, if the DN ratio is in between 500,000 and 1,000,000, the machining is referred as HSM. HSM is the 2nd landmark after the NC technology in machining.

With the application of NC, machining centers, and FMS, the idle time in machining, such as that for tool changing, loading and unloading works, was significantly reduced. During the 1980s, it was realized that the room to further increase productivity through reducing idle time almost exhausted. In this case the effort was directed to reduce the direct machining time through increasing the cutting speed and feed.

The early effort toward HSM is traced to Carl Salomon, a German scholar. He filed the first patent of HSM in 1931 (King and Vaughn 1984; Flom et al. 1984). He concluded through measuring tool temperature that there existed a critical cutting speed for each material at which the temperature reached maximum and beyond which the temperature dropped rapidly. However, his conclusion was not verified by later classical analysis of M. Merchant (Groover 2002). Partially due to this reason, Solomon's work was not publicized until many years later (Schulz et al. 2010).

One pre-requisite for HSM is good tool materials. During the period from 1920s to 1950s, the application of carbides as tool materials doubled the cutting speed in every decade.

Starting from the 1950s, studies on HSM were started with using ceramics as tool materials. The 1970s saw intensive research activities extending to many aspects of detailed applications. To the early 1990s, HSM technology approached mature. HSM has remained a highlight in all trade shows on machine tools since the EMO 1995 at Milan. Commercialization started from the late 1990s when many machine tools of HSM became available in the market. Applications typically are in the space, mold, optical, auto, and home appliance manufacturing industries. The U.S., Japan and Germany are the world leaders in research and development of HSM technology. After the 21th century, HSM became the mainstream machining technology in almost all industrialized countries.

Compared with traditional machining, HSM has the following advantages.

(1) Higher productivity: Material removal rate is generally 3–6 times of that of traditional machining.
(2) Possibly lower vibration: The high excitation frequency may be well beyond the primary natural frequencies of the system, thus, the vibration of the system may be lower.

(3) Lower cutting force: This is especially good for machining of thin-walled parts.
(4) Lower temperatures of cutting tools and work pieces: Shorter cutting time makes more cutting heat removed by chips.

The surface meter per minute (Flom et al. 1984) for machining steel and aluminum has reached 1000–1500 m/min and 7500 m/min respectively.

12.3.3 Precision and Ultra-Precision Machining

Beginning in the 1960s, precision and ultraprecision machining (UPM) technologies were developed in response to the requirement of higher manufacturing accuracy. These technologies are critical to the manufacturing of components and systems in space shuttles, satellite and many other high-tech systems.

Precision machining means the machining technologies with a precision level between 1 and 0.1 μm. Ultraprecision machining has even higher level of precision characterized by the following: less than 0.1 μm in linear error of the workpiece, less than 0.025 μm in surface finish of Ra, and 0.01 μm in programming input resolution (Solon 2012). UPM belongs to micrometer scale manufacturing. Driven by the development of MEMS technology, Nanometer scale manufacturing technologies are also under development (Yuan 2008).

Traditional precision machining depends mainly on grinding. UPM, however, includes a number of non-traditional machining technologies relying on different energy sources, such as electrical, magnetic, optical, chemical and nuclear etc.

The U.S., Britain and Japan are the leaders of the world in UPM technologies. The U.S. started development of the UPM technology in the 1950s mainly for the space industry. Diamond cutting tools and UPM machines with only air and oil bearings were both firstly invented in the U.S. Japan, although starting later than the U.S., is catching up quickly. Different from the U.S., Japan put more effort to applying UPM in civil products. One representative example is in manufacturing of the micro scale components in optical and graphical devices (Ikawa 1991). Japan has been a leader in grinding and polishing of ultraprecision mirrors and lenses, especially in ultraprecision grinding and polishing of free-form and aspheric surfaces in large optical mirrors. Ultraprecision grinding is also used in the manufacturing of the silicon wafer in large scale integrated circuit. The wafer requires very high in surface finish and flatness. Surface scratch is not tolerated.

Other precision and ultraprecision grinding and polishing methods include magnetic fluid polishing, bonnet polishing and stressed lap polishing etc.

12.3.4 Machining of Difficult-to-Cut Materials

From the view point of machining, difficult-to-cut materials can be divided into two categories (Fu 2010).

(1) High strength, high toughness materials

These include high strength steel, titanium alloys, and super-alloys. Large cutting force, high temperature and excessive tool wear are the common challenges encountered in machining these materials.

Titanium was discovered in 1791, but titanium alloys were not commercialized until the 1950s. Titanium alloys have very high corrosion resistance and high strength-to-weight ratio, making them very attractive in making airplane parts, jet engines, racing cars and submarine hulls and medical devices. Boeing and General Motor started the research on machining of titanium alloys very early. Super-alloys are also called high-temperature alloys which found wide applications in making the combustor and turbine sections of the aero-engines. Britain and the U.S. are the leaders in super-alloys.

(2) Hard, brittle materials

This group includes engineering ceramics, optical glass, and silicon. Surface scratch caused by the built-up edge and cracks are the main problems in machining these materials.

Engineering ceramics have a series of excellent characteristics, such as high compressive strength and hardness, resistance to wear and corrosion, low density and thermal expansion etc. They have found numerous applications in many industries, one of which is in internal combustion engines installed on civil and military vehicles. Ceramic components make higher operating temperature possible which means higher efficiency of the combustion of fuel. From the 1970s, many countries, including the U.S., Japan, Germany, Italy, and China, attempted to make ceramic components of internal combustion engines. The common parts which can be made with ceramics include cylinders, cams, combustors, rotors etc. some examples are shown in Fig. 12.6.

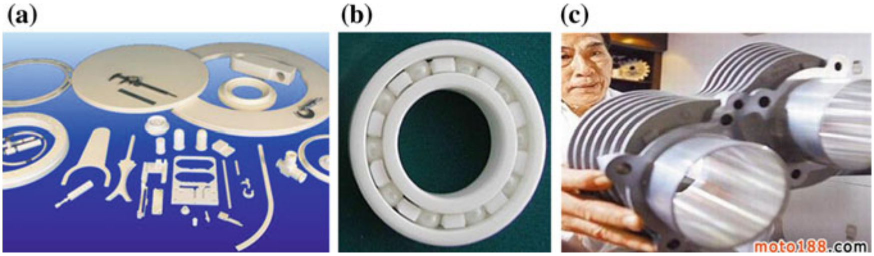


Fig. 12.6 Structural ceramic parts. **a** Various parts, **b** ceramic bearing, **c** ceramic cylinder body

Although these materials have superior properties, machining is still a big challenge. Thus, many companies keep the technologies of machining difficult-to-cut materials as business secret. Some countries even treat it as national critical technologies.

Machining of difficult-to-cut materials has some overlap with high speed machining and ultraprecision machining. Machining of difficult-to-cut materials, as any modern technology, involves cutting tools, machines and process. On the one hand, requirement of machining difficult-to-cut materials inspired the development of new cutting tools and tool materials. On the other, some non-traditional machining techniques often find applications in machining these type of materials.

12.3.5 Near-Dry and Dry Machining

Cutting fluids are used extensively in machining for purpose of reducing friction and wear, cooling the cutting zone, protecting the machined surface and flushing away the machining chips. However, issues related with cutting fluids, including the cost and contamination of environment, have caught more attention since the 1990s.

It was estimated that cutting fluids made up only 3% of the overall cost of machining 20 years ago. However, this number climbed up to 13–17% in recent years, well exceeding the cutting tool cost of 2–5%.

To alleviate the environmental impact and control the cost, near-dry and dry machining technologies have been a trend in the world since the mid-1990s (Ren et al. 2013). In the near-dry machining, a fine mist of air-fluid mixture containing very small amount of cutting fluids is applied. While in the dry machining, cutting fluids are completely removed.

Dry machining has a high requirement on the hot-hardness and toughness of the cutting tools. The advance in cutting tools has make dry machining feasible and effective in various machining operations, such as turning and milling, of various materials including steels, steel alloys and cast irons. In the dry machining, the chips have to be removed through pressurized air which is applied through the tool shank.

12.3.6 Vibration Control of Machining

The machine, cutting-tool and the work piece constitute an elastic system. The machining process itself, transmission of the machine tool and the surroundings create excitations. Thus the elastic system will vibrate under these excitations. The vibration in machining process has several detrimental effects, including reduction of machining accuracy and surface finish, life reduction of machine tool and cutting tools, and generation of noise etc.

Machining vibration was noticed very early; however, systematic study did not start until WWII (see Sect. 7.7.3). With the increase of machining speed, vibration became more severe. This is especially true in precision machining, high-speed machining and machining of difficult-to-cut materials.

12.3.6.1 Chatter and Machine Tool Dynamics

Vibration of machining systems is very complicated, involving three types of vibrations, namely free vibration, forced vibration and self-excited vibration.

Chatter, the form of self-excited vibration in machining systems, is induced and maintained by the forces generated by the cutting process itself. It is the main problem limiting the productivity of machining.

Carbides used as tool material greatly increased the cutting speed of machining. By the 1930s, the cutting speed had reached hundreds of meters per minute. Early researchers on machining chatter were almost all from three countries, the U.S., UK and Germany. The reason behind is that military production in these countries required higher cutting speed.

Research on chatter in theory did not start until the mid-1940s. The earliest report on chatter was made in 1945 (Stone 2014). Since then, many models and methods have been established, laying the foundation of machine tool dynamics. The book by Stephen Tobias (Tobias 1965), a German scholar, was the landmark of machine tool dynamics, in which the sources of vibration, modeling and analysis of vibration, mitigation of vibration as well as dynamic design of machine tools are systematically treated.

Starting in the 1960s, ultrahigh speed machining technologies were tested and developed in the U.S., Germany and Japan (星·鐵太郎 1977). In this effort the control of chatter in machining process was the key. Development of machine tools, cutting tools and relevant process for the ultrahigh speed machining then went into a booming period. Application of ultrahigh speed machining greatly improved productivity.

Machine tools are very complicated in structure and chatter is a complicated vibrational phenomenon caused by multi-factors. Early studies of machine tool chatter based on linear theory were not able to explain nonlinear phenomena. As a result, the early models were not widely accepted, being depicted as “models are to be used, but not to be believed” (Stone 2014). Chatter is self-excited vibration in nature, which can be better treated with nonlinear theory.

12.3.6.2 Up-to-Date Development in Research of Chatter

By the end of the 20th century, the machining technology had reached such a point that controlling chatter vibration of machine tools became critical. Specifically the important driving forces to the study of chatter came from the following aspects.

(1) Ultraprecision machining requires higher level vibration control due to the higher requirement on machining accuracy and surface finish.
(2) Ceramics are widely adopted as materials of tools, which are much more brittle with less resistance to impact.
(3) Ultra high-speed machining and heavy-duty machining increase the possibility of chatter to happen in machining.
(4) Lighter and thin-walled workpieces also increase the possibility of chatter.
(5) Machining centers and FMS put forward a requirement of real-time monitoring of operation because the multi-operations are enclosed in a limited area.

In recent years, two trends became obvious in the study of chatter. (1) Linear theory was replaced with nonlinear theory, (2) real-time monitoring was under fast development.

Linear models of chatter were first developed by S. Tobias during the late 1960s. After the 1990s, chaos and bifurcation, typical nonlinear vibration phenomena, were observed in several machining methods (Gradisek et al. 1997).

Shi Hanmin, a Chinese scholar, made outstanding contribution in the study of chatter with nonlinear theory. He explained theoretically some important nonlinear phenomena which were not well understood before, and discovered the stable machining zone under high speed. This finding fundamentally changed the traditional opinion that mitigation of chatter must be at the cost of sacrificing productivity. More importantly, all his theoretical findings were validated with experiments (Shi 2003).

Chatter is essentially a problem of stability. With dynamic models the border between stable and unstable cut, termed stability lob diagram (SLD), can be determined. Then chatter can be, at least in theory, avoided through properly choosing cutting parameters. However, there are some technical difficulties in practice. These include (Quintana and Ciurana 2011):

(1) The dynamic models are not accurate enough to construct the lobs accurately due to the extreme complexity and diversity of machining operation.
(2) The mechanisms of chatter for different types of machine tools and machining operations are different.
(3) In some cases, the SLD and the system cutting tool, machine tools and the workpiece are changing continuously; thus, it is difficult to predict in advance.

Due to the above reasons, online chatter detection technologies have been developed after the late 1970s through monitoring signals like vibration, sound, and power etc. These technologies fit particularly well into modern manufacturing systems, such as FMS and CIMS.

Since the 1990s, some new algorithms and technologies, such as neutral network, expert systems, wavelet analysis, and smart materials and structures etc., have been adopted in chatter detection (Jia et al. 2006).

12.3.7 Advance in Machine Tools

With the advent of NC technology, CNC Machine tools, machining centers and FMS became the mainstream of machine tools. At the same time, some other progresses were also made in response to the development in high speed machining, heavy-duty machining and precision machining.

Ball screw was first developed in the 1930s, and applied to machine tools in 1955. Without ball screws, precision linear motion, a critical component in NC machine tools for precision machining, would be impossible.

In high-speed machining, the spindle RPM and feed speed are as high as 10 times of that in conventional machining. Besides, acceleration and deceleration normally happen in very short times. All of these put forward very high requirements on both dynamic and static performance of the machine tools. Some new technologies, such as electric spindles and high speed linear motor, were developed in addressing these issues.

As a relatively new technology, electric spindles integrate the main spindle and the motor into one set as shown in Fig. 12.7, eliminating the transmissions from the motor to the spindle. Thus, acceleration can be achieved quickly and very high spindle speed can be reached. In addition, the elimination of the transmission also get rid of the several factors embedded in the transmission, such as the elastic deformation, clearance, and friction losses related to the transmission. In summary the benefits of electric spindles can be stated as high spindle speed, high power, high rigidity, high accuracy and high reliability.

Only are a few countries in the world, including Switzerland and Germany, able to make electric spindles. Although already being installed on aircraft carriers for aircraft launching in 1945, Linear motors were not applied in machine tools until the end of the 20th century. Compared with ball screws, linear motors are of smaller inertial, simpler in structure, and more accurate. Thus, they are more suitable for machine tool drives. Japan, the U.S. and China are some of the countries in the leading position of this technology (Ye 2000).

Lathes and milling machines were first developed for Ultra-precision machining. In 1983, the Large Optics Diamond Turning Machine (LODTM) was constructed in U.S. for manufacturing large optics with complex surface. The LODTM used a

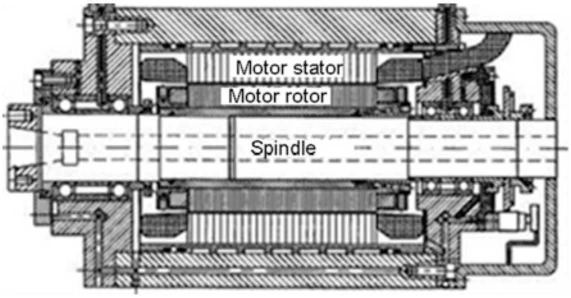


Fig. 12.7 Electric spindle

Fig. 12.8 Impeller of an aero engine (http://compressedairducation.com/tag/centrifugal/)

series of then advanced technologies, reaching a unimaginable accuracy level of 0.05 μm in spindle rotation (Yuan 2008; Yuan and Wang 2016).

12.4 Machining of Free-Form Surfaces

12.4.1 Free-Form Surface

Irregular surfaces are widely used in many industries, such as space, energy, military and automotive. Impellers in airplane engines (Fig. 12.8), screw propellers in large ships (Fig. 12.9), and stamping molds of auto-body panels are among the most representatives.

In CAD or computer graphics, these irregular surfaces are termed free-form surfaces, indicating that the surfaces can not be represented by the basic features, such as cylinders, cones, spheres and planes etc.

An important application of free-form surfaces is the "optical free-form surfaces". Spherical surfaces are most commonly used in traditional optical systems; however, more complex surfaces, such as those without rotational symmetry or

Fig. 12.9 Screw propeller (https://www.ebay.com.au)

more generally free-form surfaces, began to be used in some special optical systems, such as colorful displays and some cameras (Li 1998).

The lenses in some large telescopes are as large as meters in diameter. Some others under construction are even larger.

Machining and fabrication of free-form surfaces are very challenging.

Before the 1970s, free-form optical surfaces were made in two main steps. First the rough geometry of the surface was copied by various molding processes, such as injection molding. Then the refined surface was obtained through manual grinding and polishing. This method was very low in productivity, and had been used in manufacturing telescopes since Newton's time. The mold shaping processes in this method have pretty good repetitive accuracy, moderate production cost, being suitable for production of large quantity of optical surfaces of medium and low accuracy (Cheng and Tan 2013). However, the difficulty of making free-form surfaces was not really solved. It simply transferred the difficulty from making the optical component to making the mold.

The NC technology was invented in 1952 for manufacturing blades of helicopters. Research on automated machining of complex surfaces started in the 1960s. Now the manufacturing of free-form optical surfaces is gradually converged to multiple-axis CNC machining (Li 1998; Neo 2017).

Free-form surface allows more freedom for the optics designers to focus on the product's functional, aesthetic and ergonomic requirements. However, the manufacturing is more difficult. The common operations in manufacturing include CNC milling, grinding, polishing, measurement, and corrective polishing. The accuracy requirement on free-form optical surfaces is very high, sometimes in the order of sub-micron in dimension and sub-nanometer in surface finish. The materials, such as glass, of the optical components generally fall in category of difficult-to-cut materials.

Free-form surfaces are hard to be mathematically represented. In practice, CAD and CAM in particular, they are modeled by control points, degree, and the number of segments with spline curves which is commonly described by the Non-uniform rational B-splines (NURBS). NURBS is elegant and has the required flexibility in defining the surface. It has been adopted in the mainstream CAD/CAM packages, including UG and Pro-E.

The current trend is to integrate the design, manufacturing and measurement of complex parts with free-form surfaces into one system (DEMS 2010).

12.4.2 Machining of Spiral Bevel Gears

Among the many types of gears, spiral bevel gears have the most complicated geometry and are the hardest to manufacture. In this section we introduce the evolution of two typical manufacturing methods with an intention to illustrate the interaction of different technologies.

Spiral bevel gears are widely used in automotive differentials. The fast growth of automotive and space industries created a very high demand on spiral bevel gears and hypoid gears of high accuracy. This demand in turn inspired the development of corresponding gear manufacturing technologies (Hotchkiss 1969; Maiuri 2007).

William Gleason, an Irish immigrant to the U.S., founded a machine shop in New York in 1865 to build gear-cutting machine tools. This was the origin of the later Gleason Corporation, a prominent machine tool maker in the world. At the beginning, only machines for cutting spur gears were made in this company. In 1913, Gleason invented a method for cutting spiral bevel gears with face milling as shown in Fig. 12.10. This is the well know Gleason method, a single indexing method. The tooth trace of the bevel gear in the Gleason method is a circular arc and the tooth depth at the larger diameter is larger than that at the smaller diameter (tapered teeth). The Gleason method can also be used in grinding and lapping. In 1927, the company successfully developed the process of manufacturing hypoid gears.

In 1946, Oerlikon, a Swiss company, developed a continuous indexing method of cutting spiral bevel gears, called Oerlikon method as shown in Fig. 12.11. The tooth trace of the gear in this method is elongated epicycloid and the tooth depth along the face width is constant.

Spiral bevel gears made from different methods cannot be engaged. This is different from spur gears.

The Oerlikon method was actually coincident with a patent of Gleason in 1914.

The continuous indexing Oerlikon method is obviously more productive than the single indexing Gleason method. One may wonder why Gleason did not develop its own continuous indexing method based on the patent. The following two reasons

Fig. 12.10 Gleason process

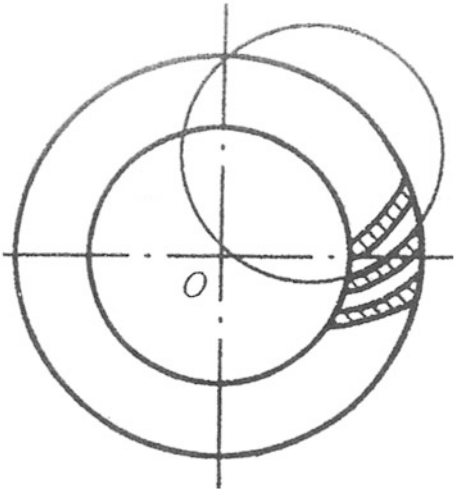
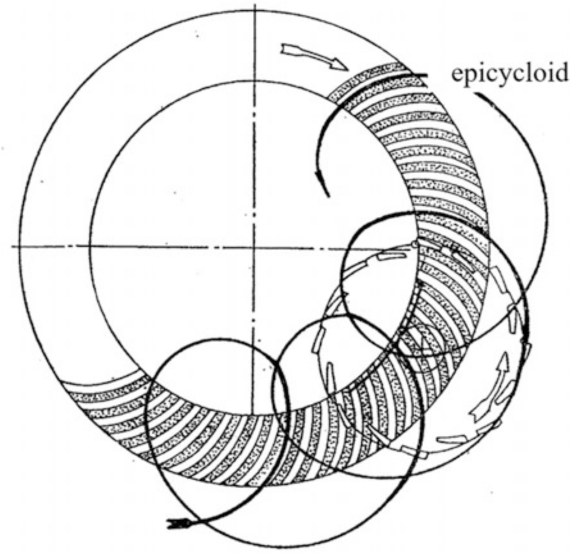


Fig. 12.11 Oerlikon process



may be responsible for this fact. First, gears made through the Oerlikon method could not be ground; ground gear set had to be manufactured exclusively in a single indexing process. However, the spiral bevel gears used in the automotive and space industries required grinding because of their hardened surface. Secondly, the constant tooth depth of the Oerlikon gears was not in agreement with the equal-strength rule. These factors made the Gleason's machines dominant in the market for several decades.

After invented in the 1950s, the NC technology quickly found application in milling, turning and grinding machines. To the 1970s, spiral gear cutting machines adopted the NC technology. This was a fundamental step making the Gleason's machine be able to cut Oerlikon gears, and vice versa. To this point the two spiral gear manufacturing methods, which used to be separated with each other with clear borders, were merged together.

In 1993, the Oerlikon Geartec AG was acquired by Klingelnberg, a Germany based company. To the 1990s, a turning point was brought to the Oerlikon method. (1) grinding of gears using the continuous indexing method became possible and economical with the advent of CNC technology. (2) drying cutting process for bevel gears was invented in 1997 and was applied to the C 28 machine.

In the year of 2002, the spiral bevel gear cutting machines from Klingelnberg-Oerlikon became the market leader for the first time in history.

12.5 Non-traditional Machining

Conventional machining processes use a sharp cutting tool to remove materials from the workpiece. While non-traditional machining methods achieves the material removal by means of mechanical, thermal, electrical or chemical energy sources.

Non-traditional machining processes have been developed since WWII when the demand for hard material components of complicated geometry came up. The machining of these parts could not be achieved through traditional machining technologies. Thus, alternative processes had to be sought. The challenges raised can be summarized as below (Bai et al. 2014).

(1) Some very hard materials, such as cemented carbides, titanium alloy, diamonds, and hardened steels, are impossible to be machined through traditional cutting and grinding.
(2) Very brittle materials, such as heat-treated alloys, glass, ceramics, and powder-metallurgy parts, are difficult to be machined without damage to the part.
(3) Some parts have complex shapes, including such features as internal and external profiles or holes with high length-to-diameter ratios.
(4) Some workpieces are too flexible or slender to withstand the forces in machining or grinding, or the parts are difficult to clamp in fixtures and work-holding devices.
(5) Special surface finish and dimensional tolerance requirements cannot be met by other manufacturing processes or are uneconomical.

There are many types of machining methods in this group, including electric discharge machining (EDM), electrochemical machining, ultrasonic machining, electron beam machining (EBM) and photochemical machining etc. In most of these machining methods no mechanical contact with the workpiece happens; thus, the above challenges do not constitute an issue.

12.5.1 Thermal Energy Processes

Machining processes based on thermal energy include electric discharge machining (EDM), laser beam machining (LBM) and electron beam machining (EBM) etc.

12.5.1.1 Electric Discharge Machining (EDM)

EDM is based on the erosion of metals by spark discharges. In this process, the tool and workpiece are connected to a DC power supply and placed in a dielectric fluid. The two main processes in this category include EDM, and wire EDM.

