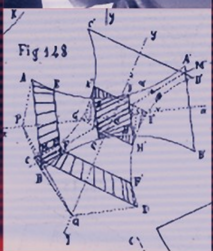
History of Mechanism and Machine Science 7

Marco Ceccarelli
Editor



Distinguished Figures in Mechanism and Machine Science

Their Contributions and Legacies
Part 2

Springer

Distinguished Figures in Mechanism and Machine Science

HISTORY OF MECHANISM AND MACHINE SCIENCE

Volume 7

Series Editor

MARCO CECCARELLI

Aims and Scope of the Series

This book series aims to establish a well defined forum for Monographs and Proceedings on the History of Mechanism and Machine Science (MMS). The series publishes works that give an overview of the historical developments, from the earliest times up to and including the recent past, of MMS in all its technical aspects.

This technical approach is an essential characteristic of the series. By discussing technical details and formulations and even reformulating those in terms of modern formalisms the possibility is created not only to track the historical technical developments but also to use past experiences in technical teaching and research today. In order to do so, the emphasis must be on technical aspects rather than a purely historical focus, although the latter has its place too.

Furthermore, the series will consider the republication of out-of-print older works with English translation and comments.

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Their Contributions and Legacies, Part 2

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Series Preface

This is the second volume of a series of edited books whose aim is to collect contributed papers within a framework that can serve as a collection of persons in MMS (Mechanism and Machine Science). This is a continuation of the first volume that was published in 2008, again combining very ancient and very recent scholars in order to give not only an encyclopaedic character to this project but also to emphasize the significance of MMS over time.

This project has the characteristic that the papers illustrate, by recognizing persons and their scientific work, mainly technical developments in the historical evolution of the fields that today are grouped in MMS. Thus, emphasis is also given to biographical notes describing efforts and experiences of people who have contributed to the technical achievements whose technical survey is the core of each contributed paper. This second volume of the project has been possible thanks to the invited authors who have enthusiastically shared in this initiative and who have spent time and effort in preparing the papers.

The stand-alone papers cover the wide field of the History of Mechanical Engineering with specific focus on MMS. I believe that readers will take advantage of the papers in this book and future ones by supplying further satisfaction and motivation for her or his work (historical or not).

I am grateful to the authors of the articles for their valuable contributions and for preparing their manuscripts on time. Also acknowledged is the professional assistance by the staff of Springer Science + Business Media and especially by Miss Anneke Pot and Miss Nathalie Jacobs, who have enthusiastically supported this project with their help and advice in the preparation of the first and second book.

I am grateful to my wife Brunella, my daughters Elisa and Sofia, and my young son Raffaele. Without their patience and understanding it would not have been possible for me to work on this book and the dictionary project.

Cassino, October 2009 — Marco Ceccarelli (Editor)

Contents

AL-JAZARI (1136–1206)

Lotfi Romdhane and Saïd Zeghloul

Abstract Ismail Al-Jazari, Arab inventor who is remembered for his design of water-raising machines and many unusual clocks and automata. His book entitled: "Book of Knowledge of Ingenious Mechanical Devices" presents a whole range of devices and machines, with a multiplicity of purposes.

From all the presented machines, two are most remarkable: his famous elephant clock, which was by far the most sophisticated clock at that time and his invention of a water pump using a crank-slider-like system, which was the first known machine to use a crank.

Biographical Notes

Al-Jazari is by far the most famous mechanical engineer of the pre-medieval era. His name is

"الشيخ رئيس العمل بديع الزمان أبو العز إبن إسماعيل إبن الرزاز الجزري",

"Al-Shaykh Rais Al-Amal Badii Al-Zaman Abu Al-Izz Ibn Ismail Ibn Al-Razzaz Al-Jazari".

This long name is actually a combination of his title and his real name. The first three titles "Al-Shaykh Rais Al-Amal" indicate that he was a notorious chief engineer, "Badii Al-Zaman" the best of all times, "Abu El-Izz" the well respected, "Ibn Ismail" sun of Ismail (his father), "Ibn Al-Razzaz" his grandfather, and "Al-Jazari"

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Fig. 1 Al-Jazari

indicates that his family came from Al-Jazira, which is the region in northern Syria and Iraq between the two rivers Tigre and Euphrates (Fig. 1).