In 1770, an English physicist, Joseph Priestley, found the erosive effect of electric discharges on metals for the first time in history. Further research was conducted almost simultaneously in the Soviet Union and the U.S. at the beginning of WWII.

B. Lazalenko and N. Lazalenko (Лазаленко), two Soviet scientists, were assigned to exploit the destructive effect of electric discharges on tungsten, but accidently discovered that the erosive effect of electric discharges could be precisely controlled. In 1943, a spark machining process, thus called at that time, was developed.

In the U.S., a research team led by Harold Stark developed a sparking machine around the same time for the removal of broken taps and drills from cast aluminum bodies of hydraulic valves. The initial machine created sparks at a frequency of 60 times per second. Later vacuum tubes were used in the circuit, increasing the frequency up to thousands of sparks per second (Jameson 2001).

The time for the evolution of wire EDM is not as clear as the EDM, roughly covering the period from the early 1960s to the early 1970s.

In 1967, a wire EDM machine was manufactured in the Soviet Union. During the 1960s, a research group in the U.S. led by David Dulebohn developed an optical line following system. In 1974, a wire EDM machines controlled by the optical line following system was constructed. Later in 1976, a CNC wire EDM machine was developed using the same computer program (Jameson 2001).

12.5.1.2 Laser Beam Machining (LBM)

In LBM, the source of energy is a laser. It focuses optical energy on the surface of the workpiece. Although the theory of laser was known very early, the first actual working laser was created by Theodore Maiman, an American physicist, in May of 1960 (Maiman 1960). In 1961, the first commercial laser was put in the market. In the Soviet Union, N. Basov (Николай Басов) proposed the idea of semiconductor laser in 1959 and built a device in 1963.

Shortly after Maiman's demonstration of a working laser, Western Electric of the U.S. developed a laser machine for drilling holes in diamond dies in 1965. In 1967, a German scientist, Peter Houldcroft, designed a laser cutting nozzle to cut 1 mm thick steel sheet with a focused CO_2 laser beam. By the 1970s, laser cutting machines with a power of several KW were developed and used in high speed cutting of various materials. Some example parts made from laser processing are shown in (Fig. 12.12)

12.5.1.3 Electron Beam Machining (EBM)

The energy source in EBM is high-velocity electrons, which strike the workpiece surface and generate heat. The theory of electron beam technology appeared in the late 19th century. The idea of using EB to build a furnace for melting, sintering and

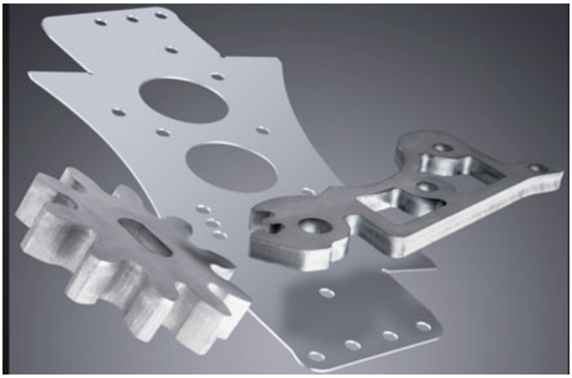


Fig. 12.12 Parts with laser processing (http://images.fabricatingandmetalworking.com)

joining was first mentioned in a paper published in 1904, and was patented in 1906 (Steigerwald 2007). Machining with EB, however, was not advanced until 1949 when Dr. Karl-Heinz Steigerwald, a German scientist, used EB to make very fine holes. The power of the EB in the first machine was only somewhere in between 100 and 200 W. Then around 1952, He built another two machines to make holes as small as 80 μm in diameter on watch bearing. In 1958, an EB machine was developed for welding based on the previous drilling model.

EB has high power density, and is able to be controlled precisely. Thus, EBM is well suited for welding, accurate machining and surface treatment.

12.5.2 Mechanical Energy Processes

Ultrasonic machining and water jet machining both use mechanical energy other than a sharp cutting tool to achieve machining.

12.5.2.1 Ultrasonic Machining (USM)

Ultrasonic machining (USM) is suitable for machining various metals, such as stainless steel and titanium, and brittle non-metal materials, such as glass, ceramics, and carbides etc.

Two American scientists first noted the application of high frequency sound wave for machining in 1927. The first patent of USM was issued in 1945 to Lewis Balamuth who found that ultrasonic wave could effectively machine various brittle materials (Balamuth 1964). In 1951, he built the first physical USM machine. Since then until the 1970s, almost all patents of USM granted in the U.S. were owned by Balamuth and his group.

Fig. 12.13 Thick steel plate cut with water jet (www.allsetengineering.com)

12.5.2.2 Water Jet Machining

Use of water jet is traced back to coal mining in the mid 19th century. Paper Patents, a company in the U.S., developed a low-pressure water jet system to cut paper in 1933.

In 1956, Carl Johnson, an engineer in Luxembourg, developed a method for cutting soft plastic shapes using a thin stream, high-pressure waterjet. In 1958, Billie Schwacha, an aviation engineer, developed a system that used ultrahigh pressure (690 MPa) liquid jet to cut steels. This was a landmark indicating that water jet technology reached a critical point of cutting hard materials. During the 1960s, several companies joined the stream to further refine water jet systems (Fig. 12.13).

In 1982 an Egyptian-born American engineer, named Mohamed Hashish, published his results based on several year research. He concluded that steel and concrete could be cut with water jet by adding abrasives to the water. This was a real breakthrough in this technology (Hashish 1984). He continued his work to develop a commercially viable abrasive water jet nozzle in 1983 for cutting hard materials. Soon this technology was used in cutting very thick glass (12 in.) for space optics mirror cores. Since then water jet has been widely used in cutting hard and brittle materials, including stainless steels, titanium, stone, ceramics, glass etc.

In 1993, OMAX Corporation was established in the U.S. specializing in abrasive water jet machining. The VP of the company, John Olsen, developed the PC controller specifically designed for abrasive jet machining.

12.5.3 Electrochemical Machining

Electrochemical machining (ECM) uses electrical energy in combination with chemical reactions to accomplish material removal. ECM is less sensitive to the hardness and toughness of the material than the conventional machining; thus, it has gained wide applications in industry. Typical processes of ECM include deburring, grinding, polishing and drilling etc.

The theoretical basis for ECM was laid during the late 19th century. The first effort was made by a Soviet Union researcher, W. Gusseff (Владимир Гуссев) (Valenti 2001). However, the concept did not progress much in the following two decades. Interest was resumed during the 1950s when the space development required the shaping of high strength alloys. In 1959, the Anocut Engineering Company in the U.S. produced the first machine of ECM using direct current. From then on, ECM was widely used in various industrial applications.

12.6 Additive Manufacturing

During the 1980s and 1990s, rapid prototyping (RP) and 3D printing were developed. These new manufacturing technologies became critical for the industry to speed up product development.

RP and 3D printing are essentially the same in principle, and are formally called additive manufacturing (AM). Both create a 3D physical model based on virtual CAD models directly without the need for process planning. The data of the 3D CAD models are broken down into a series of 2D cross-sections of a finite thickness. These cross-sections are fed into AM machines so that they can be combined, adding them together in a layer-by-layer sequence to form the physical part. The term AM is formed in contrast to the conventional subtractive manufacturing technologies, such as the various machining technologies (Gibson et al. 2015).

12.6.1 Rapid Prototyping (RP)

The practice of making objects layer by layer is dated back thousands of years in China for making lacquerware and in Egypt for making layered lumbers. In 1892, an Austrian named Joseph Blanther developed a layered method for making a mold for topographical relief maps, and was granted the patent in the U.S. this is widely regarded as the origin of the modern concept of RP. In 1974, Matsubara at Mitsubishi of Japan proposed a topographical process with a photo-hardening photopolymer resin to form thin layers stacked to make a casting mold (Bourell and Beaman 2012).

Some researchers in the U.S. and Japan independently put forward their concepts of RP during the period between the late 1970s and early 1980s. Among these includes Charles Hull, an American researcher, who was granted a patent in the U.

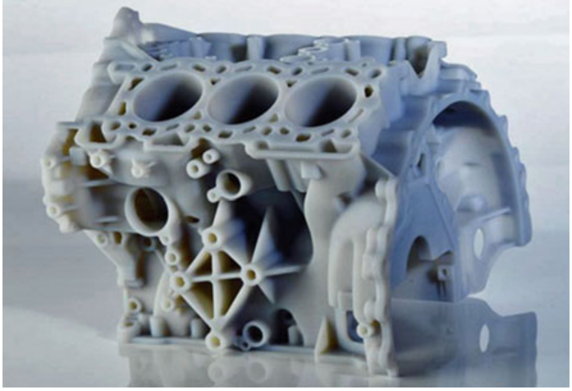


Fig. 12.14 A model of engine block with 3D Print (https://mediacopy.co.uk/3d_printing_.htm)

Fig. 12.15 New teeth with 3D print (https://blog.dentalplans.com/)

S. and started commercialization of RP through founding a company in the U.S. in 1986. Hull coined a term, “stereolithography” (Jacobs 1992), in his patent application; but, this new word was not widely accepted and was soon replaced by RP and 3D printing.

Following this came a booming of RP development. Many concepts were put forward; technologies and systems were developed. The U.S. is a main player in RP development, which made 81.5% of all the RP machines all over the world in 1999.

RP showed great potential in industrial applications. Its advantages can be summarized as below: (1) it can speed up production: design flaws and appearance imperfection could be quickly found and fixed with a physical model; (2) the physical models generated by RP are tangible and real, better than the virtue models in the computer; (3) RP can make models with any shape and geometry.

RP, however, is for making prototype model, not for real production. This is clear in its name.

12.6.2 3D Printing

12.6.2.1 Concept

As we stated in previous section, the working principle behind RP and 3D printing is the same. However, there is a fundamental difference between the two. 3D printing is for real production, not only for making prototype. Now 3D printing has found many applications, such as making dental hardware, artistic objects as well as airplane parts (Figs. 12.14 and 12.15). It should be noted that the list of application is getting longer almost every day.

If we treat “3D printing” as a printing technology, it would be traced back many years. As a manufacturing technology; however, C. Hull was the pioneer.

3D printing has high accuracy and is able to print products of any shape. Items with very complicated geometries, which are difficult to manufacture with traditional technologies, can be easily made with 3D printing. Mechanical assemblies consisting of individual components, such as gears and bearings etc., can be directly printed out without the need of assembling operation. If needed, machining, such as grinding and drilling etc., can be applied to the printed product.

12.6.2.2 Application in Aerospace Engineering

The U.S. Air Force showed great interest in 3D printing. Titanium is widely used in making airplane parts. Its density is only about half of steel. Its strength, however, exceeds almost all steel alloys. If titanium can be melt with laser, then complicated airplane part would be possible to be made through layer by layer addition of the material. Undoubtedly this would have great potential to accelerate the airplane production. In 1985, the Pentagon started to sponsor research projects in manufacturing titanium alloy airplane components with laser melting. The research was conducted secretly, and publicized in 1992.

EADS, the parent company of Airbus, also supported research in additive manufacturing of airplane components. The whole wing of an unmanned airplanes was attempted to be made by 3D printing.

Additive manufacturing shows outstanding advantages in the manufacturing of airplane components. Some are as below: (1) no need for the large presses and the expensive dies required in conventional forging operation; (2) additive manufacturing creates “near net shape” parts; thus, little additional manufacturing operations are needed to obtain the final parts; (3) parts created through additive manufacturing have better mechanical properties than that made from traditional forging operation; (4) lower overall production cost and shorter production cycle.

If implemented successfully in manufacturing of complicated components of high strength, titanium alloy, the additive manufacturing would cause a revolution to the traditional airplane manufacturing industry.

The main industrialized countries in the world all made great effort in advocating additive manufacturing. The U.S., for example, created a national network, Manufacturing USA, in coordinating the investment in emerging advanced manufacturing technologies, among which additive manufacturing is in the center.

12.6.2.3 Future Development of 3D Printing

3D printing is able to make not only prototype models but also real products, showing great advantage in manufacturing of complicated shapes. As a revolutionary technology, it will bring fundamental changes to the manufacturing, business and even society. Some of changes are listed below.

(1) 3D printing's influence goes well beyond traditional factory production. It may find its way to the manufacturing of small items for offices and homes.
(2) 3D greatly shortens the time for production.
(3) 3D also has unique advantages over conventional manufacturing technologies in reduction of cost, reduction of material consumption as well as making parts with complicated geometry which are hard to be produced through traditional methods.

Items that have been made so far through 3D printing include customized cell phones, fiddles, jewellery and ornaments, batteries and automotive parts etc. In fact the list keeps expanding everyday. It is expected that whole machines can be printed in some cases.

In addition, the 3D technology creates new windows for business opportunities. For example, real customized products with very small quantity will become feasible with 3D printing. The potential to integrate it with other new technologies, such as internet, has been a hot topic in not only the academic community, but also in daily conversation (Wright 2001; Rifkin 2011; Schwab 2016).

Although the potential is huge, it is still too earlier to say that it will completely replace traditional manufacturing technologies. Many challenges are still ahead.

12.7 Green Manufacturing

12.7.1 Green Manufacturing: From Awareness to Action

It is hard to mark the exact starting point of green manufacturing. It is generally thought that the concept was first proposed in the 1980s. The publication of the blue book of Society of Manufacturing Engineers (SME), "Green manufacturing", in 1996 defined the concept, scope and contents in a systematic way for the first time.

Kenneth Boulding proposed the concept of circular economy in 1996. It took almost 30 years to move from the circular economy to the green manufacturing of

SME. Why did it go so slow at a time when science and technology were under a fast development after WWII.

As stated in Sect. 9.2.2, the first two Industrial Revolutions brought tremendous changes to the human society. Along with the changes was the inflated desires of our society. To pedal the brake to such a huge "desire inertial", three decades seems not even long enough.

A severe consequence of the two Industrial Revolutions is the environmental pollution and over consumption of natural resources. It is a critical challenge to mitigate these problems and make the manufacturing industry sustainable (Dornfeld 2013).

Green manufacturing is a new philosophy of manufacturing in addressing the two critical challenges, preventing environmental pollution and saving natural resources. Its goal is to minimize negative effects on the environment and consumption of natural resources for the whole life cycle of a product, covering design, manufacturing, packaging, transportation, use and end of life recycling.

Green manufacturing has caught great attention from both the academia and industry. The main industrialized countries and some international organizations in the world have been establishing regulations, standards and laws to enforce the green criteria on product quality and every life cycle stage. The high green criteria form the so-called "green barriers" in international trade.

Many countries, including Japan, Canada, the U.S., Britain, and Germany, have established national green industry policies attempting to guide the national development of green manufacturing. Ecolabelling systems have been practised in more than 20 countries, including Germany, France, Switzerland, Australia, Singapore, and Malaysia etc. This practice greatly helps promote the product and service of these countries. On the other hand, customers, in the industrialized countries in particular, are becoming more aware of the environmental issues relating to unsustainable production; and tend to buy green products. This in turn pushes the further development of green manufacturing. It is estimated that "green products" make up 5–10% of the total in current market, and green products may become the mainstream in next decade.

Green manufacturing is the focus for many research groups in universities.

12.7.2 Scope of Green Manufacturing

Green manufacturing involves the whole life cycle of a product. Design of course is included. Any green products have to be designed "green".

The scope of green manufacturing can be summarized as below (CSME 2011).

(1) Green design

Energy saving and less pollution have to be considered in the design stage for any product. In addition, easy maintenance and recycling need to be planned in design stage as well.

(2) Green materials

Use “green materials” if possible, including harmless materials, recyclable materials, remanufacturable materials etc.

(3) Green process

Use production technologies of high energy efficiency and low pollution. For example, net-shaping processes does not need machining; dry machining removes the pollution of cutting fluid.

(4) Green recycling

For mechanical engineering, remanufacturing technology is the most typical, and promising measure of green recycling.

Several other concepts have certain overlapping scope with green manufacturing. These include sustainable manufacturing, environmentally benign manufacturing and lean manufacturing etc. These terms are now widely used interchangeably.

12.7.3 Remanufacturing

Starting from the 1950s, a series of initiatives had been taken in the U.S. to raise public awareness of environmental issues. The National Environment Policy Act (NEPA) was enacted in 1969 and signed into law in 1970 by the President. This is the first major environmental law in the U.S. In the same year the Environmental Protection Agency (EPA) was established. At the same time the Congress passed the Resource Recovery Act with intention to shift the nation’s attention to the practise of recycling, resource recovery and conversion of wastes into energy. Then, the 3 R’s, namely reuse, reduce and recycle, were born.

Similar concepts were developed later for different fields, and in different countries. For instance, in the automotive manufacturing, the “reduce” is replaced by repair and remanufacture; thus, the 3 R’s become 4Rs. In China, 3R’s are used, but the “reduce” is replaced with remanufacture. Figure 12.16 schematically depicts the process of the green manufacturing in which there are three loops, ①, ②, ③. Generally loop ③ is the most expensive, ② is lesser, and ① is the least.

In fact, remanufacturing already existed in the U.S. in the 1930s. During the Great Depression, most people did not have the money to buy a new car. Thus, a business came into existence to fix abandoned vehicles and resell them. In 1942, the U.S. entered WWII, and various resources were prioritized toward the war. Thus,

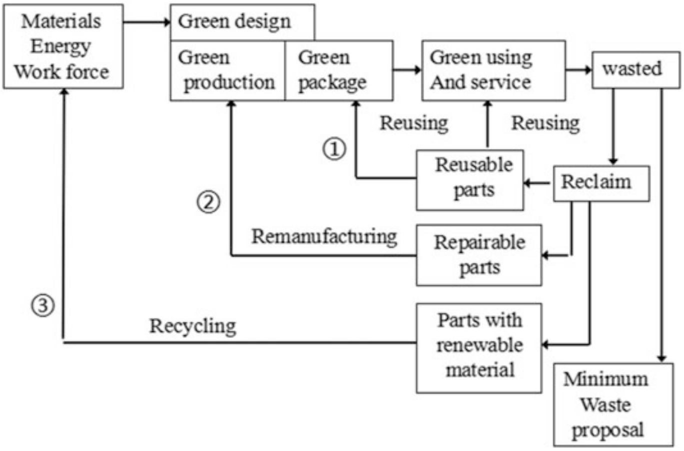


Fig. 12.16 Process of green manufacturing

many cars and trucks had to be operated through remanufacturing. At that time, remanufacturing was only a temporary measure to survive hard times. After entering the 21st century, however, it has become a strategic path to circular economy for many countries.

Remanufacturing has grown fast in the U.S. and Europe. In the U.S., automotive remanufacturing is the largest among many others. Many components, such as engines, transmissions, and brake calipers etc. are put in the market after remanufacturing.

Remanufacturing is also used in the U.S. for military vehicles and weapons, including the Apache attack helicopters, M1A1 tanks, and Minuteman II missiles.

The fundamental mechanism for remanufacturing is that the many individual components in a machine have different life spans, and reach their end of life at different times. For instance, the gearbox housing and frame in a machine tool have very long life time, while the sliding track may have much shorter life due to the many sliding actions.

With adaption of new materials and technologies, it is possible to make the remanufactured products have even better performances than the original ones. For example, nanosurface engineering can remarkably improve the wear-resistance, anti-corrosion and fatigue-resistance of the remanufactured parts.

Xu Binshi, an academician of the Chinese Academy of Engineering, is a pioneer of remanufacturing in China (Xu et al. 2007). The Chinese government has already made a long-term plan of remanufacturing. In the U.S. and Europe, remanufacturing focuses on resuming the original dimension of parts through various technologies or resuming the function of a machine through replacing broken parts. In China, however, a different path is taken. Surface engineering technologies are applied in remanufacturing based on system life evaluation. This not only improves the quality of the remanufactured products, but also significantly increases the remanufactured rate (CSME 2011).

12.8 Some Other Progresses in Manufacturing

Efficiency in direct production processes experienced dramatic increase during the period between 1870 and 1970. However, the progress in management and product design during the same period was not comparable with that in direct production. Thus, management and design became the bottleneck for further advance in productivity. Computer along with the information and communication technologies (ICT) are the real game changer. The first application was in the CAD/CAM. FMS was another application which achieved automation in production equipment. The next step was the automation in all aspects of manufacturing, including direct production and production support systems.

12.8.1 Computer Integrated Manufacturing System

12.8.1.1 Basis: Popularization of Computer

Starting from the 1970s, computers became popularized. Consequently automation has been accomplished in almost every aspect of the manufacturing industry, including:

(1) design automation: this includes computer aided drafting, optimum design, CAD and CAE etc.
(2) automation in manufacturing: this category includes CAPP, CNC, FMS, industrial robots etc.
(3) automation in process control: sensors, signal processing, decision making, control engineering, process monitoring and control, fault diagnosis etc.
(4) automation in management: this includes material requirements planning (MRP), manufacturing resource planning (MRPII), enterprise resource planning (ERP), supply chain and electronic commerce etc.

Application of computers in the above areas undoubtedly played a great role in improving productivity and product quality. However, automation in these separated areas might not necessarily lead to the optimum of the whole production system. Then integration of the automation in the whole production system became a choice.

12.8.1.2 Background of CIMS

Computer Integrated Manufacturing System(CIMS)was first proposed by a American scholar named Joseph Harrington in 1974 (Harrington 1979).

In 1976, a research project, titled as Integrated Computer Aided Manufacturing (ICAM), was started under the sponsorship of the U.S. Air Force. This project was led by Dennis Wisnosky. Harrington helped in designing the ICAM program, and expanded the concept of "CIMS" to include the entire enterprise (Savage 1996).

ICAM identified data as the center of integration and the data had to be shared by different departments within the enterprise. This was then a concept well ahead of time because no manufacturing company realized this necessity and took real action before the 1990s. The project also established the methods to analyze and document the manufacturing activities within an enterprise. Also from ICAM, the standard of modeling and analysis in management and business improvement efforts, namely IDEFs, was created.

Integration requires a network. Wisnosky is among the first to understand the importance of integration, and his work represented a major step toward shifting the focus of manufacturing from a series of sequential operations to parallel processing. ICAM strongly influenced the research activities on computer integrated manufacturing (CIM) and computer aided manufacturing (CAM) in the United States. The ICAM was initially planned to cover all aspects of a manufacturing enterprise. This was then determined to be unmanageable, costly and of high risk (Shumaker 1980). Harrington's concept, hence, was not widely accepted until the 1980s.

Starting from the 1970s, the U.S. economy has experienced a shifting from the secondary industries to the tertiary industries. Manufacturing was thus regarded as "sunset industries". With the decline of the U.S. manufacturing, the traditional industrial areas with heavy manufacturing industries became the "rust belt". This trend was not tuned until the Presidency of Bill Clinton when the U.S. made effort to revitalize its manufacturing with information technology. CIMS then regained attention from both industry and government.

12.8.1.3 Contents of CIMS

In Harrington's concept of CIMS, all the aspects within a business are inter-dependent, and should be considered as a whole. Data collection, communication and processing are the center of the whole process (Harrington 1979).

CIMS, as shown in Fig. 12.17, combines various computer technologies, including advanced manufacturing technology, information technology, automation technology and system engineering technology, to integrate all operations of manufacturing, from logistics to management, with a common data repository. CIMS can achieve the following benefits through integration and optimization: shorter product developing time (T), higher product quality(Q), lower production cost (C), better service (S) and cleaner environment (E).

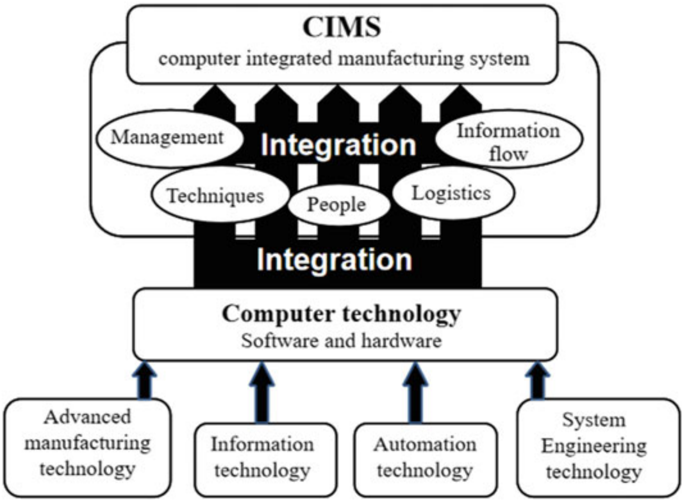


Fig. 12.17 Computer integrated manufacturing system

Since the mid 1980s, CIMS has attracted the attention from many large manufacturing companies, and created significant economic benefit to the relevant companies.

It is a revolutionary step to integrate the individual automations into a whole. CIMS represents the highest level of automation in manufacturing. Now it has been accepted by more and more manufacturing companies, in both developed and developing countries. Application is starting to expand from manufacturing of discrete products to continuous products. However, the majority are still on discrete products.

12.8.1.4 Second Thought on CIMS

One of the initial objectives of CIMS is fully automated, unmanned factories. However, it has gradually become clear that this ideal, fully automated system is not practical, at least presently. With this realization, the current effort is turned to more practical solutions with a certain level of integrated automation in the manufacturing systems (Zhang 2011).

12.8.2 Distributed Manufacturing

Internet was first developed in 1969 in the U.S. In 1991 internet entered a new era through privatization. Then came the internet penetration into manufacturing.

The great potential of internet in manufacturing was realized right after it was invented.

The first attempt was made through a project, named Information Power Grid (IPG), sponsored by NASA and NSF. IPG was initiated with an overall goal to increase the ability of NASA to use distributed computing and data resources to solve problems (Johnston et al. 1999).

A group of business executives in the U.S. compiled a vision-based strategy for the emerging global competitive environment in 1991, and the results were published as "The 21st Century Manufacturing Enterprise Strategy" in 1992 by Lehigh University. Among the main concepts proposed in this report included the agile manufacturing enterprise, factory American net (FAN), and virtual corporations (Yusuf et al. 1999; Sanchez and Nagi 2001).

Virtual corporations mean that multiple firms in different locations can come together to form temporary partnerships through online collaboration. The networked organization helps the individual firms to share skills and resources in the market without interruption of their core business.

Agile manufacturing means that enterprises are enabled to react timely to the fast changing and hard-to-predict market through combining virtual corporations, flexible manufacturing technologies and highly-skilled labor force. At the center is the virtual corporation which is based on network and information technology. In this regard, agile manufacturing bears great similarity with distributed manufacturing.

After the publication of "The 21st Century Manufacturing Enterprise Strategy", many research projects have been conducted in the U.S. under the sponsorship of the Department of Energy, Department of Defence, NSF and some companies and universities. After 1998, research on distributed manufacturing was also started in Japan, China and some European countries (Gu et al. 2001).

In 2013, the German government launched the Industry 4.0 to promote the competitiveness of German manufacturing. The foundation of this strategy is cyber-physical systems and internet of things (IoT).

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Chapter 13
Development of Theories in Mechanical Engineering of New Era

> *As long as a branch of science offers an abundance of problems, so long is it alive; a lack of problems foreshadows extinction or the cessation of independent development.*
> —David Hilbert (German mathematician, 1862–1943)

The advance in design and manufacturing after WWII put forward a demand for support from fundamental theories.

The world entered into and kept peace in general for decades after the War. Education and science resumed development quickly in the peaceful time. Many universities in the world developed into centers of innovation and research. Teaching and research were closely interlinked in these universities, and many graduates, Ph.D. in particular, were trained. These well-trained graduates became the main power in the study of fundamental theories in mechanical engineering.

Mechanical theories in this period progressed in both depth and breadth. First, the traditional fields, including mechanism analysis and synthesis, power transmission, machine dynamics, strength theory and tribology, continued development in depth. At the same time, new branches and subjects, such as robotics, and micro-electro-mechanical system (MEMS), came into birth, broadening the spectrum in mechanical theories.

This chapter focuses on the theoretical development. Some progresses in practice are also mentioned given that theories and applications are often intertwined.

13.1 Mechanism and Machine Science

Although mechanism and Machine Science (MMS) is a fundamental subject of science, it is directly connected with application as well. MMS advanced fast in both depth and breadth during the New Era. The research methodologies and the math on which MMS is based also experienced fundamental changes.

In 1969, IFTOMM, then standing for the International Federation for the Theory of Mechanisms and Machines, was established under the promotion of a Soviet

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Union professor, I. Artobolevski (Иван Артоболевский), and an American scholar, Erskine Crossley. Now IFTOMM has become one of the largest international professional association in mechanical engineering.

13.1.1 American School

As stated in Chap. 7, MMS research in the world before WWII was dominated by scholars belonging to the so-called German school and Russian-Soviet school. After the War, however, the United State rose to the position of world-leader in economy, science and technology. The center of MMS research was also shifted to the U.S., and the so-called American school in MMS were formed.

Graphical methods were the only option in mechanism analysis and synthesis before the 1950s. Ferdinand Freudenstein (Fig. 13.1), an American scholar, published two papers during 1954–1955, opening a door for four-bar linkage synthesis with computers. Due to this pioneering work, many promising graduate students were attracted to join Ferdinand Freudenstein' group. All these graduate students later became well-known scholars of MMS all around the world, forming the so-called American School (Erdman 1993; Roth 2007).

Following Freudenstein's step, many other researchers also started to abandon graphical methods, and pick up analytic methods with computers in the study of mechanism synthesis problems.

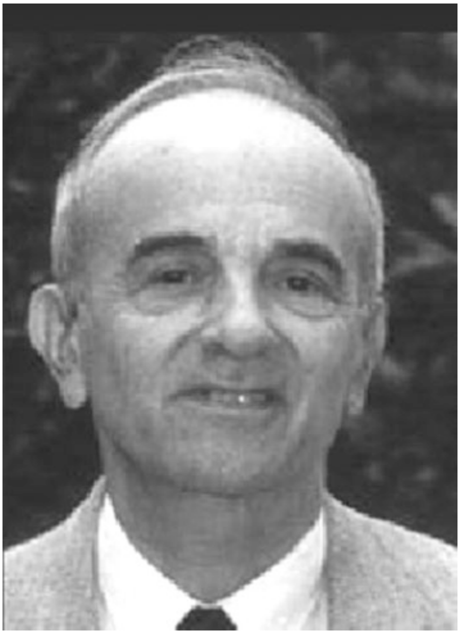


Fig. 13.1 F. Freudenstein

Graph theory was introduced into MMS study by Freudenstein and F. Crossley in 1964 and 1965 respectively.

The features of the American school can be summarized as: (1) Graph theory was the mathematic tool to represent the topology of mechanisms; (2) computers and analytic approaches were used in every aspects of MMS research, including type synthesis, analysis, kinematics, dynamics, and robotic mechanisms. These features fundamentally changed the overall picture of MMS. The American school has been in the center of MMS study for more than half a century.

13.1.2 Progress in Kinematics

13.1.2.1 Analytic Methods

Freudenstein's paper (Freudenstein 1954) was widely regarded as the starting point of MMS study based on analytic approaches and computers. However, research on analytic MMS from scholars in the Russian-Soviet school should not be neglected. N. Levitsky, a Soviet scholar, published his research paper on analytical synthesis of mechanisms even earlier than Freudenstein. Due to this reason, Freudenstein and Levitsky were both credited as the pioneers in modern kinematics of mechanisms (Angeles 1997).

With regard to mechanism synthesis, the 1960s saw intensive research on precision point synthesis. However, this method has two critical drawbacks, namely limitation on the number of precision points, and the inability in handling some constraints. This fact motivated some researchers to explore alternative synthesis methods, such as the approximate point synthesis (Fig. 13.2) developed in the late 1960s.

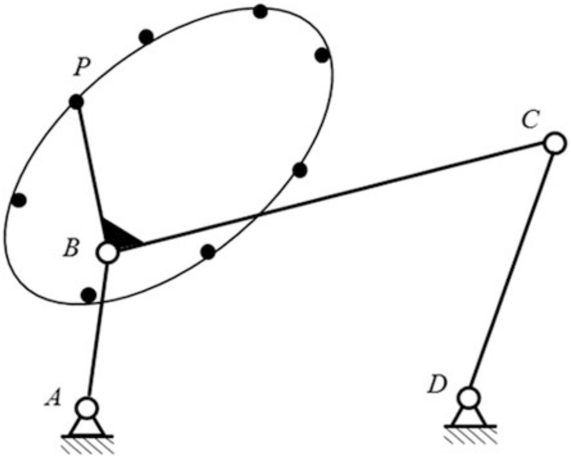


Fig. 13.2 Approximate synthesis of path generation

13.1.2.2 Optimum Design of Mechanisms

Around the mid. 1960s, nonlinear programming was introduced to mechanism synthesis, becoming one of the most commonly used tools in approximate point synthesis. This optimum method was widely accepted in later MMS study, and found successful application in the design of flying shears, harbor cranes and hydraulic excavators (Erdman 1993; Chen and Yu 2014).

13.1.2.3 Type Synthesis and Creative Design

Historically, invention of new mechanisms has heavily relied on intuition and inspiration. However, if a method is developed, which has the ability to enumerate all possible mechanisms for a given task, new mechanism design would be much more productive. Type synthesis is such a method which provides a systematic basis for new mechanism design (Erdman 1993; Huang and Ding 2003).

Since MMS was established, many scholars have worked on the presentation of the type of mechanisms. F. Reuleaux, the German kinematician, proposed a mechanism composition principle based on link-pair units. L. Assur, a scientist of the Russian-Soviet school, invented the concept of Assur group to classify and group the planar linkages. A mechanism composition principle based on loop unit modeling was established by a few American scholars. In the 1980s and 1990s, Yang Tingli, a Chinese scholar, put forward a unique theory based on single open chain (SOC) unit modeling (Mruthyunjaya 2003; Yang et al. 2018).

There may be numerous mechanisms to achieve a given motion; thus, it is almost impossible to find out all possible types relying on only intuition and experience. Type synthesis based on graph theory and computers equipped mechanism researchers and designers with new power. During the period between 1960s–1980s, all the types of linkages with 10–12 links, 1–3 degrees of freedom, were successfully synthesized based on graph theory (Erdman 1993).

Intensive market competition calls for innovative products whose performances are largely determined during the conceptual design. To speed up the design process, intelligence, visualization and other relevant technologies, such as expert system and creative design, are incorporated into conceptual design (Zou and Li 2002). All these demonstrated the importance of type and number synthesis of mechanisms.

13.1.2.4 Computational Kinematics

Mechanism kinematics mathematically end up with a set of nonlinear algebraic or functional equations (Pisla and Husty 2011, 124). For the purpose of evaluating and choosing the most suitable mechanism for a given task, all the solutions are needed. The kinematics branch for solving this problem is termed computational kinematics. Among the several solution methods, (Grobner basis) algebraic elimination method and continuation are the only two methods being capable of obtaining all solutions. The former, however, has overwhelming computation for large scale problems. While the latter, first proposed by B. Roth and F. Freudenstein in 1963, has the advantage of not requiring initial values (Erdman 1993).

13.1.3 New Types of Mechanism

13.1.3.1 Spatial Mechanisms and Robot Manipulators

Although spatial linkages were used very early, theoretical study did not start until after the WWII.

The mathematic theories used in the study of spatial linkages and robot manipulators are far broader than that in planar mechanisms. For example, geometry and algebra. Quaternion, screw theory and differential geometry all found their positions in the study of spatial mechanisms.

In 1955, the well-known D-H convention was invented, in which a 4×4 matrix is used to represent the pose, including position and orientation, of one body in space with respect to the other (Hartenberg and Denavit 1964). It provides a convenient and standard methodology to represent the kinematic equations of a manipulator.

Screw theory came into existence in the 18th century. It was first introduced into analysis of spatial mechanisms by researchers of the Soviet Union in 1950. Other researchers following this route include Kenneth Hunt (1978), an Australia professor, and Joseph Duffy (1980), an American scientist. In the recent decade, Chinese researchers caught up in this field. The two monographs by Huang et al. (2006) and Dai (2014a) detailed the progresses made in China on robotics with the screw theory.

Since 1970s, kinematics of robotic manipulators has attracted tremendous research effort, and became one of the most dynamic topics in MMS. Research effort is focused on spatial linkages of Multi DOF with open-loop and multi-loop kinematic chains.

13.1.3.2 Other New Types of Mechanisms

The integration of mechanical engineering with other disciplines created some new types of mechanisms which can't be categorized as traditional mechanisms. These mechanisms may contain hydraulic, pneumatic, piezoelectric, magnetic and photoelectric elements. Zou et al. (2007) referred these types of mechanisms as "mechanisms in broad sense". It should be noted that the study in these new types of mechanisms is still very limited, and in infancy stage.

During the 1970s, a new mechanism concept, compliant mechanisms, was proposed first in the U.S. (Howell 2001). In a compliant mechanism, the

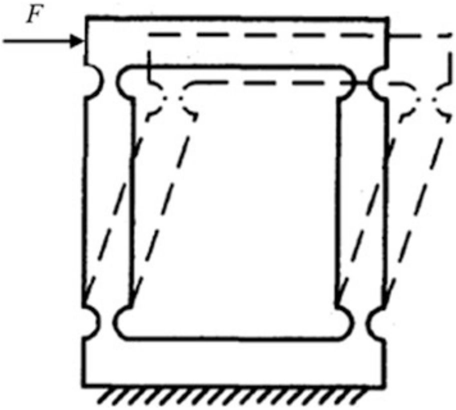


Fig. 13.3 A compliant mechanism

components are flexible. One such mechanism is shown in Fig. 13.3, in which motion can be created and transmitted without kinematic pairs. To accomplish a specific task, a compliant mechanism generally has fewer moving parts and fewer joints (kinematic pairs) than a traditional rigid mechanism. In some cases it may have no joint at all. Thus, compliant mechanisms in general cost less, and are less bothered with wear and backlash problems. Due to the unique advantages, compliant mechanisms have found applications in automobiles and precision measurement.

Another type of mechanisms, called metamorphic mechanisms, were proposed in 1996 (Dai and Rees Jones 1999). This type of mechanisms can change their form and function in adaption to the varying working conditions. The change may be in the form of number of links, topology, and degree of freedom etc. Potential of applications has been shown in space shuttles and various engineering machineries etc.

In the study of robotic manipulators and compliant mechanisms, new mechanisms mimicking living creature were explored, examples are shown in Fig. 13.4.

Early study on MEMS was mainly conducted around various micro-mechanisms (Sect. 13.7).

13.1.4 Mechanism Dynamics

The term "mechanism dynamics" came in use only decades ago. In the definition of a mechanism given by A-M Ampere in 1834 involved only "motion occurred in mechanisms, regardless of the forces producing the motion" (see Sect. 7.1.1). It seemed dynamics did not need to be considered unless the mechanism was connected to a driver. However, This situation was changed when Kineto-elasto dynamics (KED) appeared in the 1970s. Without application of a driving torque, the dynamics of a mechanism still needs attention, especially when the mechanism

Fig. 13.4 Compliant in nature (Howell 2001)

operates at high speed. Research in mechanism dynamics include KED, cam dynamics, balancing of linkages, clearances in mechanisms.

13.1.4.1 Progress of Mechanism Balancing

Study on mechanism balancing before WWII focused on partial balancing of the shaking force of slider-crank mechanisms used in internal combustion engines. With the increase of machine speed the demand for complete balancing of both shaking force and shaking moment was put forward around the War time (Lowen et al. 1983; Arakelian and Smith 2005).

For a planar four-bar linkage, several methods can achieve, at least in theory, the complete balancing of the shaking force and shaking moment. However, to achieve this objective, it is always at the cost of worsening other parameters, complicating the mechanism or increasing the total mass. These technical challenges greatly limited the application of complete balancing in engineering.

In view of the above limitation, more comprehensive balancing techniques were developed through introduction of optimization methods and comprehensive objective functions combining multiple parameters, such as shaking force, shaking moment, input torque, and reaction force of joints etc. Comparatively these techniques are more practical.

13.1.4.2 Dynamics of Cam Mechanism

Entering the 20th century, the dynamics of cam-actuated engine valves became outstanding due to a series of dynamic consequences, such as over-stress, fast wear, fatigue and high noise. To the 1930s, it was realized that the failure of cam mechanisms could not be well analyzed through the then existing methods.

J. Hrones, an American professor, conducted theoretical and experimental study on the cam mechanism of an internal combustion engine around 1950, and concluded: (1) the real motion of the rod follower pushing the poppet valves deviated from the theoretical one significantly at high speed, (2) cams designed with the then widely used parabolic motion program caused very severe vibration of the follower.

To reach the above two conclusions, Hrones developed a vibrational model with the part elasticity considered. His work marked the start of cam dynamics study. During the 1970s the speed of internal combustion engines reached 8000 rpm, and NC machining greatly improved the accuracy of cam profile. Research of cam dynamics then saw a flourish period (Chen 1982). Two dynamic design methods, experience-based and dynamics-based, were developed.

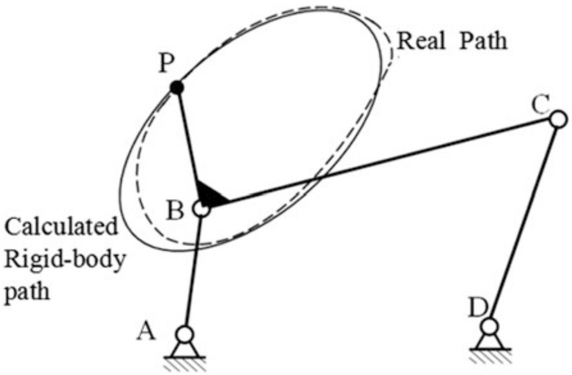
In 1947, W. Dudley, an American scholar, proposed the polynomial dynamic method, also called Polydane method, for cam design (Dudley 1948). It starts from a vibration model and an assumed follower displacement of polynomial form. Then, the cam profile is obtained based on the boundary conditions. Obviously this is a inverse-dynamics-based method.

The Polydane method stirred great sensation in the community of cam dynamics. Although the method is rarely used now, it was indeed a breakthrough at that time in cam design. It was the first cam design method based on dynamics, fundamentally changing the then popular static design method. The method was later adopted into the synthesis of cam mechanisms with single and two DOF (Erdman 1993).

13.1.4.3 Elastodynamics of Linkages

For linkages operating at high speed, the deflection of links become nonneglegible, and the real path described from one point would deviate from the one calculated based on rigid links. This is schematically illustrated in Fig. 13.5. The inertial load is more likely to excite resonance at high speed. Other potential issues related with high speed include vibration, noise and fatigue caused by cyclic stresses.

Fig. 13.5 Path generation



There are two conflicting requirements in modern machine design. First the machine is expected to be designed as light as possible. Second, the operation speed and accuracy required are getting higher and higher. Driven by these two factors, dynamics of mechanism became a research topic. Arthur Erdman and George Sandor first adapted the finite element method to the analysis of mechanism dynamics, and referred it as Kineto-Elastodynamics (KED) (Erdman et al. 1972).

Following Erdman and Sandor's work, many researchers made great effort to the study of KED and stability analysis of mechanisms. It is worth to mention that some Chinese scholars made outstanding contribution to the study of KED of linkages. In many topics, such as KED analysis, synthesis, control, balance and clearance effect etc., Chinese scholars occupied the leading position of the world (Zhang et al. 1997).

13.1.5 MMS in China

Among the many branches of mechanical engineering, MMS and tribology are the two in which Chinese scholars made outstanding contribution.

During the 1920s, Liu Xianzhou, a Chinese professor, edited the first college textbook of MMS in Chinese, and conducted study on ancient Chinese inventions in mechanisms (Yan et al. 2007). During the 1950s, the Chinese government selected a group of MMS instructors from Chinese universities and sponsored them to study at institutions of the Soviet Union. They all became the backbone scholars in their home universities after back to China. Amongst them was professor Zhang Qixian, who started the research on spatial linkages early in 1962, and made outstanding contribution to both spatial mechanisms and robotic manipulators (Zhang 1984).

In 1986, Liao Qizheng and others derived the input-output equation of a general spatial 7 link 7 R linkage (Liao et al. 1986), solving what the academia calls "Mount Chomolangma (Everest) in analysis of linkages"(Freudenstein 1973). Huang Zhen, Yang Tingli and Dai Jiansheng also did remarkable research on spatial mechanisms (Sects. 13.1.2 and 13.1.3).

To the 1980s, Some Chinese researchers had already got to the frontier in spatial mechanisms, robot dynamics, elasto-dynamics of linkages, balancing of linkages. The recent 30 years saw an even faster development and wider research scope on MMS in China. The number of involved researchers, published papers and monographs has been unprecedented, bring China to one of the research centers of the world in MMS (Dai 2014b).

13.2 Mechanical Power Transmissions

Study on theories of power transmission already started during the 1st Industrial Revolution; however, maturity was not achieved until after WWII when the power and speed of various machines experienced significant increase. Among the many types of mechanical drives, gears are the most widely used, and intensively studied.

13.2.1 Standards for Strength Evaluation of Gears

The formulas for calculation of the bending stress and the surface contact stress of gear teeth were already proposed in 1893 and 1908, respectively. However, both were very basic, containing many assumptions and neglecting several important factors.

Based on systematic studies in both theory and experiments after WWII, modifications were made to the formulas, mainly in the following aspects: (1) fatigue was incorporated in the formulas, (2) the dynamic factor was refined, (3) effect of dozens of factors, including uneven load distribution, size, material, surface, temperature etc., was included.

These modified formulas were quickly adopted by national standards in the main industrialized countries, such as DIN (Germany), AGMA (the U.S.), and ГОСТ (Soviet Union). With these modifications, the gear strength calculation method approached maturity. In 1980, ISO launched its gear strength standard (Zhu and Zhongkai 1992).

Theories on scuffing and wear have also been developed; but, none has adopted yet in standards.

Surface hardened gears were initially limited to weight-sensitive applications, such as automotive and tanks. Now the application has been expanded to much wider areas. Even in general purpose gearboxes, surface hardened gears are used mainly due to the high load capacity. Traditionally surface hardened gears were manufactured through grinding after hardening. Given the fact that grinding operation is expensive and time consuming, hobbing and shaving processes of hardened materials were developed. In addition to metals, some lighter and cheaper non-metallic materials, such as high strength plastics, were also used to make gears. Some new technologies, such as surface engineering, also found their way in improving performance of gear drives (Dudley 1988; Qin 2003).

During the 1960s, some applications put forward tougher requirements on gear drives. For example, the gear trains in rocket engine, navigating systems and space shuttles are required to be more compact, and more reliable.

13.2.2 Gear Dynamics

With the continuous increase of operational speed, vibration and noise in gear drives caught wide attention, especially those in airplanes, automotive and ships.

The first vibration model of gear pairs was proposed by an English research, William Tuplin in 1950. Before then dynamics on gears was typically based on the impact theory proposed by Earle Buckingham. Gear dynamics has advanced dramatically after Tuplin's work; many factors essential to the dynamics, such as time-varying stiffness, meshing impact and tooth error etc., have been incorporated into theoretical models (Li and Wang 1997; Zhang 2009).

During the 1970s and 1980s, gear dynamics models were refined to include the nonlinearity caused by tooth backlash and the randomness excitations. To the 1990s, gear dynamics was treated as a component in the system consisting of gears, shafts and housing.

Transverse profile modification, such as root and tip relief, was already applied in vibration control of gears around 1940. To the 1990s, profile modification had been conducted along all three dimensions. Specially designed NC machine tools dedicated for gear profile modification were also developed.

In addition to dynamics, research on operation monitoring, fault diagnosis, and failure prediction of gear systems also started. For example, fault diagnosis systems were developed for the large and critical gear trains in ships, metallurgy plants, and power plants (Zhang 2009).

Study on noise of gear systems started in the 1960s. Since then research has advanced significantly in mechanism of noise generation, noise calculation and evaluation, as well as design of low noise gears etc. It is worth pointing out that design of low noise gears involves multiple and comprehensive factors, including selection of parameters, profile modification, accuracy, manufacturing methods, interaction between the gears and the shaft and housing structure, damping and measures of vibration and noise isolation etc. (Li and Wang 1997).

13.2.3 Progress in Theory of Gearing

In addition to the factors analyzed in the above section, deformation of the teeth under loading, distortion caused by heat treatment, and manufacturing errors also cause vibration and noise. Increasing manufacturing accuracy has a limit effect on vibration and noise control, and is always accompanied by higher cost. Thus, an alternative route to control the vibration and noise is to compensate the potential errors in milling the teeth based on the prediction of the manufacturing error and the deformation of heat treatment. The real line of action and its length would deviate from the theoretical ones in this case; thus, new toothing theories are in demand. Actually, some works have been done in this regard (Sun 2006).