He lived most of his life away from his homeland in Diyar Bikr in Upper Mesopotamia, which is in present-day southern Turkey. He was in the service of three consecutive Artuqid rulers: Nur al-Din Muhammad ibn Arslan (1174–1185), Qutb al-Din Sukman ibn Muhammad (1185–1200) and Nasir al-Din Mahmud ibn Muhammad (1200–1222). The only known information about his life is that given in his book. He completed writing his book in early 1206 and it took him 7 years to complete it. He recorded that when he started writing his book he had more than 25 years of experience in building machines. Hence, historians concluded that he started his active life in around 1175. Several aspects of his life made him different: the first one is that in the contrary of most scientists (علماء oulama in Arabic) at that era of Islamic civilization, he was interested only in inventing and building machines. Indeed, most of the scientists of that time were pluri-disciplinary, in the sense understood nowadays. Some of the most famous scientists, like Al-Farabi, Ibnou-Sina (Avicenna), Al-Khawarizmi, to name a few, were excelling in several disciplines going from poetry to theology to philosophy to science to medicine. Al-Jazari, however, was a true mechanical engineer and he excelled in his job as a chief engineer in the court of the Artuqid rulers.

His Work

Al-Jazari finished his single contribution in 1206. His book is entitled: الجامع بين العلم والعمل النافع في صناعة الحيل i.e., “Al Jamaa byna al ilm wal amal ennafii fi sinaat al hiyal”, which was translated in several ways (Fig. 2).

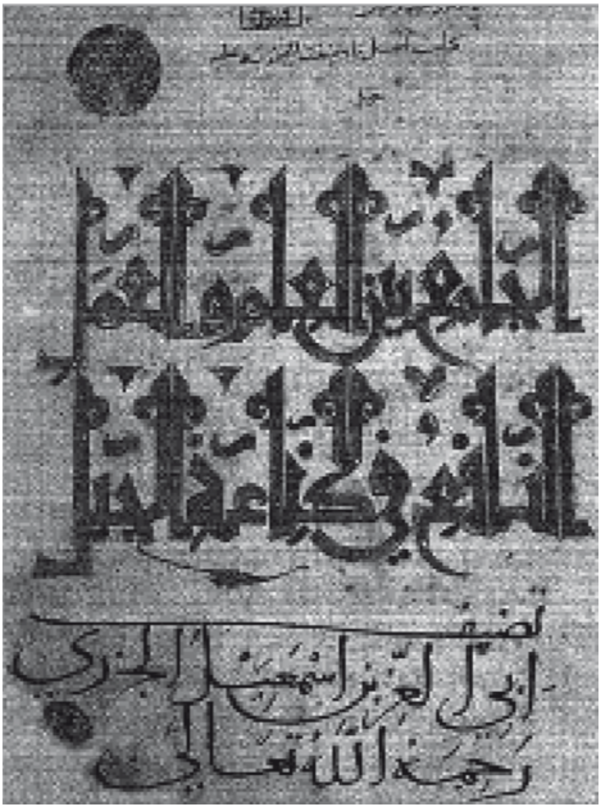

Fig. 2 First page of Al-Jazari's book (The Topkapi Palace Museum, Istanbul, N° A 3472)

The first attempt to translate this book was by Wiedmann and Hawser, who translated parts of it into German in the first quarter of the twentieth century (Hill 1998). The most known translation of this book, however, is by Hill and is entitled "The Book of Knowledge of Ingenious Mechanical Devices" (Hill 1974). Others preferred translating it as "A Compendium on the Theory and Practice of the Mechanical Arts" (Al-Hassan 1976). Some sources refer to the same book simply as "Automata" (Chapius and Droz 1958). All these attempts tried to capture the meaning of this long and very eloquent title. If we analyze the key words of the title we can find the word "ilm علم ", which means science or knowledge in its broadest sense. "amal ennafii العمل النافع" can be translated as the useful work or power, but from the meaning of the whole title, it is probably intended for practice or the practical aspect of design or simply engineering. Al-Jazari tried by allying science and practice to design machines called here "hiyal الحيل", which is the plural of «hyla حيلة » meaning an artifact or a tricky way to get something done.

Al-Jazari's book presents a whole range of devices and machines, with a multiplicity of purposes. What is interesting to note is the considerable degree of engineering skill required to manufacture these devices, and the use of delicate mechanisms and sensitive control systems. In this respect, Al-Jazari can be called a true design engineer more than a scientist. Dimargonas, in his recent book on mechanical design (Dimargonas 2001) said: "…thus, Al-Jazari's work is really a study in systematic machine design!"

Al-Jazari's book is divided in six types (أنواع Anwaa, which is the plural of Nawâ نوع type in Arabic) totaling 50 different devices (أشكال Ashkal, plural for Shakl شكل: : geometric form in Arabic):

- Ten different Clocks
- Ten designs of Automata vessels dispensing wine and water for drinking sessions
- Ten designs of Water dispensers for ritual ablution (oudhou الوضوء in Arabic) and bloodletting devices
- Ten fountains and musical automata
- Five different designs of water raising machines
- Five miscellaneous machines like instruments for measuring spheres and locks