Theories of localized conjugate and mismatched gearing already found applications in industry. Contact analysis of spatial gearing was also developed. Load distribution and stress analysis were applied (Qin 2003).

13.2.4 New Types of Meshing Transmission

After WWII, several variations of gears and worm gears were developed for the purpose to increase load capacity and life expectation, to reduce transmission volume and to obtaine large speed ratio.

A German professor Gustav Niemann proposed the concave-convex worm-gear drive, also called the Niemann worm gear in about 1950 (Nieman and Heyer 1953; Litvin n.d.). The research on worm gears later focused on making the relative sliding velocity be perpendicular to the instantaneous line of contact. The advantages of worm gear transmissions include high load capacity, high durability and less wear due to oil film is easily formed.

The contact strength used to be the barrier to further increase the power and load capacity of gear trains. To overcome this issue, M. Novikov (Михайл Новиков), a Soviet scholar, invented the Novikov gearing concept (Fig. 13.6), also called circular arc gears, in 1956. The Novikov gearing concept changes the convex-to-convex contact of the tooth flank in the conventional gearing to convex-to-concave contact. In addition, the radii of curvature of the mating flanks are very close; thus, the contact strength of the gear teeth is dramatically increased. Due to the concept is for helical gears, the contact point moves along the axial direction.

In the U.S., Wildhaber was granted a patent early in 1926 on a helical gearing concept of circular arc tooth profile. For this reason, the Novikov gearing was called Wildhaber-Novikov gearing in the U.S. for some time. However, this is not appropriate because Wildhaber's concept is fundamentally different from the

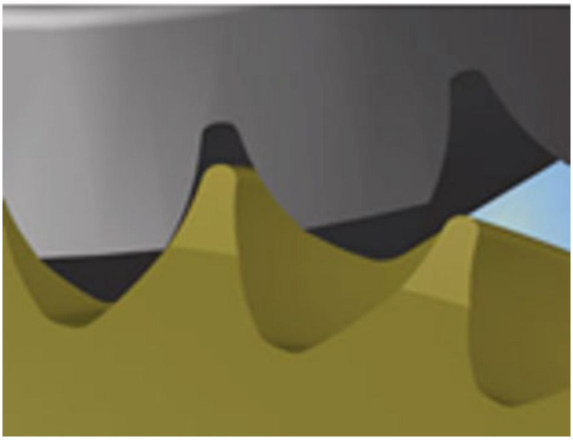
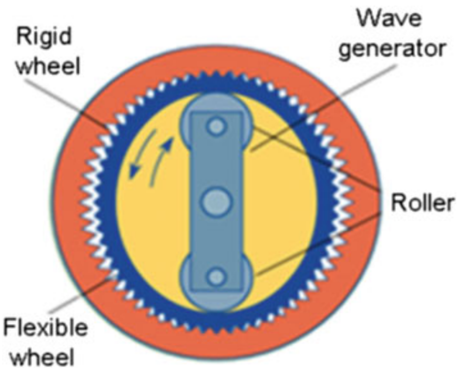


Fig. 13.6 Novikov gearing

Fig. 13.7 Harmonic drive



Novikov's (Litvin n.d.; Radzevich 2012). Novikov gears have been used in some applications of high-power transmissions, particularly in the Soviet Union and China.

In 1957, Clarence Musser, an American engineer, invented the harmonic drive as shown in Fig. 13.7 (Musser 1960). In this drive, a flexible spline is deformed through the rotation of a wave generator and the flexible spline meshes with a rigid circular spline in two regions of opposite sides. Due to the difference between the flexible spline teeth and the rigid spline teeth is small, a very large speed ratio can be achieved. Other advantages of harmonic drives include compactness, light weight, no backlash, and co-axial input and output shafts etc. It has found application in many fields, including the Apollo Lunar Roving Vehicle, the Skylab Space Station, as well as many robots (Shen and Ye 1987).

In a cycloidal drive, the input shaft drives a cycloidal gear engaging with the gear pins, while a series of pins or rollers directly drive the output shaft as shown in Fig. 13.8. This drive concept, first proposed in Germany, has various advantages, such as compactness, and high speed ratio. Japan made the first effort to

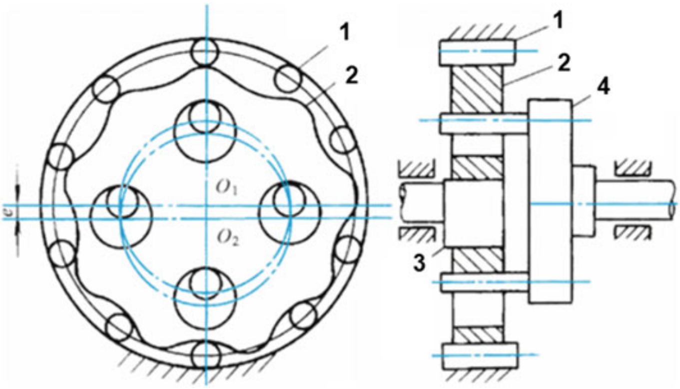


Fig. 13.8 Cycloidal drive. 1—gearpin, 2—cycloidal gear, 3—input shaft, 4—output disc

manufacture this type of drives during the 1930s. However, its real application did not come until the 1960s when cycloid grinders became available. The main components in this drive are made from bearing steel through grinding. In addition, multi-pairs of teeth are in contact in operation. These features make the drive operate very smoothly, have very high load capacity, and be very durable. Some disadvantages of the drive include the high requirement on manufacturing and the complicated structure.

A variation of the cycloid drive is the involute planetary gear drive with small difference of tooth number, in which the cycloidal teeth and the pins are replaced with involute external teeth and internal teeth. This change greatly simplifies the gear structure and reduces the contact stress of the gear teeth. Generally the gear tooth surfaces in this drive do not need hardening and no specialized machines and tools are required in manufacturing. One potential issue of this drive is that interference in gear cutting may occur due to the small difference of tooth number. Thus, the gear parameters need to be determined with great care. In 1949, a Soviet scholar, N. Skwortsowa (Н. Скворцова), developed a procedure of parameter selection for the tooth number difference being 1, and manufactured a physical drive successfully (Скворцова 1949). Some Western countries realized the potential of the drive after, and started to develop and apply it in several products. After the 1960s, computers completely removed the hurdle of calculation and parameter selection, expanding the application to many fields. In the recent decade, effort was made toward replacing the involute spur gear teeth with movable teeth and helical gear teeth.

13.2.5 Other Mechanical Power Transmissions

13.2.5.1 Continuously Variable Transmission

The development of continuously variable transmissions (CVT) has been closely related to the automotive industry. Daimler-Benz was a pioneer in applying CVT in automotive; v-belt CVT were installed in its vehicles in 1886. Since then, more than 30 types of CVT have been developed (Cheng et al. 2008).

In 1958, the Dutch car maker, DAF, developed and installed the Variomatic, a CVT consisting of a V-belt and two pulleys, in its vehicles. However, the automotive industry in general did not realize the value of CVT then mainly because of two limiting factors. (1) The belt at that time was made from rubber and the power transmitted was thus very limited; (2) the clutch produced then had issues in stability and consistency. During the late 1960s, Hubert van Doorne, the co-founder of DAF, proposed to make the belt with steel, which greatly improved the power capacity, paving the way toward wider application in the automotive industry. In 1987, the Fuji Heavy Industries Ltd. (FHI) in Japan developed the steel belt CVT (Fig. 13.9), called Justy, which has been adopted in many vehicles manufactured in Japan and Italy.

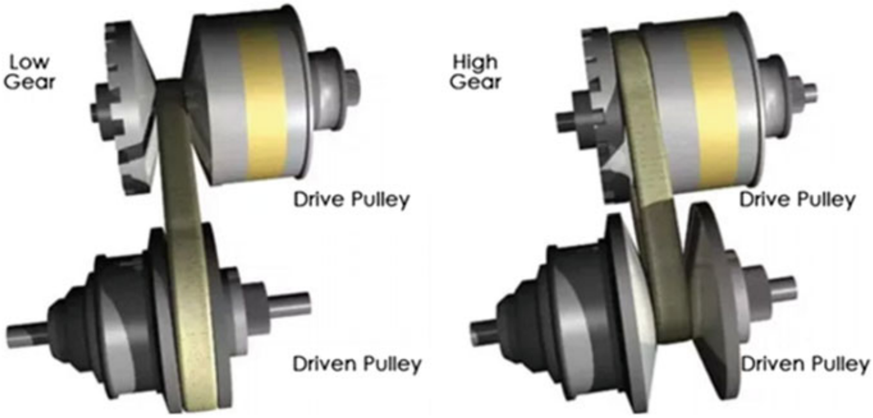


Fig. 13.9 Metal belt CVT (www.quora.com)

Mechanical transmissions with fixed speed ratio were the main stream in the automotive industry before CVT. In this arrangement the transmission and engine are two separated units. CVT, however, integrates the engine and the transmission into one unit and the engine performance can be optimized through adjusting the speed ratio and the fuel supply.

The energy crisis awakened the world in saving energy and protection of the environment. All the car makers in the world have invested heavily in development of CVT in order to keep their competitiveness in the market. Now CVT has become a strong competitor to the traditional mechanical transmission and automatic transmission, which have been in the auto-industry more than 100 and 50 years respectively.

13.2.5.2 High-Speed Intermittent Mechanism

Geneva and ratchet mechanisms have been the most popularly used intermittent mechanisms since the 1st Industrial Revolution. Compared with the ratchet mechanism, the Geneva mechanism has lower vibration and noise in operation. However, dramatic acceleration change happens at the intersections between the motion and the dwell. Thus large impact loads are generated, making it unsuitable for high-speed operation.

After the 2nd Industrial Revolution, packaging machinery went through significant increase in operational speed, putting forward a demand for high speed intermittent mechanisms. In 1952, a scholar in the U.S., Constantine Neklutin, invented the indexing cam mechanism (Neklutin 1969) which was put in production in the Ferguson company (Fig. 13.10). This mechanism is smoother in operation, more accurate and reliable in rotation and indexing. The stop numbers and other motion parameters in this mechanism depend on the cam profile; thus,

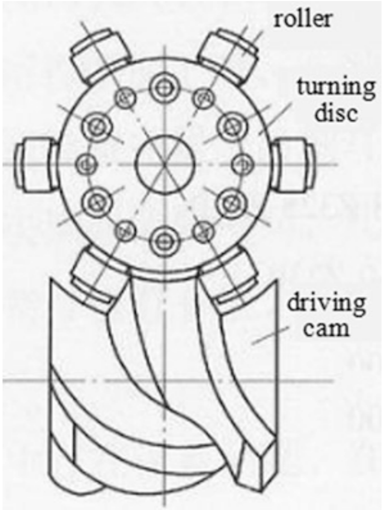


Fig. 13.10 Ferguson indexing mechanism (http://www.chinabaike.com/t/9715/2013/)

different motions can be achieved through adjusting the cam profile. Carefully designed indexing cam mechanisms have much lower impact and dynamic load compared to the traditional Geneva and ratchet mechanisms. Now mechanisms of this kind operating at 3000 rpm input was reported.

Indexing cam mechanisms are regarded as the best and most accurate high-speed, intermittent mechanism. Application has been found in various machines, such as high-speed press, machining centers, packaging machines and multi-color printers etc.

13.2.5.3 Toothed Belt

Toothed belts, also called timing belts, are a variation to traditional belts, but with much higher power capacity. The earliest report on toothed belt appeared in 1945. Now timing belts (Fig. 13.11) have found wide application in automotive engines, sawing machines, and copying machines etc.

13.2.6 Informatizition and Intelligentization

Automatic transmissions have widely used in automotive and many other construction machines. With the computer control technology, the speed ratio can be automatically adjusted to fit the engine's performance. In modern motor vehicles, three types of automatic transmission are widely used, namely hydraulic automatic transmission, CVT, and automated mechanical transmission (AMT).

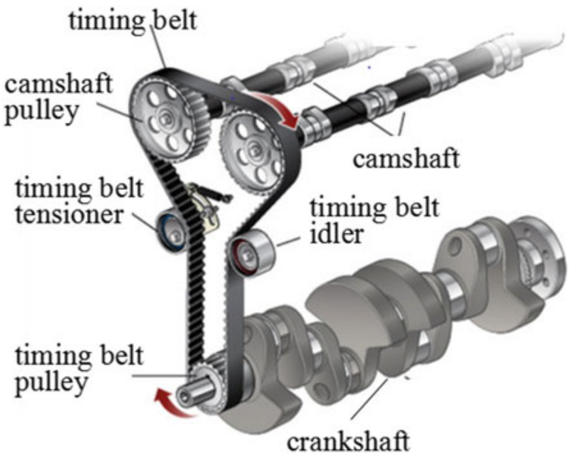


Fig. 13.11 Timing belt used in an engine (from www.repairpal.com)

The other successful example in informatizition and intelligentization is the computer control of all-wheel vehicles.

13.3 Robotics

In Chap. 10, the development of robots have been presented with more details. Robotics is a subject specifically studying the science and application of robots; it combines MMS, mechatronics, computer science, information and control.

13.3.1 Robot Kinematics

Robot mechanisms, as a branch of MMS, are one of the pillars in robotics which have been undergone extensive study. During the 1980s and 1990s, many researchers originally working in general MMS switched their research efforts to robot mechanisms. Robot mechanisms are far more complicated than general planar mechanisms. Due to the fact that servo-motors are generally used as the driver in robots, the kinematics and dynamics are also related to the control of the actuator.

Robot mechanisms cover composition principle, motion analysis, work space analysis, singularity analysis, and trajectory planning etc. Due to the fact that most robot mechanisms belong to spatial mechanisms, the two subject branches of MMS, robot mechanisms and spatial mechanism, are in fact intertwined.

Kinematics, especially the position analysis, has been an important topic in robot mechanisms all the time. There are two types of problems in robot kinematics, namely inverse kinematics and direct kinematics. Direct kinematics determines the pose of the end effector with the given motion of the actuator; while the inverse problem looks for the actuator's input with the motion of the end effector known. For serial robots, the inverse problem is more difficult than the direct problem; while for parallel robots, the direct problem is harder to solve than the inverse. Position analysis of parallel robots is characterized with multi-solutions. For example, the 6/6 Steward mechanism has more than 40 solutions in the direct position problem. Many researchers obtained closed form solutions of position analysis using different mathematic tools, such as vector algebra, matric theory, and screw theory. Joseph Duffy, an American researcher, made a comprehensive review on the closed form solutions (Duffy 1980). Closed form methods lack overall applicability although they give more insight in analysis. Numerical techniques, thus, have been developed. The methods of continuation are typical numerical algorithms which have the capacity to find all solutions without the need of initial values. Due to this reason, the methods were widely applied by kinematicians (Erdman 1993).

In 1982, D. Tesar and his associates proposed the concept of kinematic influence coefficient, which became a powerful tool in velocity and acceleration analysis (Huang et al. 2013).

Path and trajectory planning determines the inputs of the joint actuators for a specified end-effector's motion.

Research on workspace and singularity of serial robots started in the 1970s. The singularity problem of parallel robots is more complicated than that of serial ones. An Australian scientist, Kenneth Hunt, is among the earliest pioneers treating the singularity problem of parallel robots (Erdman 1993).

Serial robots appeared earlier than parallel ones, and are relatively simpler in topology. After many year evolution, serial robot mechanisms are narrowed down to only several ones. Parallel mechanisms, however, are much more complicated in topology due to the multiple DOF and loops. The topological synthesis of lower mobility parallel mechanisms is more difficult and critical, attracting many researcher's effort in the recent decade. Methods developed for this problem include screw theory, Lie group theory and position and orientation characteristic (POC) set (Hunt 1990; Huang et al. 1997; Yang et al. 2018).

Type synthesis is also an important branch in robotic mechanisms. large number of mechanisms are obtained through type synthesis which can achieve the specified function. However, very few are feasible in practice because many important criteria, such as stiffness and accuracy, are not considered in the synthesis. In view of the limitation of type synthesis, many researchers suggested that type synthesis and optimization of performance should be conducted simultaneously (Huang et al. 2005).

13.3.2 Robot Dynamics

Dynamics is essential to the design of the manipulator, design of the controller and dynamic performance analysis.

Robot dynamics is also classified into two types of problems, namely inverse and direct dynamics.

The direct dynamics basically solves differential equations with numerical algorithms. It is also named dynamic simulation. The inverse dynamics, on the other hand, constitutes the base for design of the controllers, being considered more critical.

In the inverse dynamics, a particular important consideration is the efficiency of the algorithm. To achieve an accurate, real time, and feed back control of the robot, the time for solving the problem has to be lower than the sampling time. In another word, real time computation is needed.

13.3.2.1 Dynamics of Rigid Robots

(1) Rigid dynamics of serial robots

Study on robotic dynamics started with the inverse problem of rigid mechanisms shortly after robots were invented. During the 1970s and 1980s, research effort focused on the search for efficient algorithms in order to achieve real time control. A huge challenge came from the minimization of floating point multiplication and addition. In modeling the robot dynamics, three methods, namely the Newton-Euler method, the Lagrangian method and the Kane's method, are commonly used. These methods may vary in the degree of complexity of derivation and the form of the equations; however, they are the same in essence (Liu 1989).

In the direct dynamics, computation intensity is not as critical as in the inverse problem. Rather, the adaptability and flexibility of the computation algorithm are a more important consideration so that the algorithm can be used in computer simulation in case of design changes.

(2) Rigid dynamics of parallel robots

Parallel robots are much more complicated than the serial ones. Research so far has been focused on kinematics, workspace, and singularity etc. Little work has been conducted in dynamics.

One application of parallel mechanisms is in machining tools. With a given displacement, velocity and acceleration of the end effector, the input torque of driving motors can be calculated in the inverse dynamics. This type of analysis constitutes the basis for dynamics of the machine tool, selection of motors, dimension synthesis, dynamic design of the whole system as well as controller design. The inverse dynamics of rigid parallel mechanisms now focuses on the following two aspects; (1) developing concise and simple dynamics models suitable for use in dynamic control, (2) optimizing the robot's structure and link's inertial through inverse dynamics in order to minimize the driving torque of motors.

13.3.2.2 Dynamics of Elastic Robots

Generally, links in robots are with enough rigidity through conservative design. However, over-sized parts and links consume more materials and power. More importantly the large inertial of the links makes it difficult for trajectory tracking. In view of the negative effect of over-sizing, light weight became an important criterion in robot design. In this case, the elasticity of links and the flexibility of joints have to be considered. Light weight design has a series of benefits, such as lower cost, higher speed, high payload/weight ratio, lower energy consumption and easier operation etc. (Fig. 13.12).

In addition, elastic robots are especially important for some applications requiring soft and gentle touch. Examples include robots in surgery, deburring, grinding, painting and drawing.

The spatial manipulators on space stations for retrieving satellites are made very slender and required to be light weight. Light weight is critical to control the launching cost. The slender design of the manipulator leads to larger deflection, making it a challenge to track the trajectory. The flexible multi-body-dynamics was developed during the early 1970s mainly for this challenge. Numerous papers and monographs have been published on spatial manipulators ever since (Dwivedy and Eberhard 2006).

One critical issue in elastic robots is that the vibration of the end effector causes positioning accuracy. To solve this problem, many researchers have devoted their effort to the study of robotic vibration since the 1980s.

To achieve desired accuracy in machine tools of parallel robots, the dynamic characteristics of the elastic links have to be taken into account. The dynamic

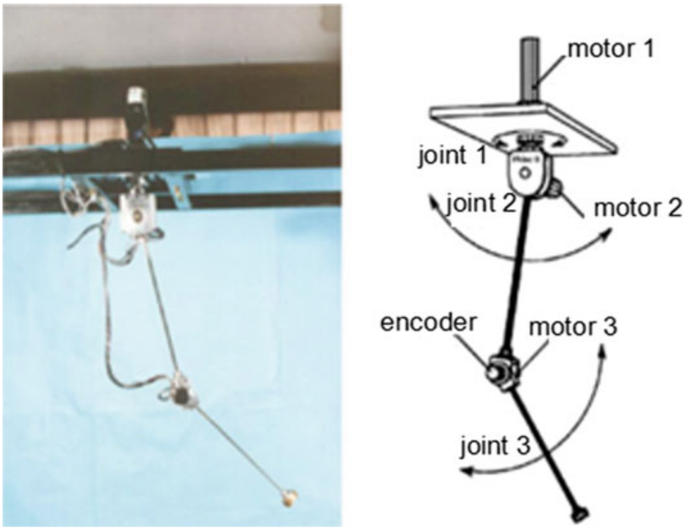


Fig. 13.12 A flexible robot

modeling and simulation, however, is much more complicated than that in traditional machine tools due to the coupling between mechanisms and structures, time varying parameters and nonlinearities.

13.3.2.3 Dynamics of More Complicated Robots

(1) Redundant Robots

A robot having more DOF than needed for executing the specific task is termed redundant robot. Research on redundant robots started in the 1970s, and reached a peak in the 1990s (Chiaverini 2013).

In rigid dynamics of redundant robots, research has been conducted on improving kinematic and dynamic performance with the redundant DOF, such as increase of agility; avoidance of obstacles and singularity; optimization of joints velocity, acceleration, torque and power etc. In elastic dynamics, research work progressed in trajectory planning and vibration control. In the trajectory planning, the redundant DOF is taken advantage of to control the effect of elastic deformation. Due to their unique features, redundant robots have attracted much attention in recent years.

(2) Cooperative operation of manipulators

When the object to be handled is complicated in shape and large in size, it is beneficial to use more than one robot to work in coordination. This concept has great potential of application in automation, military, space, and many others. Research on this topic has attracted much effort since the 1980s.

Accounting for the elasticity, redundancy and cooperative operation of robots simultaneously in research is even harder. Some researchers have started working on this challenging problem (Miyabe et al. 2002; Liu et al. 2005)

(3) Biped walking robot

Biped walking is a unique form of motion found only in some higher animals. It is challenging either to study this motion form in theory or to implement it with machines.

Vukobratovic and Juricic (1969), a Yugoslavian researcher, was a pioneer in the study of bipedal walking robots. He first studied the static walking in which balance and stability were the main consideration. In static walking the center of gravity is always projected vertically within the polygon of the supports formed by the feet; thus, balance is always maintained. To this end, the center of gravity has to move short in a step. The downside of static walking includes slow moving speed and high energy consumption. In contrast, dynamic walking does not require the center of gravity within the support area, thus is much faster. Human and many other animals walk in the dynamic way.

In the past four decades, hundreds of different bipedal robots have been developed around the world (Li 2005). Japan has been the leader in the study of humanoid robotic technology (see Sect. 10.3). To this point, bipedal robots have not yet found wide application. Although various walking mechanisms have been developed, the fundamental walking theory, such as dynamics, stability and control mechanism etc., has not yet fully understood (Fu and Chen 2006).

(4) Application of modern mathematics

During the 1970s and 1980s, some differential geometry theories, such as Lie group, and Lie algebra, were brought into the robotic study (Li et al. 2007). The new mathematic tools have showed great potential in many topics of robotic study, such as type synthesis, kinematics, singularity analysis, accuracy analysis, dynamics and control etc. However, a systematic, theoretical framework has not been formed yet.

13.4 Machine Dynamics

13.4.1 Introduction

After WWII, machine dynamics has developed into a comprehensive subject (Zhang 2009).

On the one hand, development in relevant fields, such as aerospace vehicles, high speed vehicles and robots, continuously put forward challenges in dynamics. On the other hand, progress in mathematics, mechanics, and signal analysis provides more powerful tools to dynamics study.

Machine dynamics has developed significantly in breadth; forming many specialized branches, such as mechanism dynamics, transmission dynamics, rotor dynamics, robotic dynamics, vehicle dynamics, machine tool dynamics etc.

The depth of machine dynamics has also been greatly expanded, many topics, including modeling, analysis, simulation, dynamic design, vibration control, operation monitoring, as well as fault diagnosis, have been included in machine dynamics.

Computers provide the most powerful tool to machine dynamics. Dynamic analysis requires intensive, and very complicated computation, most of which is hard to be implemented by hand nowadays. Several important branches of machine dynamics, in fact, did not advance much until computers became available. With the powerful symbolic tools, the governing equations of motion can be derived automatically by computers. Study of machine dynamics nowadays is almost impossible without involvement of computers.

Progress in mechanics, the finite element method in particular, has greatly increased the capacity of dynamics modelling. Nonlinear science and nonlinear vibration advanced the dynamics theory from linear to nonlinear level. Compared with the situation before the WWII, the problems nowadays have been much more complicated, and the scope and breadth of machine dynamics have been widely expanded.

13.4.2 Analytical Modeling

Many modeling methods have been developed for specific real systems (Zhang 2009).

For systems consisting of multiple rigid components, the Newton-Euler method, Lagrange method, as well as Kane's method etc. are well suited. Software packages based on these methods are available in market.

For small magnitude vibration analysis of lumped parameter systems, the Newton's 2nd law would be enough for modeling. The method of Lagrange equation, however, is more versatile, being applicable to not only lumped parameter systems, but also continuous systems.

For dynamics analysis of mechanical components, commercial FEA packages are a good option. FEA has been applied to dynamics analysis of gear teeth, elastic linkages as well as machine tools.

The number of DOF is generally high in modeling dynamics with FE. During the 1960s, the concepts of modal coordinate and modal synthesis were proposed and the method of dynamic substructure was developed, which can significantly reduce the DOF of the problem (Hurty 1960; Gradwell 1964).

In 1921, H. Holzer developed a method to calculate the fundamental as well as higher order torsional frequencies from an assumed value through iteration (Holzer 1921). To the 1940s, the Holzer's method was extended to lateral vibration of shafts. Also during the 1940s, the Holzer's method advanced one important step by expressing it in the form of transfer matrix. Transfer matrix method is easily adaptable for computerization, being a method still in use for computation of the natural frequencies of shaft and other chain-like systems.

A hurdle in modeling a dynamic system with the above stated theories is that the boundary conditions, damping and stiffness are difficult to be determined accurately. Thus, the model developed may have significant deviation from the real system. Since the 1970s, experimental modal analysis has been developed. Japanese scholars were pioneers in determining the values of damping and stiffness through dynamic modal experiments (大久保信行 1982).

In some systems, such as space shuttles and elastic robots, large amplitude rigid motion and small amplitude elastic deformation are coupled. Flexible multibody methods are suitable for modeling such systems. Elastic linkages, in which coupling of large rigid motion and small elastic deformation exists as well, can be analyzed through elastodynamic analysis after some simplification (Zhang et al. 1997).

13.4.3 Refining Dynamic Modeling

When vibration is analyzed with linear theory, simplifications have to be made through linearization. However, linearization is not only a matter of accuracy. In some cases, fundamental features of the system are lost after linearization, leading to severe consequence, such as shaft breaking in large generators. The realization of nonlinearity in dynamics has been accompanied by catastrophic accidents.

In this case, the demand to refine dynamic modeling was raised with more factors, including nonlinear factors, taken into account. Common nonlinearities in mechanical systems include clearance in kinematic pairs, internal damping of materials, geometrical nonlinearity, material nonlinearity, nonlinear stiffness, coupling of rigid motion and elastic deformation etc. Nonlinearity is even more critical in modeling complicated systems.

Complex electromechanical systems gained fast development after WWII. In the dynamic analysis of these systems, the coupling of different sub-systems have to be modeled (Zhong et al. 2007). Some examples of this kind are as follow:

The coupling between mechanical and electrical systems within a large steam turbine may lead to severe torsional vibration.

Vibration of the antenna in a satellite may cause instability of the satellite pose (Fig. 13.13). This vibration is a coupled effect of rigid motion and elastic deformation.

In the Hubble Space Telescope (Fig. 13.14), the flexible solar array experienced severe bending vibration caused by the coupled thermal and structural effect (Thornton and Kim 1993).

In liquid propelled rockets, liquid filled satellites, and space shuttles, the dynamics of liquid sloshing is critical to the control of the pose. The sloshing involves the coupling between the liquid and solid structure.

In large hydraulic turbine and generator systems, the fluctuation of hydraulic pressure may cause severe vibration in the system, piping system as well as the civil structures. This involves the coupling of fluid, mechanical and structural systems.

In high speed trains, the coupling between the vehicle and bridge, as well as between the vehicle and the air flow is critical.

A common feature in modeling these complex electromechanical systems is the proper account of the many nonlinear factors, and the coupling of different sub-systems and media.

Dynamics of complex electromechanical systems fundamentally changed the overall picture of dynamics. In the past, Euler and Lagrange methods were common and individual systems were treated. For a complex system nowadays, however, fundamental theories and applied science have to be combined to solve the dynamics problems. Very often experts from different areas with different knowledge bases are teamed for a specific problem.

Fig. 13.13 Artificial satellite and its antenna (www.timetoust.com)

Fig. 13.14 Hubble space telescope (www.bbc.co.uk)

13.4.4 Progress in Dynamic Analysis and Simulation

The huge power of computers in numerical analysis, logic reasoning and graphic display has fundamentally changed engineering design.

The dynamics of a mechanical system is represented generally as a set of differential equations or algebraic-differential equations. Traditionally the modeling, analysis, coding and simulation were all conducted by individual designers for specific systems. However, this method obviously lacks generality. Since the 1960s, various general purpose, commercial dynamics software packages, mainly FEA packages, have become available in the market.

These packages generally have the following functions: (1) providing various planar and spatial elements, and being able to treat distributed loads, concentrated loads as well as moments; (2) being able to solve static and dynamic problems, including linear elastic and nonlinear problems; (3) coming with pre-processing and post-processing modules for automatic meshing and graphically representation of the analysis results.

The FEA tools greatly increased the capacity to analyze large scale engineering problems, and have been widely adopted in almost all engineering fields, such as nuclear power, space engineering, mechanical engineering, energy, electronics, ship-building, vehicles, and civil engineering etc.

In addition to the pre-processing, solution and post-processing, some packages even have the virtual prototyping function and animating function of motion. With these powerful functions, design parameters and their effect on performance can be quickly compared. The cost and time for new product development can be reduced due to the elimination of the need to build physical prototypes.

It is reported that the Boeing 777 plane was developed completely through virtual prototyping technology in which all design, analysis, evaluation and assembly were completed virtually on computers. The developing time and cost were reduced by 50% and 25% respectively.

13.4.5 Branches of Machine Dynamics

Several branches have been formed under the umbrella of machine dynamics mainly based on the object under investigation.

Mechanism dynamics, transmission dynamics and rotor dynamics had been formed before WWII, and continued development in the New Era. Dynamics of machine tools, robots and railway vehicles, however, did not take shape until after the War.

Dynamics of space shuttles and aero-planes has some unique features; thus, it is rarely covered in general machine dynamics texts. Despite of this fact, it is still closely linked with general machine dynamics. Many new techniques and methods in machine dynamics, in fact, were transferred from dynamics of aerospace systems. Examples include FEA, and fault diagnosis.

Mechanism dynamics and transmission dynamics were already discussed in Sects. 13.1, 13.2 and 13.3, and machine tool dynamics was presented in Chap. 12. In the following section, the development of rotor and vehicle dynamics in the New Era is briefly presented.

13.4.5.1 Rotor Dynamics

Flexible rotors appeared during the early 20th century. The idea to consider the flexibility of rotors and supporting bearings simultaneously was also formed roughly the same time (see Sect. 7.4).

The capacity of steam turbo-generators kept growth during the late 20th century. This could be achieved through three routes, namely, increasing the operation speed, the size and the number of impellers. The increase of speed and diameter of rotors was limited by the material strength and the increased centrifugal force; thus, increasing the number of impellers became a more realistic option. In this case, the rotor has to be designed more slender and flexible. It is reported that some rotors operated above the 3rd and even the 4th critical speed (Wen 2000).

Flexible rotors are more vulnerable to severe vibration. Many failures of large turbo-generators due to vibration have been reported in the recent half a century, leading to significant economic losses (Huang et al. 2006). Thus, vibration control of rotors became a critical research topic.

The vibration of a rotor system, however, is very complicated and consists of many different components, including bending and torsional vibrations of the shaft, the vibration of the impeller as well as the blades on the impeller, oil whirl, and the coupling of mechanical and electrical systems.

Rotor dynamics has evolved into a comprehensive subject, in which the main contents are (1) free vibration and forced vibration, (2) dynamic balancing of flexible rotors, (3) nonlinear rotor dynamics, (4) dynamic stability, (5) fault diagnosis, and (6) active vibration control.

13.4.5.2 Automotive Dynamics

An automotive vehicle experiences vibration of 6 DOF as shown in Fig. 13.15. The 6 DOF can be treated simultaneously; however, the vibrations are not coupled if the vehicle is well controlled. Thus, these vibrations are generally treated separately as lateral dynamics, vertical dynamics and longitudinal dynamics (Yu and Lin 2005; Segel 1993).

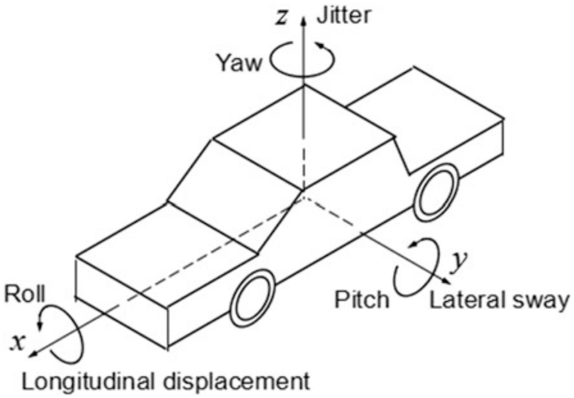


Fig. 13.15 Degree of freedom of car's vibration

(1) Vehicle handling dynamics deals with the handling and stability of the vehicle mainly through the yaw and lateral DOF. The contents in handling dynamics include ① lateral properties of the tyre, ② the dynamics of the steering system, and ③ handling and stability and control (Abe and Manning 2009).

(2) Driving dynamics treats the vibration in vertical direction through inclusion of the vertical and pitch DOF. The main contents include: ① excitation of the road and road model, ② properties of components related with the ride comfort, such as the tyre and suspension, ③ occupant response to vibration, ④ modeling of driving dynamics and ⑤ active control of the suspension.

(3) Longitudinal dynamics investigates the force and motion along the longitudinal direction as well as the control. It involves the driving, braking and fuel consumption etc. In some publications the torsional vibration of the transmission is also included in the longitudinal dynamics (Yu and Lin 2005). In addition, collision is also a dynamics problem and the most fatal collision is in the longitudinal direction.

Handling dynamics, as the most challenging part, is critical to the handling and safety of the vehicle.

13.5 Theories of Strength

Theories of strength have gone through three historical stages in development (Guo 2003; Li 2006):

(1) Theories of static strength on the basis of stress and strain analysis,
(2) Traditional fatigue strength,
(3) Theories of damage tolerance and endurance based on fracture mechanics.

13.5.1 Fatigue Design Methods

Fatigue of materials was already noticed in the 19th century (see Sects. 6.2 and 7.6).

Since A. Wöhler presented the famous S-N curve in 1870 which described the relationship between the fatigue life and the cyclic stress, the design method for infinite fatigue life became an option.

The finite life design method seeks, however, the safety of a part within a time duration. In this case, the stress is allowed to go above the endurance limit. The core problem of this method is how to account for the accumulated damage effect. Although this design method was already proposed in the early 20th century, it did not become technically feasible until A. Miner improved A. Palmgren's linear cumulative damage rule in 1945 (see Sect. 7.6). With this method machines can be designed lighter, a critical benefit for some weight sensitive machines, such as airplanes. To improve the accuracy, some nonlinear cumulative damage rules were developed in the 1950s (Li 2006).

In both the infinite and finite life design methods, the nominal value of stress is the base. However, almost all machine components contain some geometric or microstructural discontinuities, such as notch and crack, where the fatigue failure begins. Thus, various local stress-strain fatigue methods were proposed after the 1960s.

Scatter and randomness are an inherent characteristic of properties of the material and the component, such as the strength, endurance limit, surface quality and size etc. these properties are generally obtained through tests, and scatter in a range. Thus, measures have to be taken in design to account for the uncertainties and randomness.

13.5.1.1 Reliability for Static Strength

This method calculates the failure probability of a mechanical component accounting for the randomness of the component in geometry, load, and mechanical properties of the material. The probabilistic reliability model was first developed in the 1940s. In recent years, random FEA and simulation were formed through incorporation of the randomness of parameters into FEA, laying a solid foundation for reliability analysis based on static strength.

13.5.1.2 Reliability for Fatigue Strength

In addition to the randomness stated in the above, this method treats the micro-structure of material and the initial cracks as random.

Damage tolerance design methods are more advanced fatigue tools based on fracture mechanics. Currently the traditional fatigue methods are still in use due to the following reasons: (1) the smallest cracks which can be measured presently in mechanical components are responsible for above 80% of the total fatigue life; (2) traditional methods are far easier to use than the damage tolerance approaches. However, we should keep in mind that traditional fatigue methods bear obvious limitation. For important structures and components, damage tolerance design methods should be took recourse to.

13.5.2 Development of Fracture Mechanics

Alan Griffith, an English aeronautical engineer, made a crucial contribution toward the establishment of fracture mechanics by developing a fracture criterion in 1921 (see Sect. 7.6). However, the value of Griffith theory was not recognized by the technical and scientific community until more than 20 years later.

During WWII and for a short time afterword, many ships and air craft failed by sudden, seemingly inexplicable ways (Fig. 13.16). Some famous examples are as below. The Liberty Ships and T2 oil tankers, built in the U.S. during WWII, experienced more than 1000 accidents, among which 238 ships were completely wrecked. During the 1950s, the solid-fueled Polaris missile experienced explosion in the U.S. Also in the 1950s, the UK's air craft, de Havilland DH 106 Comet, had three fatal crashes in one year. Initially these failures were thought caused by poor welding quality. But later it revealed that the true cause of the failures was brittle fracture of the materials. This finding intrigued the interest in Griffith's work.

George Irwin led a team at the U.S. Naval Research Laboratory, conducting research on the brittle fracture of oil tankers in 1946. Following Griffith's theory, Irwin demonstrated in 1957 that the stress field around the crack tip might be described by the stress intensity parameter through examining the crack tip

Fig. 13.16 Failure at anchor of the Schenectady tanker (www.mdp.eng.cam.ac.uk)

plasticity. The criterion for the crack extension was established on the basis of stress intensity parameter. Irwin's work laid the foundation of linear elastic fracture mechanics (Yarema 1996; Erdogan 2000).

Fracture mechanics, as a branch of solid mechanics, studies the strength of and the propagation of cracks in materials. The main contents in fracture mechanics include obtaining the fracture toughness of materials, determining if fracture happens under certain loads or establishing the fracture criteria, looking at the crack growth within the materials, and determining if fracture happens under both environmental and stress effects, which is the stress corrosion problem.

In the late 1960s, a F-111 air craft crashed due to brittle fracture which was the result of propagation of initial cracks. This directly led to the proactive measures taken in the design of B-1 Bomber in the 1970s, requiring prediction of components based on the measured initial crack size. This was the first record of application of fracture mechanics in design. In 1967, the Silver Bridge connecting Point Pleasant, West Virginia and Gallipolis, Ohio, collapsed suddenly during rush hour. Investigation afterwards pointed the cause of the collapse to corrosion and fracture of a suspension link resulted from growth of initial cracks. This fatal accident pushed the U.S. government to upgrade the design requirements of bridges (Seim 2008).

Fatigue prediction with damage tolerance is based on the theory of fracture mechanics. The residual strength of a component, in which initial cracks exist, is predicted with measured fracture toughness and fatigue crack growth rate. This method intends to design a component being safe within a certain period.

With the advance in fundamental mechanism of material failures, traditional fatigue theory and fracture mechanics tend to be integrated. The traditional fatigue theory attributes the course of materials to cracks; while the fracture mechanics look into the growth of the crack. It is expected that two design methods, traditional fatigue and damage tolerance, will be integrated in the future.

In the main industrialized countries, the damage tolerance method has been widely applied in many fields, such as aerospace, automotive, mechanical, material, and energy industries. In some countries, it has become mandatory to check the fatigue life of some systems with the damage tolerance method.

If the nonlinear plastic deformation is confined to a small region near the crack tip, the linear elastic fracture mechanics is applied. While if large regions of plastic deformation happen, the elastic-plastic fracture mechanics applies. Now fracture mechanism has been progressed from the 2 dimensional elastic fracture theory to 3 dimensional elastic plastic fracture theory. The subject scope has also been expanded from treating only long cracks to micro-cracks, and from prediction of crack propagation life to the whole life of a component.

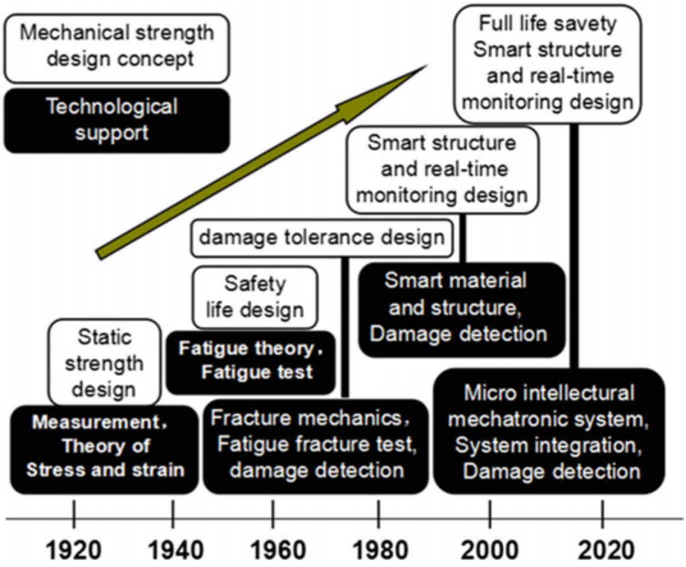


Fig. 13.17 Historical development of machine design of strength

13.5.3 *Intelligent Structure and Health Monitoring*

A further development of the damage tolerance design method is the intelligent structure and healthy monitoring, which is based on smart materials and structural technologies (Gandhi and Thompson 1992). It contains the following main contents:

(1) Monitoring the stress and strain within the material with embedded micro-sensors.
(2) With advanced life prediction theory, developing structural life prediction methods which have comparable accuracy to lab tests.
(3) Warning potential structural safety issues, and controlling of structural fractures, including self healing technology and other advanced automatic control technologies.

Figure 13.17 gives a brief time line of the development of strength theories in mechanical design.

13.6 Tribology

Tribology is a science and engineering subject which studies the mechanism of friction, lubrication, and wear between interacting surfaces in relative motion.

Statistics indicated that friction consumes about 1/3 of the total primary energy in the world, and 60% of materials loss is from wear. In several industrialized countries, for example, the U.S., UK and Germany, the economical loss related to friction and wear falls in between 2 and 7% of the gross national product (GNP) (Xie et al. 2009).

13.6.1 Modern Progress in Research on Friction, Wear and Lubrication

13.6.1.1 Friction

Human already noticed the phenomenon of friction very early. However, the understanding of friction progressed little in a long time. Leonardo da Vinci, G. Amontons and C. Coulomb are among the early researchers (see Sect. 3.2). Coulomb, a French scientist, explained the mechanism of dry friction by a simple roughness model in 1785 (Khan et al. 2017). The understanding of friction did not go beyond Coulomb's theory during the 19th century.

To the 1940s, scholars noticed that the seeming area in contact differed from the real area in contact with consideration of the micro-roughness. In 1954, David Tabor, a British physicist, proposed a model attributing friction to two factors, namely asperity deformation and adhesion. This is a well established and wide adopted friction model (Dowson 1998).

13.6.1.2 Wear

Modern study on wear started in Germany around 1930. After summarizing earlier works, Erich Siebel categorized different forms of wear in 1938, including dry surfaces, lubricated surfaces, sliding friction and rolling friction. He also mentioned the wear caused by vibration, abrasive particles, as well as erosion of fluid. More importantly he pointed out that collaboration between physicists, chemists, metallurgists, and engineers was critical to solve a real wear problem. This insightful idea was well ahead of the time, preluding the birth of the subject of tribology.

To the 1960s, advance in measurement and analysis instruments put the wear study on a fast track.

In 1973, Nam-pyo Suh, a Korean scholar, put forward the delamination theory which is developed on the dislocation theory, the plastic deformation and fracture of metals near the surface. It envisioned that wear is the result of development of subsurface cracks and voids, and the subsequent formation of flak-like wear particles (Suh and Saka 1980).

13.6.1.3 Lubrication

Classical laws are only for dry friction. However, human already knew that lubricants could greatly reduce friction. As stated in Chap. 7, a Russian engineer, N. Petrov (Н. Петров), developed sliding bearings during the 2nd Industrial Revolution. O. Reynolds derived the famous Reynolds equation in 1886, which is the basis of theory of hydrodynamic lubrication. Later on, R. Stribeck and W. Hardy further developed Reynolds work. Under the guidance of these theories, sliding bearings advanced significantly in both theory and application.

13.6.2 Contemporary Advance in Tribology Research

13.6.2.1 Birth of Tribology

After WWII, machines tended to be operated in high speed, under heavy duty and, in some cases, high temperature. To the early 1960s, technological issues related with wear dramatically increased. On the other hand, the loss caused by a failure became higher than ever due to the more complicated working process and the high cost of the machines. Driven by these two factors, the study on friction, wear and lubrication caught more interest in the main industrialized countries, such as the U. S., Germany, and U.K. Scientific journals were launched and national research plans were established.

Peter Jost, a British scholar, first coined the term, tribology, in 1966 in a Department of Education and Science Report. The new word was derived from the Greek root "*τριβ*-" and a suffix –logy, and was quickly adopted by the academic community as a formal subject after it was invented. Many scholars classified themselves as tribologist.

13.6.2.2 Contents of Tribology

The scope of tribology includes lubrication, lubricants, friction, wear and bearing (Dowson 1998). It is a subject of interacting surfaces in relative motion, and closely related to mechanical engineering, physics, metallurgical engineering and chemistry.

Many countries established national research centers and academic organizations on tribology. Research was conducted in many colleges and universities. In the engineering fields listed in UNESCO (2010), tribology was placed in parallel with mechanical and material engineering.

The main research topics in tribology related to mechanical engineering include:

(1) Friction pairs, such as the lubrication and wear in sliding bearings, wear and scuffing of gear pairs.

(2) Friction and impact of working media on surfaces of mechanical components, for example, rotors in a hydro-turbine.
(3) Effect of friction in machining, for example, the effect on cutting force, machining heat and wear of tools.
(4) Friction in elastic sliding pairs, such as between automotive tyres and the road, as well as between dynamic seals and leakage.

Tribology involves fluid mechanics, elastic and plastic contact, rheology of lubricants, surface profile, heat transfer, thermal dynamics, friction chemistry, and metallurgy. Several changes are under way in the current research on tribology and application; including from macro to micro scale, from static to dynamic conditions and from qualitative to quantitative study.

After the 1990s, some new branches have grown out of tribology; a couple of examples are as below:

Nanotribology: the study of friction, wear and lubrication phenomena at the nanoscale.
Biotribology: the study and application of tribology in biological and medical fields, for example, human joint replacements and dental materials.
Green tribology: the study of ecological and environmental effects of tribology, for example, tribology in renewable energy, green lubricants, as well as biomimetic approaches in tribology etc.

13.6.2.3 Tribology Study in China

Wen Shizhu, the Academician of the Chinese Academy of Sciences, is one of the prominent tribology researchers in China. His main contribution includes the finding of a transit zone in between the traditional boundary and hydrodynamic lubrication zones, the invention of oil film measurement at nanoscale, and the establishment of elastohydrodynamic lubrication theory etc. (Lei 2009).

However, the application of tribology theory in engineering is not satisfactory in China. Tribological design has not yet been widely adopted in the industry (Xie et al. 2009).

13.7 Micro-electro-Mechanical System

With the proceeding of electronic technology to micro-scale, electronic devices are becoming smaller and smaller. Some mechanical scholars, thus, wondered if a machine can be made to the microscale as what happened in the electronics. This idea led to the creation of a new multidisciplinary subject, micro-electro-mechanical systems (MEMS), which combines MMS, electronic technology, material science, and manufacturing technologies etc. MEMS is a land mark in the development of mechanical engineering (Zhou et al. 2000).

Machines with a dimension between 10 μm and 1 mm are referred to as micro-machines. If the dimension is between 10 nm and 10 μm, then the machine is termed super micro machines or nano machines. Combination of micro machines and nano machines makes MEMS.

13.7.1 Birth and Development of MEMS

The invention of IC in 1958 is a milestone toward the birth of MEMS.

In 1959, Richard Feynman, the Nobel Laureate in physics, delivered the famous lecture, “There’s Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics” (Feynman 1992). In this lecture, he postulated that the manufacturing would develop toward making smaller and smaller objects, and it would be possible to directly manipulate individual atoms. Feynman offered a prize of $1000 in the lecture for the first person to construct a motor smaller than 1/64 in (0.4 mm). This speech opened a door toward the Nano-technology.

The subject of MEMS was obviously not created by the direct demand from mechanical engineering. It has, instead, more to do with the development of IC technologies.

Charles Smith, an American researcher, first found the piezoresistive effect of silicon and germanium in 1954 (SCME 2008). In 1961, the first integrated silicon piezoresistive sensor was developed by an American company, the Kulite. During the period of 1964–1968, Harvey Nathanson constructed the first batch fabricated MEMS device, in which a metal cantilever gate electrode was contained (SCME 2008; PFP 2003). To the 1970s and 1980s, many MEMS devices, including accelerometers, pressure sensors using silicon diaphragm and blood pressure monitors, were successfully produced. The early devices, however, were most sensors due to the relatively simpler structure and motion. In 1988, the first rotary electrostatic side drive motor, as shown in Figs. 13.18 and 13.19, was made at UC Berkley. The rotor diameter in this motor was only 60–120 μm, turning the Feynman challenge posted 29 years ago into a reality and causing great sensation in the world. In 1987, the word, MEMS, was formally adopted first in the U.S.

Fifteen scientists from some top U.S. universities submitted a proposal to the U. S. government for research of micropower systems. In this proposal micro-machine was set as a prioritized area of research. MEMS then became a hot research topic all around the world.

Fig. 13.18 The electro-static micromotor, Berkeley, 1987 (engineering.dartmouth.edu)

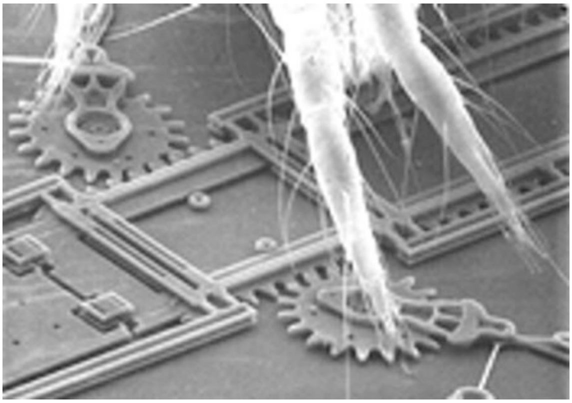


Fig. 13.19 The micro mechanism at the foot of an insect (PFP 2003)

13.7.2 Application Prospect of MEMS

The creation of a subject may not necessarily be directly related to application. However, further development is almost impossible without the driving of application (SCME 2008). The U. S. National Science Foundation (NSF) listed 25 potential areas of MEMS application in a report; these included medical diagnosis, surgery, communication, industry, space and military etc.

In 1991, ADI, an American company, successfully developed the first MEMS accelerometer and used it as an airbag actuator. This achievement symbolized the commercialization of MEMS.

MEMS can be made as sensors or actuators installed in automotive safety systems, engines and power systems, fault diagnosis and operation monitor systems etc. Compared with the traditional mechanical counterparts, MEMS devices are much cheaper and have better performance. For example, MEMS accelerometers reduced the cost of an automotive airbag from $180 to $5.

Application in medical and biological fields includes cell manipulation, micro-surgery, and ultrasonic imaging etc. In the aerospace area, inertial navigation, micro power generation and devices in harsh environment are representative. In addition, MEMS is also applied in making micro internal combustion engines, micro motors, as well as micro batteries etc. In military, great potential also exists; examples include micro airplanes, and Nano satellites.

The market value of MEMS all over the world in 2004 was only 12 billion dollars. To the year of 2009, it was increased to 25 billion dollars (Meng and Zhang 2008). As a new technology, although MEMS has not widely applied yet, great potential has taken shape. It is expected that MEMS will bring revolutionary change to the world.

13.7.3 Theoretical Researches on MEMS

MEMS, as a multidisciplinary subject, is built around two main cornerstones, mechanical and micro electronic engineering, with involvement of solid mechanics, optics, pneumatic dynamics, fluid dynamics, thermal dynamics, acoustics, material science and bionics etc.

MEMS was first advanced in manufacturing. Early in the late 1980s, IC technology was directly used in making micro actuators. Research on design and theory, however, came later.

The MEMS differs from macro machines in many ways. In the first place, surface forces dominate in MEMS due to the micro size. Many other effects, such as optical, acoustic, magnetic and thermal etc. become significant also because of the micro size. This is called the micro-scale phenomena. In addition coupling between micro and macro scale parts, and between different physical media generally exist in MEMS (Zhang 2012).

All these differences call for systematic theoretical research on MEMS, which is still in the infancy stage.

Design of MEMS is still in the level of individual devices, and generally only statics and mechanism kinematics are considered.

Study on dynamics of MEMS already started as well. However, some unique challenges are encountered in the dynamics of micro-systems. These challenges can be classified into three broad categories: nonlinearity, physical field coupling and micro scale phenomena. Newton mechanics is applicable to only systems in macro scale, (characteristic length $>1\ \mu\text{m}$). If the characteristic length lies in 10 nm–1 μm, Brownian motion has to be considered. For systems in atom and molecule scale, quantum statistical mechanics has to be used. Progress has been made in modeling and simulation of MEMS; some of which contain nonlinear dynamics modules.

Now research on MEMS is very active all over the world. Some monographs have been published and dozens of scientific journals have been launched. However, there is still a long way to go in MEMS theory, simulation, design and dynamics etc.

13.8 Fluid Transmission and Control

The first hydraulic press in the world made in 1795 marked the start of utilization of fluid power. The real development of hydraulic power, however, did not happen until the establishment of the hydraulic component industry around the early 20th century. In 1927, hydraulic power was used in milling machines for the first time, symbolizing the era of semi-automation in the machine tool industry. The control of hydraulic systems started almost simultaneously. Since then, PID control, negative feedback control, control of flow rate and pressure as well of system stability were all established (see Sect. 7.5).

The theoretical breakthrough in hydraulic power and relevant control technologies took place after the WWII (Yang et al. 2003). Great progress has been made in both theory and technological development thereafter.

The war time needs during WWII accelerated the development of high precision hydraulic components and control systems, among which the Electro-hydraulic servo system was typical. After the War, the technology was soon spread to many civil applications, including machine tools, construction machinery, agriculture machinery, automotive, ships, space exploration and nuclear power etc. At the same time, product standardization, serialization and generalization quickly advanced.

During the period between the late 1960s and the early 1970s, proportional control technology, which stands in between the fixed value control and the servo control, was developed very fast (Yang et al. 2003).

During the 1960s and 1970s, various forms of components, such as plate mounted and modular, were developed. Standardized control units and modular integrated units appeared later. To the 1980s, the technology of hydraulic power transmission approached maturity in both theory and technology.

The 20th century saw great progress in control theory, laying the foundation for developing control technologies of hydraulic systems.

Permanent magnet torque motors and electro-hydraulic servo valves with pilot nozzle flappers were successfully developed in the 1950s, making electro-hydraulic servo systems the then most quickly responsive and accurate. RWTH Aachen University in Germany and MIT in the U.S made outstanding contribution in developing electro-hydraulic servo mechanisms. The application was found first in airplanes, then in cannons and machine tools (Lu 2001).

After the 1990s, new progress was made in hydraulic technologies, in which the most representatives are as below:

(1) Combination of hydraulic and electronic technologies made it possible to integrate mechanical, electronic and hydraulic components into one unit (component or system).
(2) Due to the inherent nonlinear, low damping and time-varying features, it is hard to model hydraulic systems accurately; thus, classical PID control is not satisfactory in hydraulic systems. Alternative control technologies, including adaptive control, robust control, and intelligent control, were developed as alternative solutions (Wang and Zhang 2003).
(3) Other progresses include analysis and simulation of the flow field in hydraulic systems with FE, application of CAD in hydraulic system design, and fault diagnosis of hydraulic systems.

In addition, the application of hydraulic technology was expanded to a much wider range, including machine tools, robots, automatic machining and assembly lines, rolling equipment, injection molding equipment, construction machinery, agricultural machinery, coal mining machines, drilling systems, aerospace systems, and ships. It is worth mention that the hydraulic system in a tunnel boring machine represents one of the most important applications.

Pneumatic power transmission started much later than hydraulic transmissions. Fast development came during the 1960s. It was mainly used as the auxiliary system in heavy duty applications. With the help of electronic technologies, pneumatic technologies quickly penetrated into applications in wide areas. Pneumatic control was also upgraded to closed loop, proportional and servo technologies from the traditional switch technology (Wang 2001).

13.9 Contemporary Evolution of Discipline of Mechanical Engineering

In the Sect. 7.8, we stated that there are 4 paths in the evolution of mechanical engineering subjects, namely subject parturition, subject advancing, subject extension and subject intercrossing. During the first two Industrial Revolutions, parturition and advancing were the main forms. To the 3rd Industrial Revolution, however, the subject developed mainly through advancing, extension and intercrossing.

13.9.1 Subject Advancing

The progress in nonlinear programing created the theory of optimum design, which has the potential to greatly improve design quality. Adoption of physical and chemical knowledge formed some nontraditional machining technologies. Also advance in solid mechanics, such as fatigue theory and fracture mechanics, always improve the level of strength calculation of mechanical components.

Advance in relevant technological fields can also push the mechanical engineering forward. For example, application of creatology and bionics in mechanical design formed the mechanical creative design and bionic design. In particular, advance in computer technology formed the computer graphics, which constitutes the foundation of CAD and CAM and fundamentally changed the overall picture of mechanical design and manufacturing. The internet technology is creating a new manufacturing concept, distributed manufacturing.

13.9.2 Subject Intercrossing

With the merging of multiple subjects, new branches may come into birth on the border. This is called subject intercrossing.

Different from the subject advancing in which the object of research does not change, subject intercrossing creates new subjects. For example, adoption of computer in mechanical design formed CAD. Due to the object under research is still machine, CAD is regarded as the advancing of mechanical design. Examples of subject intercrossing include robotics, MEMS as well as mechatronics,

Leonardo da Vinci, C. Coulomb, and O. Reynolds are the pioneers in theory of friction, wear and lubrication, respectively. However, their works were independent of each other, and not rigorous because each involves unjustified assumptions. Some scholars have proposed to combine these theories to solve the wear problems since the 1930s. On the other hand, wear became an outstanding problem in many machines after WWII. Tribology was created then in combination of the three originally separated fields.

With the fast development of electronic technology, many mechatronic products were created after WWII. Mechatronics, as a subject, involves mechanical engineering, electronic technology, control technology, computer science as well as sensing technology.

Robots are also mechatronic products in essence. However, robotics is treated as a separated subject differing from mechatronics for the following reason. In robotics, there are very rich and intensive mechanical content. For example, robot mechanisms are an important, active part in the study of MMS. Robotic dynamics is an important branch of machine dynamics as well.

MEMS, on the other hand, were built around two pillars, namely MMS and microelectronics. Besides, contents are also included from the subjects like, solid mechanics, optics, fluid dynamics, thermal dynamics, acoustics, magnetics, material science, as well as bionics. The creation of MEMS was closely linked with integrated circuit which was invented in 1958. In the following year, Richard Feynman, the Nobel laureate, made the famous prediction in a talk that manufacturing would get to the level of atom-by-atom assembly.

13.9.3 Subject Extension

The subject extension takes mainly two forms.

The first form is the extension of the objects under research. Machine dynamics is a typical case of this form. Research on the dynamics of mechanical systems and rotors already existed before WWII. After the WWII, however, many new branches, such as machine tool dynamics, vehicle dynamics, robot dynamics, and mechanism dynamics etc., appeared. The two driving forces behind this extension include (1) machine's operation speed was in continuous increase, (2) new systems, such as flexible rotors and robots, were developed.

The three branches in the contemporary mechanical engineering, mechanical design, manufacturing, and MMS, have been developed for a long time; each has very rich content and is interacted with the others.

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Chapter 14
Development of Other Manufacturing Processes

> *What are the most brilliant of our chemical discoveries compared with the invention of fire and the metals?*
> —Benjamin Disraeli (English Prime Minister and novelist, 1804–1881)

In the machine building industry, many other manufacturing processes produce the rough shapes of the parts which are generally made to the net shape through machining. These processes include casting, forging, welding, extrusion, spinning as well as power metallurgy. In order to improve the properties of mechanical parts, heat treatment operations are needed often.

In some countries, casting, metal forming and welding are placed under the umbrella of material science. However, they all are closely linked to mechanical engineering.

In this chapter, a brief historical development of these manufacturing processes is discussed.

14.1 Development of Casting Technology

Casting was first used around 4000 BC for making ornaments, arrowheads, and various other objects. Technically casting has been developed in parallel with metal smelting (Wu 1984).

The earliest casting method appeared in history was sand casting. Sand casting has several outstanding advantages, including (1) sand is cheap and readily available; (2) molds are easy to make; and (3) sand casting is suitable for almost any production quantities ranging from low to mass production. Due to these advantages, sand casting is still in wide application today, accounting for 60–70% of total casting of the world in terms of tonnage.

Lost wax casting was used in south Israel, Egypt and China very early in ancient times. Metal mold casting was also found in ancient China.

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In ancient times, metal casting existed as a craft. The development of casting technology in ancient times is given in Sect. 14.2.3.

14.1.1 Casting Technology During Industrial Revolutions

After the 1st Industrial Revolution, steam engines, textile machinery and railway vehicles underwent fast growth, putting forward high demand on castings. Correspondingly many foundries were established to serve the industry.

During the 19th century, casting production grew dramatically in quantity; however, quality did not catch up at the same time. In 1879, the Tay Bridge in Scotland suddenly collapsed when a train carrying seventy-five passengers and crew was crossing the bridge. All the passengers and the crew members were killed in this accident. Among the many possible reasons for this tragedy, the quality of the support columns was questioned. It was later found that the cast columns were excessively porous and the imperfections were simply filled with lead or resin.

This disaster caused a crisis of confidence on castings, inspiring the casting production to be transformed from traditional shops relying on craftsman to modern foundry. Measurement and control of parameters of casting process, such as temperature and mold material etc., developed into scientific track. Casting grew into a technique from craft (Beeley 2001).

Casting went into fast track after entering the 20th century mainly due to two factors. On one hand, the development of machine science put forward higher requirements on the mechanical properties and machinability of castings. On the other hand, new technologies and theories, of measurement and inspection in particular, provided technological support to the control of casting process and improvement of casting quality. For example, electron microscopes made it possible to examine the microstructure of the casting metals; theory of metal solidification provided guideline to casting practice.

Several casting technologies appeared during the 19th and the first half of 20th century.

14.1.1.1 Centrifugal Casting

Demand for water pipes had existed already before the 1st Industrial Revolution. In China, casting was used to make water pipes early in the 14th century (Ming Dynasty). Germany and France also started production of casting metal pipes in the 15th and 17th century, respectively. Centrifugal casting, in fact, was initially developed mainly for the purpose of manufacturing water pipes. The first recorded patent on centrifugal casting was granted in 1809. However, the real industrial production did not appear until 1919 when Dimitri de Lavaud, an American engineer of Brazilian origin, invented the watering cooling pipe casting machine. His invention then was widely used for casting of iron pipes, making the centrifugal

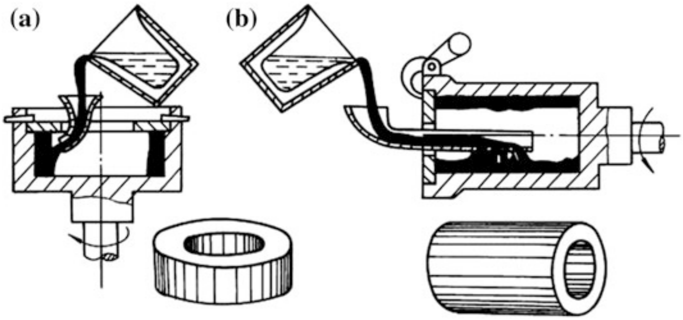

Fig. 14.1 Centrifugal casting. **a** Vertical, **b** horizontal

casting the second most commonly used casting method next only to sand casting (Zhang 2004). Now, it is still widely used in casting many other types of hollow parts, such as bushings in internal combustion engines, as shown in Fig. 14.1.

Centrifugal casting has a series of advantages as below: (1) gating systems and risers are not needed; (2) high output; (3) castings have a higher density and a finer grained structure with less porosity, and (4) two materials can be cast by introducing a second material during the process. Due to these features, it is suitable for making hollow, cylindrical, and thin-walled parts, such as pipes, bushings, and flywheel etc.

14.1.1.2 Investment Casting

The modern investment casting was formed during the 1940s on the basis of earlier development (DeGarmo et al. 2003). The main driving force for this development came from airplane manufacturing. Engine blocks, blades, rotors and jet engine nozzles shown in Fig. 14.2 are some of the parts typically manufactured with investment casting. These parts generally have complicated shapes and very high requirement on dimension accuracy.

14.1.1.3 Metal Mold Casting

Metal mold casting dates back to the Warring States Period in China. However, the modern permanent mold casting technology was not rooted in the old Chinese technology. Rather, it was developed in the first half of the 20th century. Compared with sand casting, permanent mold castings have better mechanical properties, closer dimension tolerance, better surface finish and lower consumption of liquid metals. In addition, the casting process is easy to be mechanized and automated; thus, high production rates can be achieved (DeGarmo et al. 2003).

Fig. 14.2 Parts made with investment casting

14.1.2 Casting Technology in New Technological Revolution

14.1.2.1 Evaporative-Pattern Casting (EPC)

In 1956, the first patent for an evaporative-pattern casting process was filed by Harold Shroyer. He patented the use of foam patterns embedded in traditional green sand for metal casting. The pattern is evaporated upon contact with the molten metal to form the cavity for the casting. West Germany introduced the patents from the United States, and first applied the EPC process in industry.

After the 1980s, EPC became widely used all over the world. The casting process has a series of advantages, including high dimensional accuracy, good surface finish, complicated shapes can be cast without using cores or drafts (Huang et al. 2004).

14.1.2.2 Shell Mold Casting

In shell mold casting, the mold is a hard, thin shell formed with a mix of sand and thermosetting resin binder. It was first developed by Johannes Croning, a German inventor, in 1944. A complete report on this method was made public in 1947 (DeGarmo et al. 2003). With his continuous developments on not only shell casting, but also machines, volume production with shell molds bounded with synthetic resin became possible after 1950 and widely accepted in Germany, the U. S. and the UK.

Shell casting can produce many castings of various alloys with close dimensional tolerances and good surface finish. Very little rework is needed to achieve the required shape of the components. It is especially suitable for volume casting of small to medium size, complicated shape and thin-walled parts requiring high precision.

14.1.2.3 Mechanization and Automation

From the 1930s, machines were used for mold and core making in some industrialized countries. To the 1940s, hydraulic molding machines were developed. The 1950s saw the development of automated and semi-automated production lines of molding. Production lines of high-pressure mold making were widely adopted in the industrialized countries in the 1960s. As a result, productivity of casting was greatly improved along with a dramatic increase of casting output and an improvement in casting quality (Lin and Fan 1991). During the 1970s, vacuum molding was developed.

In casting production, mechanization, automation and intelligence (computer control and robots) have been widely accepted. For important castings, non-destructive testing (NDT) and molten metal filtering have been used to improve the tensile strength and ductility of the casting materials. In mass production of small items, computer controlled green sand mold making machines as well as molding production lines are common. Automated pressure casting and lost foam casting are successfully used in the production of aluminum engine blocks and cylinder heads. In addition, CAD/CAM and RPM are widely used in process planning and die machining.

14.2 Development of Metal Forming

Metal forming contains a large group of manufacturing processes, including forging, rolling, stamping, extrusion and drawing etc. In these processes, plastic deformation is used to change the shape or mechanical properties of metal workpieces.

14.2.1 Forging

Forging is one of the oldest metalworking operations, dating back to about 5000 BC, much earlier than smelting technology.

In 1842, James Nasmyth, a Scottish engineer, invented the steam hammer, opening a new era for the forging operation. In 1861, John Haswell, a Scottish engineer, patented and introduced the hydraulic press into shops of Imperial and Royal State Railway at Vienna. However, the press was used for stamping, not forging (Lange and Mayer-Norkemper 1977). In 1884, hydraulic presses were introduced to the Sir Joseph Whitworth and Co. in Manchester for forging. Due to

Fig. 14.3 Forging manipulator (www.tradekorea.com)

the much lower vibration and noise level, many types of hydraulic presses were developed during the period between 1887 and 1888. Steam hammers larger than 5 t in capacity were gradually displaced by hydraulic presses.

After the mid of 20th century, a series of technological upgrades have been made to forging operation with hydraulic presses. Computer control technology, for example, was embedded into forging machines and process. Manipulators were also adopted into forging production as shown in Fig. 14.3. These new technologies have greatly improved the dimension accuracy of the forged parts and productivity, and lowered the requirement of labor intensity. The open die forging process was fundamentally changed with the automation and other technologies.

With the advent of high pressure, high flow rate oil pumps, high capacity hydraulic presses with oil media became the main stream forging equipment. In 1996, a hydraulic press made in Germany for open die operation reached 10,000 t in capacity. A closed-die press specially designed for forging airplane components in China in 2012 has an unimaginable capacity of 80,000 t (Fig. 14.4). This machine is 42 m in height and 22,000 t in weight. Currently only a few countries in the world, such as the U.S., Russia, France and China, have the capacity to develop these huge machines (China Aviation News 2014).

Impression die forging was initially conducted by hand in shops, and gradually evolved into a forging operation widely used in the industry around 1870. The main driving forces behind the development came from the automobile and aeroplane industries. Impression die forging has several advantages, among which the following two are especially attractive to the auto-industry and the aero-industry. (1) it is conservation of metal and has favorable grain orientation, thus higher strength/weight ratio (compared with machining); (2) it is a near-net-shape or net shape operation, requiring very little, or not at all, machining (Fig. 14.5).

Nowadays parts made through impression die forging become larger, heavier and with more intricate shapes. At the same time, the dimensional tolerance becomes tighter. To meet these requirements, impression die forging is developing toward a net shape operation. On the equipment side, presses are more common

Fig. 14.4 Large die forging machine made in China

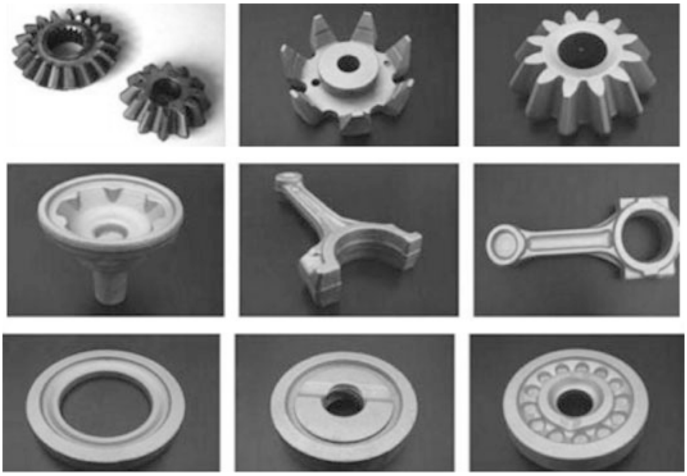

Fig. 14.5 Die forging (www.dropforging.net)

than hammers because of the lower vibration and noise level (Lange and Mayer-Norkemper 1977).

14.2.2 Rolling

The conceptual origin of rolling is traced back to Leonardo da Vinci who made the sketch on his notebook of a hand rolling mills in 1480 for rolling soft metals like gold and silver. In 1565, hand driven rolling of lead into the profile of H was accomplished in Germany (五弓勇雄 1978).

Modern rolling technology, however, is attributed to Henry Cort, an English engineer. In 1783, a patent was granted to him for the use of grooved rolls for rolling iron bars. A mill with his design was able to produce at least 15 times the output with a tilt hammer (Roberts 1978). Although his invention was contested at a later date on the ground that he was not the first to the grooved roll concept, he was still credited as “the father of modern rolling”.

The earliest rolling mills were all operated by hand. The first water driven mill appeared in England in 1590, followed by the first steam driven mill constructed also in England in 1698. The upgrade of driving power provided much larger rolling force, which was critical for the fast growth of rolling thereafter.

Hot rolling of various profiles, such as flats and rails did not come until the beginning of the 19th century. In 1848, the universal mill was invented in Germany. Also in Germany, Reinhard Mannesmann invented the process to produce seamless tubes through rolling in 1885 and obtained the patent the next year. This was known throughout the world as the “Mannesmann process” (Wessel 2000).

Rolling operation is mainly for the production of various profiles, such as tubes, bars, plates, structural beams and rails etc.

14.2.3 Pressworking

Modern pressworking technology has been developed upon the demand mainly from the auto-industry and motor industry (Fig. 14.6).

The input materials in pressworking are sheet metals of either hot or cold rolling. It is estimated that about 60–70% of the total consumption of steels in the world is in the form of thin sheet of metals. The final products of pressworking are called stampings. Typical stampings include auto-body parts, chassis, beverage cans, panels of home appliances, kitchen utensils, and many other industrial and consumer products (五弓勇雄 1978).

Almost every factor in pressworking, including materials, equipment, process and stamping dies, is closely tied with the automotive industry (Cui 2003). In the several main auto-making countries of the world, such as Germany, the U.S., Japan and China, at least 40% of dies are made for the auto-industry. While in an

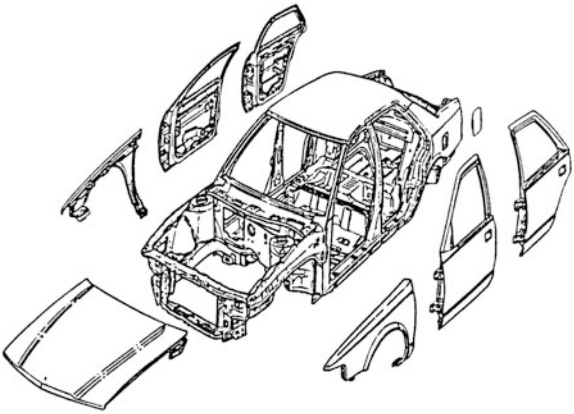

Fig. 14.6 Car white bodywork (Cui 2003)

automotive vehicle, about 60–70% of the parts are manufactured through pressworking. To make a typical family car, about 1500 dies or moulds are needed.

A progressive die performs multiple operations on a sheet metal coil at multiple stations with each press stroke (Fig. 14.7). The coil is fed from one station to the next and different operations, such as punching, bending, and blanking, are performed at each station. When the part leaves the final station it has completed and cut off from the remaining coil. A progressive die has very high production rate, and automation is easy to be implemented (Kalpakjian and Schmid 2013).

Dies for pressworking are expensive and require high manufacturing accuracy. Thus, pressworking is only justified by very high production volume.

For the auto-industry, there is a need for improving crash safety and fuel efficiency all the time. One solution to these challenges is to make the auto-body lighter with high strength materials. However, stamping operation of high strength steels at room temperature has several challenges, such as quick die wear and stamping springback. Thus, hot stamping becomes a natural choice, which combines the martensitic hardening of high strength steels and the better plastic

Fig. 14.7 Forming process of workpiece in progressive die (http://www.gestiondecompras.com)

formability at high temperature. Some other benefits of hot working include lower requirement on the press power, higher formability and avoidance of springback.

14.2.4 Extrusion

Extrusion is a compression process in which the work metal is forced through a die opening to produce a desired cross-sectional shape (Fig. 14.8). In extrusion the work material is under compression in all three directions. In extrusion, large deformation takes place without fracture.

Due to the friction between the material and the container, extrusion generally requires huge forces to make the material flow through the die opening. The first extrusion process in history was patented by Joseph Bramah in 1797 for making pipes from soft metals (Backus et al. Backus 1998). In his invention, the material was first preheated, and then forced out of the die using a hand-driven plunger. He was also the inventor of hydraulic presses which were used to extrude lead pipes in 1820.

After 1910, extrusion of aluminum was developed for the airplane manufacturing need. Due to the high strength of the aluminum used in airplane, the power capacity required in extrusion became very large (五弓勇雄 1978).

Extrusion of steels appeared in 1930. However, wide application did not start until 1941 when glass lubricant was invented.

Typical products of extrusion include various pipes, wires, structural shapes, turbine blades as well as some engine parts.

After the 1980s, demand from the sectors of construction, transportation, electricity and electronics has risen dramatically, not only in quantity, but also in quality. Requirement for higher extrusion accuracy and more complicated shapes became common. To meet the higher demand, some innovative extrusion

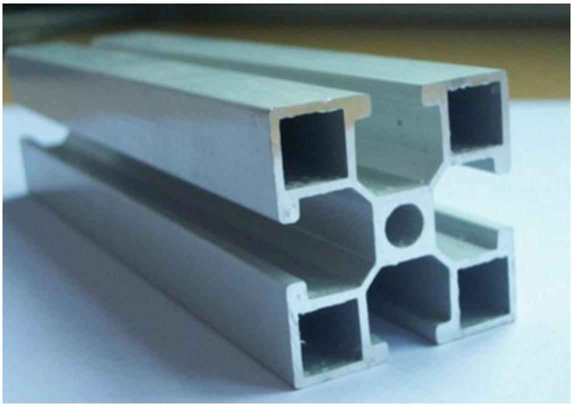

Fig. 14.8 Aluminum extrusion (molding http://www.firstratemold.com)

processes, including high speed extrusion, hydrostatic extrusion, semi-solid extrusion and continuous extrusion etc., were invented (Wen 2003).

14.2.5 Cold Forging

Forging may be conducted at room temperature (cold forging) or at elevated temperature (warm or hot forging), depending on if the temperature is below or above the recrystallization temperature. Materials of cold forging include aluminum and its alloys, copper and its alloys, low and medium carbon steels, as well as some low alloy steels. These materials generally have good ductility and less resistance to deformation at room temperature. Cold forged parts generally have better surface finish and dimensional accuracy, as well as better strength.

Cold forging was first developed in Germany in 1938 for making artillery shells and other items for war purpose. After the War, some American firms noticed the idea in 1945, and soon realized the potential to use cold forging in making cost effective consumer goods. To the early 1950s, it had been already adopted by several large car and truck makers in the manufacturing of brakes and spark plugs; this greatly pushed the development of this manufacturing process (五弓勇雄 1978).

14.2.6 Spinning

Spinning is a metal-forming process in which an axially symmetric part is gradually shaped over a mandrel or form by means of a rounded tool or roller (Fig. 14.9). The tool or roller applies a very localized pressure (almost a point contact) to deform the work by axial and radial motions over the surface of the part (Groover 2007).

Fig. 14.9 Spinning process and products (https://www.thomasnet.com)

There are basically three types of spinning operations, namely conventional spinning, shear spinning, and tube spinning.

The earliest record of spinning operation in China dates back to the 10th century (see Sect. 14.2.3).

Advantages of spinning process include lower tooling cost and being able to make complicated parts. While lower productivity, high labor intensity and requiring considerable work skills are among the downsides of this operation. Thus, spinning is generally used in low quantity production.

During the 1950s, power spinning was developed mainly for the aerospace and military industry. It is reported that power spinning has the capacity of manufacturing cylindrical parts as large as 4 m in diameter.

In addition to wide applications in manufacturing of airplanes, rockets, missiles, satellites, and other military objects, spinning has also been employed in many civilian manufacturing sectors, such as chemical, metallurgical, mechanical, and electrical engineering (Wang et al. 1986).

14.3 Development of Welding Technology

Welding is used to permanently join two or more parts into an assembled entity. It is widely used in mechanical, civil and naval engineering. It is estimated that about 45% of the total steel output in the world is used in welded structures or parts.

The origin of welding technology could be traced back to the forging welding first used by the Egyptians around 3000 BC.

The modern welding technology, however, was not established until the 1800s, later than the modern forging and casting technologies (Cary and Helzer 2004).

14.3.1 Welding Technologies in 19th Century

The science for modern welding technologies was created during the 1st Industrial Revolution. In 1801, Humphry Davy, a Britain chemist, discovered the short pulsed electric arcs, electric sparks. Vasily Petrov (Василий Петров), a Russian physicist, discovered the continuous electric arcs in 1802, and published a report in the following year on potential practical applications, including welding (Anders 2003). This laid the foundation for arc welding.

Edmund Davy, also a chemist in Britain, discovered the acetylene gas in 1836, laying the foundation of oxyacetylene welding (Roscoe and Schorlemmer 1833). In 1841, James Joule, also a scientist from Britain, developed the Joule's first law, establishing the relationship between the heat generated and the resistance. This was the scientific base for later resistance welding (Joule 1841).

Most welding technologies, however, were not developed until the 2nd Industrial Revolution. Among the many welding technologies, arc welding, oxyacetylene welding and resistance welding were the most commonly used before the 20th century.

14.3.1.1 Arc Welding

The electric generator invented after the mid-19th century made it possible to provide sustainable electric power. A. de Meritens, a French electrical engineer, used the heat generated by electric arcs to join lead plates of storage batteries while working at the Cabot Laboratory in 1881. Later N. Benardos (Николай Бенардо́с), a Russian inventor, and another Russian were granted a British patent in 1885 and a U.S. patent in 1887. In the patent carbon electrodes were involved. This was the beginning of carbon arc welding.

In 1890, Charles Coffin at Detroit of the U.S. was awarded the first arc welding patent with metal electrodes. This was the earliest record that metal melted from the electrode worked as filler metal in the joint to make a weld. N. Slavyanov (Никола́й Славя́нов), a Russian, was also independently developed this technology around the same time.

A. P. Strohmenger developed a coated metal electrode in Britain between 1909 and 1912. In his method, a thin coating of clay or lime covered the weld to provide a more stable arc. Oscar Kjellberg, a Sweden, invented a coated electrode during the period of 1907–1914. In 1905 Russian scientist V. Mitkevich (Владимир Миткевич) proposed the usage of three-phase electric arc for welding. In 1919, alternating current welding was invented by an American, Claude Holslag, but did not become popular for another decade (Cary and Helzer 2004).

14.3.1.2 Oxy-Acetylene Welding

Edmund Davy's discovery in 1836 did not catch much attention until 1860 when Marcellin Berthelot, a French chemist, rediscovered Edmund's work and coined the name "acetylene." In 1895, Henry Le Chatelier, A well-known French chemist, found that combustion of equal quantities of acetylene and oxygen produced a flame far hotter than any gas flame previously known. This was a critical step toward real application in welding. The first oxygen-acetylene welding, however, was developed in 1903. Oxygen-acetylene welding and cutting were later widely used all over the world; Oxygen-acetylene welding, in particular, became one of the most widely used welding process in the industry. However, this dominant position was replaced by arc welding later due to its relatively lower welding speed.

14.3.1.3 Resistance Welding

The first patent on resistance welding was issued to an American, Elihu Thompson, in 1885, about 30 years after Joule's discovery (Hughes 2004).

14.3.2 Welding Technologies in First Half of 20th Century

The welding technologies gained fast development during the first half of the 20th century (Cary and Helzer 2004). The main driving force behind this fact was the dramatic advance in industrialization and mechanical technology during this period, specifically including

(1) Automobiles were invented in 1886, and made in mass production during the early 20th century.
(2) Airplanes were invented in 1903. Metals started to replace wood materials for fuselage construction after 1915.
(3) The ship-building industry, war ships in particular, grew fast. The U.S., Japan and Britain built aircraft carriers during 1912–1934.
(4) The development of chemical and petroleum industries required the construction of pipelines and large containers.
(5) Skyscrapers were built in the U.S. starting from the late 19th century.

All these required not only huge amount, but also high quality, of welding work. In addition, the WWI also greatly pushed the development of welding technologies because the manufacturing of both fighter aircraft and warships was involved heavily with welding. The specific examples for the above stated driving factors are as below

(1) Ford started mass production of automobiles through its Model T around 1912.
(2) In 1920, both the U.S. and Britain launched new ships built through welding.
(3) In 1922, pipe line of 200 mm in diameter and 224 km in length was started to be constructed along the Gulf of Mexico, Texas.
(4) An all metal monoplane with the fuselage structure welded from steel tubing successfully crossed the Atlantic in 1927.
(5) The construction of the Empire State Building was completed in 1931. This was a huge steel structure having very high requirement on both quantity and quality of welding.

To the time of WWII, the manufacturing of planes, warships, tanks as well as various heavy weapons put up an even higher demand on quantity and quality of welding work. In 1943, atomic hydrogen welding, submerged arc welding, and gas metal arc welding were applied to make components in airplane propellers.

Several welding processes were developed during the first half of the 20th century; these include gas shielded welding, submerge-arc welding, atomic hydrogen welding, bead welding, ultrasonic welding, explosion welding and stud welding.

During the 1920s, gas shielded welding started to catch attention due to the fact that it could protect the weld from oxygen and nitrogen in the air. Gas tungsten arc welding became a mature technology in 1941 after developments in about two decades. Gas metal arc welding was developed in 1948 initially for welding non-ferrous materials, but soon expanded application to welding of steels.

Fig. 14.10 Underwater welding (http://underwaterweldingschools.org)

Compared with other welding processes, gas metal arc welding had faster welding speed; however, the shielding gas was pretty costly then. After the 1950s, coated electrodes became available, making it one of the most commonly used welding process.

During the 1920s, automated welding was achieved with continuous feed of the coil. In 1932, underwater welding was first implemented in the Soviet Union (Fig. 14.10).

14.3.3 Welding Technologies in Third Technological Revolution

During the Third Technological Revolution, the progress continued in welding technologies with some new processes invented (Meng 2017).

In 1950, F. Buhorn, a German, discovered the plasma. In 1955, a company in the U.S., Union Carbide's Linde Division, first applied plasma in cutting.

In arc welding, an external shield of inert gas was used initially to prevent the arc and the pool of molten metal from picking up oxygen from the air. Later, covered electrodes in which the metal electrode was covered with fluxing agent was developed in the early 1950s. A variation of this development was the flux cord welding rod, also called inside-outside electrode, which had the fluxing agents on the inside of the rod. These developments to the arc welding played a big role in improving welding quality.

The development of continuous and automated electrode feeding mechanism in 1957, on the other hand, made the main contribution to the improvement of productivity.

Some other notable developments during this period included the high frequency induction welding in 1955, friction welding in 1956, electroslag welding in 1958 as well as the gas arc welding in 1961.

Laser was discovered in 1960. Shortly after the discovery, laser beam welding was invented in Japan in 1967, and since then has gained wide application in industry.

In 1962, the electron beam welding process was firstly applied in the manufacturing of the B-70 bomber and supersonic aircraft.

In 1993, digital welding systems were developed.

Some iconic achievements and representative applications of welding technologies during this period are summarized as below:

(1) The Apollo 10 in the United States Apollo space program launched in 1969 involved significant part of welding work.
(2) In 1967, the first welded submarine pipeline was constructed in the Gulf of Mexico, the U.S.
(3) In 1983, the external tank, the largest and heaviest component of the space shuttle, was manufactured through welding.
(4) In 1969, the Soviet cosmonaut conducted the first welding experiment in space.
(5) Since 1988, robotic welding has been widely applied in automotive manufacturing industry.
(6) Around the 1990, the invertor technology became available, greatly reducing the weight and size of welding equipment.

14.4 Development of Other Blank Forming Method

14.4.1 Explosive Forming

The origin of explosive forming is traced back to the explosive test conducted by Daniel Adamson, an English engineer, in 1878 for the assessment of the resistance of various steel plates to impulse load. In 1888, Charles Munroe, an American chemist, used it tested engraving on steel plate with guncotton (Kennedy 1990).

Industrial applications of explosive forming started around the 1950s (Fig. 14.11).

Driven by the two World Wars, great progresses were made in theory, technologies and effects of explosion, which provided strong support to the development of explosive forming process.

On the other hand, the arms race between the two blocs during the Cold War created some new technologies and technology-intensive industrial sectors, such as nuclear power and aerospace. In these systems, there were some components which had irregular and complicated shapes, and very high requirement on manufacturing precision. Consequently, they could not be manufactured through traditional

Fig. 14.11 Prototype part of an Airbus fuselage, created by explosive forming (www.sciencecodex.com)

machining at that time. The United States made effort to form sheet metal components with explosive forming during the WWII. This technology spread to many industries during the 1950s. To the 1960s and 1970s, both the United States and the Soviet Union conducted intensive research on this new forming technology (Stzohecker et al. 1964; ANON 1984; White 2003).

14.4.2 Powder Metallurgy

Power metallurgy comprises a family of production technologies making materials or components from metal powder through pressing and sintering (DeGarmo et al. 2003).

Modern powder metallurgy first appeared in the United States in 1910. During the 1920s, cemented carbide machining tools were first made in Germany. The U.S. made self-lubricating bearings through powder metallurgy during the 1940s. Japan and the U.S. manufactured parts of aluminum alloy and tungsten alloy in 1964 and 1970 respectively. A wide range of parts and components can be made through powder metallurgy techniques, such as gears, cams, machining tools, and moulds, brake pads, connecting rods etc. (Fig. 14.12). The automotive industry now constitutes the largest market of powder metallurgy components.

14.4.3 Shaping of Plastics

Plastics can be shaped into a wide range of products. There are more than 30 specific processes commonly used in the industry. The plastic shaping technologies have developed mainly through the following three stages (Sun and Zhang 2012).

Fig. 14.12 Powder metallurgic products (http://www.ydgear.com)

Celluloid, the first thermoplastic, was first registered in 1870. The first fully synthetic thermoset was developed in the early 20th century. At that time no specialized shaping and forming equipment was developed yet. Shaping technologies of plastics were primarily directly borrowed from metal casting, rubber extrusion, and glass blowing. Correspondingly the productivity was pretty low, and only parts of simple shapes could be produced.

During the period between 1920 and the mid-1950s, more plastics were developed, and plastic shaping became an important industrial sector manufacturing a wide variety of products. In response to this fast growing industry, study on theory of plastic shaping started. Development of dedicated technologies advanced. The first screw type extruding machine dedicated for shaping plastics was designed in 1936. This was a landmark in plastic shaping technology marking the successful implementation of continuous extrusion of thermoplastics with screws.

During this period, dozens of plastic shaping processes were developed, including most of the shaping technologies currently in use, such as injection molding, extrusion, compression molding and blow molding. Fully mechanized production lines of plastics shaping appeared also during this period.

After the mid-1950s, a series of new plastics with some super properties appeared. At the same time, requirements on performance and accuracy of plastic products became higher, especially in the fields of high-technologies. The dimension of plastic products was pushed further to the two extremes, very large and very small. Examples of very large items include containers larger than 5000 L, car and ship body panels heavier than 100 kg, and larger than 2 m in size, and films wider than 30 m etc. Very small plastic components include micro gears and bearings weighing in mgs and films with thickness in micrometers. The wide adoption of computers makes the plastic shaping develop toward continuous, automation and programmable.

14.5 Heat Treatment

Some heat treatment operations of metals already existed in Antiquity; however, skills then were only kept by the blacksmiths as secret.

The invention of microscopes in the late Middle Ages gave a great impetus to the development of heat treatment (Tylecote 1992; Aitchison 1960).

During the 1860s, mass production of steel was achieved and the consumption dramatically increased. As a result, metallurgy and heat treatment were established as scientific subjects.

In 1876, Josiah Gibbs, an American scientist, created the phase equilibrium theory in thermodynamics, laying the foundation of later study on phase changes.

In 1890, Floris Osmond, a French scientist, observed and names the three phases in the iron and steel structures, namely the α-Fe (ferrite), γ-Fe (austenite) and β-Fe, leading to the establishment of the allotropic theory. However, his theory did not catch consensus acceptance until the x-ray diffraction was used in the study of alloy structure.

In 1896, William Roberts-Austen, a British metallurgist, published the first Fe-C phase diagram, which was a landmark in the history of metallography. In honor of his contribution to metallography, the austenite γ-Fe was named after him.

Although some heat treatment practices, such as annealing and quenching, already applied in ancient times, the mechanism of hardening was not understood until the late 19th century.

Adolf Martens, a German metallurgist, published his first paper on microscopical characterization of iron in 1878. Following this, he published a series of other important papers in several years, which focused on the technique of polishing and etching sections of iron-based materials with a diluted acid, and comparison of the observed structures. In honor of his outstanding contribution to the metallography subject, the martensite, a non-equilibrium phase in steel, was named after him.

After the 20th century, two important new driving forces appeared, which are: (1) the development of physical metallurgy, and (2) the appearance of various alloy steels with special properties.

Gas carburizing was introduced around the beginning of the 20th century, and followed by the nitriding in the 1920s. To the 1960s, Plasma nitriding and carburizing were developed. Later surface hardening methods based on laser and electron beam, as well as heat treatment operations based on chemistry were also developed.

Gears, those used in an automotive transmission in particular, are subjected to very complicated dynamic loads, including frequent impact. Thus, good surface hardness as well as favorable core microstructure are required. A systematic gear heat treatment operation, including carburizing, quenching and tempering, was formed and approached maturity during the 1930s. This operation is among the most intricate and complicated heat treatment processes. In almost the same time, materials for making gears also advanced; special alloy steels which better fit the gear hear treatment operation was successfully developed (Rakhit 2000).

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Appendix: People in This Book

Name	Birth and death year	Nationality	Chapters
Adamson, Daniel	1820–1890	English	14
Adolphus, Gustavus	1594–1632	Swedish	3
Ajtay, Z.		Hungarian	5
Al-Jazari, Ismail	1136–1206	Kurdish	2, 3
Altshuller, G.	1926–1998	Soviet-Russian	11
Amontons, Guillaume	1663–1705	French	3
Ampère, André-Marie	1775–1836	French	7
Andrade, Edward N. da C.	1887–1971	English	7
Angeles, Jorge		Canadian	11
Appold, John George	1800–1865	English	4
Archimedes of Syracuse	287 BC–212 BC	Greek	2
Aristotle	384 BC–322 BC	Greek	2
Arkwright, Richard	1732–1792	English	2, 3, 4
Armstrong, William G.	1810–1900	English	4, 7
Arnold, V.	1937–2010	Soviet-Russian	9
Aronhold, Siegfried	1819–1884	German	7
Artobolevsky, Ivan I.	1905–1977	Soviet	7, 13
Asimov, Isaac	1920–1992	American	10
Assur, L.	1878–1920	Russian	7
Babbage, Charles	1791–1871	English	4
Babbitt, Isaac	1799–1862	American	7
Bacquerel, Henri	1852–1908	French	9
Bailey, Richard William	1885–1957	British	7
Balamuth, Lewis		American	12
Ball, Robert S.	1840–1913	Irish	7

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(continued)

Name	Birth and death year	Nationality	Chapters
Banu Musa brothers	in 9th century	Persian	2
Barber, John	1734–1801	English	5
Bardeen, John	1908–1991	American	9
Basov, N.	1922–2001	Soviet-Russian	9, 12
Bassal, Ibn	fl. 1038–1075	Spanish	2
Bell, Henry	1767–1830	Scottish	4
Benardos, Nikolay N.	1842–1905	Ukrainian-Russian	14
Benz, Karl F.	1844–1929	German	5, 7, 8
Bernoulli, Daniel	1700–1782	Swiss	6
Bernoulli, Johann	1667–1748	Swiss	3, 6
Bernoulli, Jacob	1655–1705	Swiss	3, 6
Bertalanffy, Ludwig von	1901–1972	Austrian	9
Berthelot, Pierre Eugène Marcellin	1827–1907	French	14
Bessemer, Henry	1813–1898	English	5
Bi Sheng	990–1051	Chinese	2
Black, Harold Stephen	1898–1983	American	7
Blake, Eli Whitney	1795–1886	American	4, 5
Blanther, Joseph E.		Austrian	12
Bobillier, Étienne	1798–1840	French	7
Bostock, Francis John	1881–1943	English	7
Boulding, Kenneth E.	1910–1993	American	12
Boulton, Matthew	1728–1809	English	4
Bourdon, François	1797–1865	French	4
Boyle, Robert William	1627–1691	Anglo-Irish	4
Bramah, Joseph	1748–1814	English	4, 7, 8, 14
Branca, Giovanni	1571–1645	Italian	5
Braun, Wernher von	1912–1977	German-American	9
Brown, Joseph R.	1810–1876	American	4, 5
Brunel, Marc I.	1769–1849	French-English	4
Brunel, Isambard Kingdom	1806–1859	English	4
Bruno, Giordano	1548–1600	Italian	3
Buck, John		American	5
Buckingham, Earle	1887–1978	American	7
Buhorn, F.		German	14
Burmester, Ludwig	1840–1927	German	7
Bushnell, David	1740–1824	American	4
Camus, Charles-Étienne-Louis	1699–1768	French	3
Carlson, Chester	1906–1968	American	5

(continued)

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Name	Birth and death year	Nationality	Chapters
Carnot, Nicolas L. S.	1796–1832	French	4, 5
Cartwright, Edmund	1743–1823	English	4
Cauchy, Augustin-Louis	1789–1857	French	6
Cayley, Arthur	1821–1895	English	6
Chasles, M.	1793–1880	French	7
Chatelier, Henry Louis Le	1850–1936	French	14
Chebyshev, P.	1821–1894	Russian	6, 7
Clausius, Rudolf J. E.	1822–1888	German	4
Clavel, Reymond	1950–	Swiss	10
Clough, Ray William	1920–2016	American	9
Cocquilhat, H.		French	7
Coffin, Charles L.		American	14
Colt, Samuel	1814–1862	American	4
Columbus, Christopher	1473–1543	Italian	3
Cone, Samuel I.	1865–1949	American	7
Constantinesco, George	1881–1965	Romanian	7
Copernicus, Nicolaus	1473–1543	Polish	1, 3
Cormack, Allan M.	1924–1998	South African-American	10
Cort, Henry	1740–1800	English	14
Coulomb, Charles–Augustin de	1736–1806	French	3, 6
Crandall, Stephen H.	1920–2013	American	9
Crompton, Samuel	1753–1827	English	4
Croning, Johannes	1886–1957	German	14
Crossley, F. R. Erskine	1915–	American	13
Curie, Pierre	1859–1906	French	9
Curie, Marie Skłodowska	1867–1934	Polish-French	9
Curtis, Charles Gordon	1860–1953	American	5
D'alembert, Jean	1717–1783	French	3, 6
Daguerre, Louis-Jacques-Mandé	1787–1851	French	4
Dahlquist, Germund	1925–2005	Swedish	9
Dai Jiansheng (Dai, J. S.)	1954–	Chinese	13
Daimler, Gottlieb W.	1834–1900	German	5, 7
Darby I, Abraham	1678–1717	English	3
Davy, Edmund	1785–1857	English	14
Davy, Sir Humphry	1778–1829	English	14
Den Hartog, J. P.	1901–1989	Dutch-American	7
Descartes, René	1596–1650	French	3
Devol, George Jr.	1912–2011	American	10

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Name	Birth and death year	Nationality	Chapters
Dickinson, John	1782–1869	English	4
Dickson, William Kennedy-Laurie	1860–1935	American	5
Diesel, Rudolf	1858–1913	German	5
Dobrovolsky, W.	1880–1956	Russian-Soviet	7
Dolivo–Dobrovolsky, Mikhail	1862–1919	Polish-Russian	5
Dondi, Giovanni de'	1330–1388	Italian	3
Doorne, Hubert Jozef van	1900–1979	American	13
Drais, Karl von	1785–1851	German	5
Drebbel, Cornelius J.	1572–1633	Dutch-British	4
Du, Shi	?–31	Chinese	2
Dudley, Darle W.		American	13
Duffy, Joseph		American	13
Duhamel, Jean-Marie-Constant	1797–1872	French	6
Dulebohn, David H.		American	12
Dunlop, John B.	1840–1921	Scottish	5
Edison, Thomas A.	1847–1931	American	5
Eichenlaub, Jesse B.		American	11
Einstein, Albert	1879–1955	German(Jewish)-American	3, 8, 9
Eratosthenes of Cyrene	276 BC–194 BC	Greek	2
Erdman, Arthur G.		American	13
Euler, Leonhard	1707–1783	Swiss	3, 6, 7
Evans, Oliver	1755–1819	American	4
Faraday, Michael	1791–1867	English	1, 5
Fellows, Edwin R.	1865–1945	American	5
Feng, Kang	1920–1993	Chinese	9
Ferguson, Harry	1884–1960	Irish	5
Fermat, Pierre de	1601–1665	French	6
Fermi, Enrica	1901–1954	Italian-American	8, 9
Feynman, Richard P.	1918–1988	American	13
Fischer, Friedrich	1849–1899	German	7
Fischer, Otto	1861–1916	German	7
Fitch, Stephen		American	4
Floquet, Gaston	1847–1920	French	3
Ford, Henry	1863–1947	American	5
Föttinger, Hermann	1877–1945	German	7
Fourier, Joseph	1768–1830	French	3, 9
Francis, James B.	1815–1892	British-American	5
Franke, R.		German	7

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Name	Birth and death year	Nationality	Chapters
Freissler, Anton	1838–1916	Austrian	5
Freudenstein, Ferdinand	1926–2006	German(Jewish)-American	8, 13
Fulton, Robert	1765–1815	American	3, 4
Galilei, Galileo	1564–1642	Italian	2, 3, 6
Gates, Bill	1955–	American	9
Gates, John		American	7
Gates, Philters W.		American	5
Gatling, Richard J.	1818–1903	American	5
Gauss, Johann C. Friedrich	1777–1855	German	6
Gear, Charles William	1935–	American	9
Genichi Taguchi	1924–2012	Japanese	11
Gibbs, Josiah Willard	1839–1903	American	14
Girard, Louis Dominique	1815–1871	French	7
Gleason, William	1836–?	Irish-American	5, 12
Gochman, Chaim	1851–1916	Russian	7
Gordon, James E. H.	1852–1893	English	5
Gordon, William J. J.	1919–2003	American	11
Gough, V. Eric		Romanian	10
Gramme, Zénobe T.	1826–1901	Belgian	5
Grashof, Franz	1826–1893	German	7
Griffith, Alan A.	1893–1963	English	7, 13
Gropius, Walter A. G.	1883–1969	German	11
Grübler, M.		German	7
Guericke, Otto von	1602–1686	German	4
Guilford, Joy P.	1897–1987	American	11
Guillaume, Maxime		French	5
Guo Shoujing	1231–1316	Chinese	2
Gusseff, Wladimir		Soviet	12
Gutenberg, Johannes	1395–1468	German	3, 4
Hachette, Jean N-P	1769–1834	French	7
Hamilton, William R.	1805–1865	English-Irish	6
Hardy, William Bate	1864–1934	English	7, 13
Hargreaves, James	1720–1778	English	4, 5
Harrington, Joseph		American	12
Harrison, James	1816–1893	Scottish-Australian	4
Harrison, John	1693–1776	English	3
Harrison, Thomas		English	5
Hashish, Mohamed	1947–	Egyptian	12

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Name	Birth and death year	Nationality	Chapters
Haswell, John	1812–1897	Scottish	14
Haug, Edward J.		American	9
Heilig, Morton Leonard	1926–1997	American	11
Heisenberg, Werner	1901–1976	German	9
Helmholtz, Hermann von	1821–1894	German	4
Henlein, Peter	1485–1542	German	3
Hermite, Charles	1822–1901	French	9
Hero of Alexandria	10–70	Greek	2, 5
Héroult, Paul	1863–1914	French	5
Hertz, Heinrich R.	1857–1894	German	6, 7
Hill, George W.	1838–1914	American	3
Hoe, Richard M.	1812–1886	American	5
Holland, John Henry	1929–2015	American	11
Holslag, Claude J.	1885–1945	American	14
Holz, Frederick		American	5
Holzer, H.		German	7, 13
Hooke, Robert	1635–1703	English	3, 6, 7
Hounsfield, Godfrey N.	1919–2004	English	10
Howe, Elias	1819–1867	American	4
Hrones, J. A.		American	13
Hu, Haiyan	1956–	Chinese	11
Huang, Daopo	1245–1330	Chinese	2
Huang, Zhen	1936–	Chinese	13
Huber, Maksymilian T.	1872–1950	Polish	6
Hull, Charles W. (Chuck Hull)	1939–	American	12
Humboldt, Wilhelm von	1767–1835	German	7, 8
Hunt, Kenneth H.	1920–2002	English-Australian	10, 13
Huntsman, Benjamin	1704–1776	English	3
Hussey, Obed	1790–1860	American	4
Huygens, Christiaan	1629–1695	Dutch	3, 6
Irwin, George R.	1907–1998	American	13
Jacobi, Moritz Hermann von	1801–1874	Russian-Prussian	5
Jacquard, Joseph M.	1752–1834	French	4
Janney, Reynolds		American	7
Jastrzębowski, Wojciech	1799–1882	Polish	11
Jeffcott, Henry H.	1877–1937	English	7
Joessel		French	7
Johansson, Carl Edvard	1864–1943	Swedish	5
Johnson, Carl		Luxembourger	12

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Name	Birth and death year	Nationality	Chapters
Jost, Peter	1921–2016	English	13
Joule, James Prescott	1818–1889	English	4, 14
Kálmán, Rudolf E.	1930–2016	Hungarian-American	9
Kane, Thomas R.	1924–	American	9
Kaplan, Viktor	1876–1934	Austrian	5
Kármán, Theodore von	1881–1963	Hungarian-American	6, 8
Karnopp, Dean C.		American	11
Kay, John	1704–1779	English	3, 4
Kelvin, William T. (Lord Kelvin)	1824–1907	Scottish-Irish	4
Kemper, Hermann	1892–1977	German	10
Kennedy, Alexander	1847–1928	English	7
Kepler, Johannes	1571–1630	German	3
Kilby, Jack St. Clair	1923–2005	American	9
Kirk, Alexander C.	1830–1892	Scottish	4
Kirkpatrick, S.	1941–	American	11
Kirsch, Gustav	1841–1901	German	6
Kjellberg, Oscar	1870–1931	Swedish	14
Klein, Christian Felix	1849–1925	German	6
Koenig, Friedrich G.	1774–1833	German	4
Kolchin, N. I.	1894–1975	Soviet	7
Kolmogorov, A.	1903–1987	Soviet	6, 9
Krupp, Alfred	1812–1887	German	4
Kutta, Martin W.	1867–1944	German	3
Kutzbach, K.		German	7
Lagrange, Joseph–Louis	1736–1813	French	3, 6, 9
Lanchester, Frederick W.	1868–1946	English	7
Laplace, Pierre-Simon	1749–1827	French	3, 6
Lasche, O.		German	7
Laval, Gustaf P. de	1845–1913	Swedish	5
Lavaud, Dimitri Sensaud de	1882–1947	Brazilian	14
Lawson, Henry John	1852–1925	English	5
Lazalenko, B. R.		Soviet	12
Leeuw, Adolph L. de		American	5
Leibniz, Gottfried W. von	1646–1716	German	3
Lenoir, Jean Joseph Étienne	1822–1900	Belgian	5
Leonardo da Vinci	1452–1519	Italian	3, 4, 7, 14
Lépine, Jean-Antoine	1720–1814	French	3
Levitsky, N		Soviet	13

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Name	Birth and death year	Nationality	Chapters
Lévy, Maurice	1838–1910	French	6
Lewis, W.		American	7
Liang, Lingzan		Chinese	2
Liao, Qizheng	1947–	Chinese	13
Lilienthal, Otto	1848–1896	German	5
Linde, Carl von	1842–1934	German	4
Litvin, Faydor L.	1914–	Soviet-Russian	7
Liu, Xianzhou	1890–1975	Chinese	2, 13
Lobsinger, Hans	fl. 1550	German	2
Lorenz, Friedrich W.	1842–1924	German	7
Lorenz, Edward N.	1917–2008	American	9
Lovelace, Ada	1815–1852	English	4
Lumière, Louis	1864–1948	French	5
Lumière, Auguste	1862–1954	French	5
Lyapunov, A.	1857–1918	Russian	6
Lysholm, Alf J. R.	1893–1973	Swedish	5, 7
Ma, Jun	fl. 220–265	Chinese	2
Magalhães, Fernão de	1480–1521	Portuguese	3
Maiman, Theodore H.	1927–2007	American	12
Mannesmann, Reinhard		German	14
Mariotte, Edme	1620–1684	French	4
Markov, A.	1856–1922	Russian	6
Martens, Adolf K.	1850–1914	German	14
Martin, Pierre–Émile	1824–1915	French	5
Martinson, Henry		Canadian	7
Matsubara		Japanese	12
Mauchly, John W.	1907–1980	American	9
Maudslay, Henry	1771–1831	English	4, 8
Maxim, Hiram S.	1840–1916	American-British	5
Maxwell, James C.	1831–1879	Scottish	5
Maybach, Wilhelm	1846–1929	German	5
McCall, Thomas	1834–1904	Scottish	5
McCormick, Cyrus	1809–1884	Irish-American	4
Meikle, Andrew	1719–1811	Scottish	4
Merchant, M. Eugene	1913–2006	American	7, 12
Meritens, Auguste de	1834–1898	French	14
Merthalov, Nikolai I.	1866–1948	Russian	7
Meschersky, Ywan W.	1859–1935	Russian	7
Metropolis, N.	1915–1999	American	11

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Name	Birth and death year	Nationality	Chapters
Miles, Lawrence D.	1904–1985	American	11
Mill, Henry	1683–1771	English	5
Miner, M. A.		American	7, 13
Minorsky, Nikolas	1885–1970	Russian-American	7
Mises, Richard von	1883–1953	Austrian(Jewish)-American	6, 8
Mitkevich, Vladimir F.	1872–1951	Russian	14
Mitrovanov, S. P.	1915–2003	Soviet-Russian	12
Moissan, Henri	1852–1907	French	5
Monge, Gaspard	1746–1818	French	6, 7, 8
Monier, Joseph	1823–1906	French	5
Morland, Samuel	1625–1695	English	4
Moser, Jürgen Kurt	1928–1999	German	9
Mozzi, Giulio	1730–1813	Italian	7
Munro, Alfred Horner		Canadian	5
Munroe, Charles E.	1849–1938	American	14
Mushet, Robert F.	1811–1891	British	5
Musser, Clarence Walton	1909–1998	American	13
Muybridge, Eadweard	1830–1904	English	5
Nartov, Andrey K.	1693–1756	Russian	4
Nasmyth, James	1808–1890	Scottish	4, 8, 14
Nathanson, Harvey C.	1936–	American	13
Navier, Claude-Louis	1785–1836	French	6
Nayfeh, Ali H.	1933–2017	American	9
Needham, Joseph T. M.	1900–1995	English	2, 3
Neklutin, Constantine N.		American	13
Neumann, John von	1903–1957	Hungarian-American	9
Neumann, Karl Erik		Swedish	10
Newcomen, Thomas	1664–1729	English	3, 4, 7
Newkirk, Bert L.		American	7
Newton, Isaac	1642–1727	English	1, 3, 9
Nielsen, Jens		Denish-American	7
Niemann, Gustav		German	13
Niordson, Frithiof	1922–2009	Denish	11
Norton, Charles H.	1851–1942	American	5
Norton, Wendell P.	1861–1955	American	5
Novikov, Mikhail	1915–1957	Soviet	13
Noyce, Robert N.	1927–1990	American	9
Nyquist, Harry	1889–1976	Swedish-American	7

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Name	Birth and death year	Nationality	Chapters
Ohain, Hans von	1911–1998	German	5
Olivier, Theodore	1793–1853	French	7
Olsen, John		American	12
Opitz, H.		German	12
Oppenheimer, J. Robert	1904–1967	American	9
Ørsted, Hans C.	1777–1851	Denish	5
Osborn, Alex F.	1888–1966	American	11
Osmond, Floris	1849–1912	French	14
Otis, Elisha G.	1811–1861	American	4
Otis, William	1813–1839	American	4
Otto, Nikolaus A.	1832–1891	German	5
Owens, Michael J.	1859–1923	American	5
Palmgren, Arvid	1890–1971	Swedish	7, 13
Papin, Denis	1647–1712	French	3, 4
Parker, Stanley		English	7
Parsons, Charles A.	1854–1931	English	5
Parsons, John T.	1913–2007	American	12
Pascal, Blaise	1623–1662	French	3, 6, 7
Pelton, Lester	1829–1908	American	5
Peter Houldcroft		German	12
Petrov, Vasily V.	1761–1834	Russian	14
Petrov, Nikolai P.	1836–1920	Russian	7, 13
Pfauter, Robert H.	1854–1914	German	5
Plank, Max	1858–1947	German	9
Poincaré, Henri	1854–1912	French	6, 9
Poisson, Siméon D.	1781–1840	French	6
Poncelet, Jean-Victor	1788–1867	French	6
Presbyter, Theophilus	1070–1125	German	2
Priestley, Joseph	1733–1804	English	12
Prohorov, A.	1916–2002	Soviet-Russian	9
Qian Xuesen (Tsien Hsue-Shen)	1911–2009	Chinese	9
Qin Jiushao	1208–1268	Chinese	9
Rabinow, Jacob	1910–1999	American	11
Rankine, William J. M.	1820–1872	English	6, 7
Rateau, C-E Auguste	1863–1930	French	5
Rayleigh, John William	1842–1919	English	6, 7, 9, 11
Redtenbacher, Ferdinand J.	1809–1863	German	8
Reeves, Milton O.	1864–1925	American	7

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Name	Birth and death year	Nationality	Chapters
Renard, Charles	1847–1905	French	5
Renold, Hans	1852–1943	Swiss	7
Rerich, K.		Russian	7
Reuleaux, Franz	1829–1905	German	7, 8
Reynolds, Osborne	1842–1912	Irish-British	6, 7, 13
Riemann, Bernhard	1826–1866	German	6
Ritz, Walther	1878–1909	Swiss	6
Roberson, Robert E.		American	9
Robert, Louis-Nicolas	1761–1828	French	4
Roberts, Richard	1789–1864	English	4, 8
Roberts, Samuel	1827–1913	English	7
Roberts-Austen, William C.	1843–1902	English	14
Rochas, Alphonse E. B. de	1815–1893	French	5
Rogers, William B.	1804–1882	American	8
Röntgen, Wilhelm C.	1845–1923	German	9
Root, Elisha K.	1808–1865	American	4
Rosenhain, W.		English	7
Ross, Douglas T.	1929–2007	American	11, 12
Roth, Bernard	1932–	American	13
Runge, Carl D.	1856–1927	German	3
Saint, Thomas		English	4
Saint-Venant, Barré de	1797–1886	French	6
Salomon, Carl J.		German	5, 12
Sandor, George N.		American	13
Sasson, Steven J.	1950–	American	10
Savary, Felix	1791–1841	French	7
Savery, Thomas	1650–1715	English	3, 4
Schmitt, Otto Herbert	1913–1998	American	11
Schrödinger, Erwin	1887–1961	Austrian	9
Schröter, Karl		German	5
Schubert, A.		German	7
Schwacha, Billie		American	12
Sellers, William	1824–1905	American	4
Shabana, Ahmed A.		American	9
Shannon, Claude E.	1916–2001	American	9
Shaw, Milton C.	1915–2006	American	7
Shi, Hanmin	1939–	Chinese	12
Shi, Zhongci	1933–	Chinese	9
Sholes, Christopher L.	1819–1890	American	5

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Name	Birth and death year	Nationality	Chapters
Shroyer, Harold F.		American	14
Siebel, Erich	1891–1961	German	13
Siemens, Carl Wilhelm	1823–1883	German	5
Siemens, Werner von	1816–1892	German	5
Simon, Herbert A.	1916–2001	American	11
Singer, Isaac M.	1811–1875	American	4
Sivrac, Comte Mede de		French	5
Skwortsowa, N.		Soviet	13
Slavyanov,Nikolay G.	1854–1897	Russian	14
Smith, Charles S.		American	13
Sokolovsky, A.		Soviet	7
Song, Yingxing	1587–1661	Chinese	2
Spencer, Christopher M.	1833–1922	American	5, 7, 12
Sprague, Frank	1857–1934	American	5
Stark, Harold		American	12
Starley, John K.	1854–1901	English	5
Stavrianos, Leften S.	1913–2004	Greek-Canadian	3
Steele, Jack E.	1924–2009	American	11
Steigerwald, Karl-Heinz	1920–	German	12
Stephenson, George	1781–1848	English	4, 7
Stevin, Simon	1548–1620	Flemish	3
Stewart, D.		English	10
Stirling, Robert	1790–1878	Scottish	4
Stokes, George G.	1819–1903	English	6, 7
Stribeck, Richard	1861–1950	German	7, 13
Strohmenger, A. P.		English	14
Su, Song	1020–1101	Chinese	2, 3
Suh, Nam-Pyo	1936–	Korian-American	13
Sutherland, Ivan E.	1938–	American	11, 12
Swift, Herbert Walker	1894–1960	British	7
Tabor, David	1913 –2005	British	13
Taguchi, Genichi	1924–2012	Japanese	11
Taylor, Frederick W.	1856–1915	American	5, 7
Tesar, D.		American	13
Tesla, Nikola	1856–1943	Serbian-American	5
Thimonnier, Barthélemy	1793–1857	French	4
Thoma, Hans		Swiss	7
Thompson, Elihu	1853–1937	American	14
Thomson, Joseph J.	1856–1940	English	9

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Name	Birth and death year	Nationality	Chapters
Thomson, Robert W.	1822–1873	Scottish	5
Timme, Ivan		Russian	7
Timoshenko, Stepan P.	1878–1972	Ukrainian-American	6, 7
Tobias, Stephen A.		German	12
Toffler, Alvin	1928–2016	American	9
Townes, Charles H.	1915–2015	American	9
Trent, Edward Moor	1913–1999	English	7
Tresca, Henri Édouard	1814–1885	French	6, 7
Trevithick, Richard	1771–1833	English	4
Tsiolkovsky, K. E.	1857–1935	Russian-Soviet	7, 9
Tsung-Dao Lee	1926–	American	1
Tuplin, William A.	1902–1975	English	13
Turing, Alan M.	1912–1954	English	9
Vaucanson, Jacques de	1709–1782	French	3, 4, 7
Vickers, Harry F.	1898–1977	American	7
Videky, E.		German	7
Vukobratovic, Miomir	1931–2012	Selbian	13
Walker, Oakley Smith	1857–	American	5
Wang, Huaming	1962–	Chinese	12
Wang, Zhen	1271–1368	Chinese	2
Wankel, John H.	1902–1988	German	10
Watson, H. A.		American	11
Watt, James	1736–1819	Scottish	1, 3, 4, 5, 7, 8
Weierstrass, Karl T. W.	1815–1897	German	6
Wen, Shizhu	1932–	Chinese	13
White, Maunsel		American	5
Whitney, Eli	1765–1825	American	4, 7
Whittle, Frank	1907–1996	English	5
Whitworth, Joseph	1803–1887	English	4, 5, 8, 14
Wiener, Norbert	1894–1964	American	9
Wildhaber, Ernst	1893–1979	American	7, 13
Wilfley, Arthur Redman	1860–1927	American	5
Wilkinson, John	1728–1808	English	4
Williams, Harvey		American	7
Williamson, David T. N.		English	12
Willis, Robert	1800–1875	English	7
Winslow, Willis M.		American	11
Wisnosky, Dennis E.	1943–	American	12

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Name	Birth and death year	Nationality	Chapters
Wittenbauer, Ferdinand	1857–1922	German	7
Wittenburg, Jens		German	9
Wöhler, August	1819–1914	German	6, 7
Wolle, Francis	1817–1893	American	5
Woolf, Arthur	1766–1837	English	4
Wright, Orville	1871–1948	American	5
Wright, Wilbur	1867–1912	American	5
Wu Cheng	1940–	Chinese	12
Wuensch, G.		German	7
Xi, Zhong	in 2100–2100 BC	Chinese	2
Xu, Binshi	1931–	Chinese	12
Yan, Hongsen	1952–	Chinese	11
Yang, Shuzi	1933–	Chinese	12
Yang, Tingli	1940–	Chinese	13
Yershov, A.	1818–1867	Russian	7
Yi Xing (Zhang Sui)	683–727	Chinese	2
Young, Thomas	1773–1829	English	6
Zarghamee, Mehdi S.		Iraian	11
Zeppelin, Ferdinand von	1838–1917	German	5
Zhang, Heng	78–139	Chinese	2
Zhang, Qixian	1925–2002	Chinese	13
Zheng, He	1371–1433	Chinese	2
Zheng, Xuan	127–200	Chinese	6
Zhukovsky, Nikolai Y.	1847–1921	Russian	7
Zhuravsky, D. I.	1821–1891	Russian	6

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