From all the presented machines, two are most remarkable: his famous elephant clock, which wasby far the most sophisticated clock at that time, and his inventions of a water pump using a crank-slider-like system. Even though, only a few of his inventions can be classified as utilitarian machines, Al-Jazari still departed from his predecessors when he presented these inventions. Indeed, despite him living in the court of his ruler, he was also listening to the needs of the people. The fifth chapter of his book presents five different, useful inventions mainly to raise water for irrigation and domestic purposes. This attitude was unusual at that time since most of the scientists (*Oulama* علماء) were at the service of the caliphs and their concern is mostly motivated by responding to the need of these rulers. Moreover, in writing his book, he tried to use simple Arabic and to clarify as much as he can the way his machines work and he even gave precise information on how to build the different parts of these machines. At that time, this way of writing was unusual, since most of the scientists (*Oulama* علماء) were more interested in impressing their peers by writing their books using a sophisticated language hardly understandable by common people, hence limited to the elite.

The rest of his book, but an important part of it, presents another type of engineering that is different from the utilitarian technology described in the fifth chapter. This type of technology is usually called "fine technology", since its distinguishing features derived from the use of delicate mechanisms and controls. Some of these devices had obvious practical uses: water clocks were used in astronomical observations and were also erected in public places. Others gave amusement and aesthetic pleasure to the members of royal circles, which led him to invent the first programmable humanoid robot in 1206. Al-Jazari's robot was a boat with four automatic musicians that floated on a lake to entertain guests at royal drinking parties (Margaret 2006; Franchi and Güzeldere 2005). Some of these devices functioned as curiosities.

Review of his Main Work on Mechanism Design

To show the ingenuity of the proposed designs, we will be mainly interested in water-raising machines, some of which are original and can still be seen in several contemporary machines. By far the most important contribution of Al-Jazari to mechanism design is the crank-slider system and his use in a machine. This first description of a crank-slider mechanism came 300 years before Western Engineers, e.g., Francesco di Giorgio Martini and Leonardo Da Vinci, who used the crank-slider-type mechanism in the fifteenth century (Al-Hassan 1976). Ramelli also used the crank-connecting rod in a pump in his book of 1588 (Teach and Ferguson 1994).

We also present some of his inventions in designing clocks. To show the ingenuity of Al-Jazari who, according to several historians (Ören 2001), laid down the foundation of automatic mechanical control as perceived today.

It is also interesting to note that the degree of precision in the description of his devices allowed people with no background in mechanics, to understand how these machines should work.

Water Raising Machines

Throughout history, the supply of water for domestic and irrigation purposes has always been a vital consideration. Earlier designs can be found since the antiquity. The water-raising technology was of great benefit to the people of that time and it also laid the foundation for the machinery of irrigation and the machine design, in general.

Despite being at the service of the Artuqid rulers, Al-Jazari was sensitive to the needs of the common people and he proposed in his book five different designs of water raising machines. These machines are intended to help people in everyday life and to alleviate some of their burden. Two different machines, which are mostly an improvement of the most ancient water raising machine, called the "Shaduf", are first presented. This type of machine lies on a lever system with a counterweight at one end to help fill a bucket, attached at the other end, and lifting it. This system is still in use nowadays in some Middle Eastern countries.

Al-Jazari suggested the use of a hollow tube as a lever instead of the beam and a scoop at the end instead of a bucket, so when it is raised the water can flow inside it to the irrigation system. This system made raising water easier and faster.

Al-Jazari's third machine was an improvement of the "Saqiya". The classical design of the "*Saqiya*" is an animal-powered mechanism of two perpendicular wooden gears. An animal is harnessed to the vertical axis of the horizontal wheel. The second gear is driving a vertical wheel with clay pots attached to its circumference (pots-wheel). As the vertical pots-wheel rotates, the pots are dipped into the water one by one. As each pot reaches the top, its water pours into a wooden sluice.

The first idea of Al-Jazari is to take advantage of the power of the water, in the form of a flow, and to use it to drive the system. He presents his invention (Fig. 3) where he does not eliminate completely animals from the driving system but rather he designs a complementary system to help the animal. Hence, depending on the flow of the water, the system can be fully autonomous, but if the flow is not enough (during the dry season, for example) the animal can still drive the system. This way of thinking drove most of the Al-Jazari's inventions.

The second idea of Al-Jazari is to use a pots-chain instead of a wheel with pots as it was known at that time (Fig. 3). The chain-like system solution allowed the use of the "Saqiya" in places like wells, where the classical design could not be used due to the limited space. Moreover, the proposed design can be adapted easily for different heights by simply changing the length of the chain.

Therefore, Al-Jazari improved the well-known design of "Saqiya" in two ways: the first one was by adding a water wheel to help driving the system in an autonomous way, and the second one was by replacing the wheel with pots, in the classical design, by a chain-like system containing the pots.

The way this machine was sketched is also very interesting. Al-Jazari tried to make his drawing as clear as possible by trying to show the 3D aspect of the

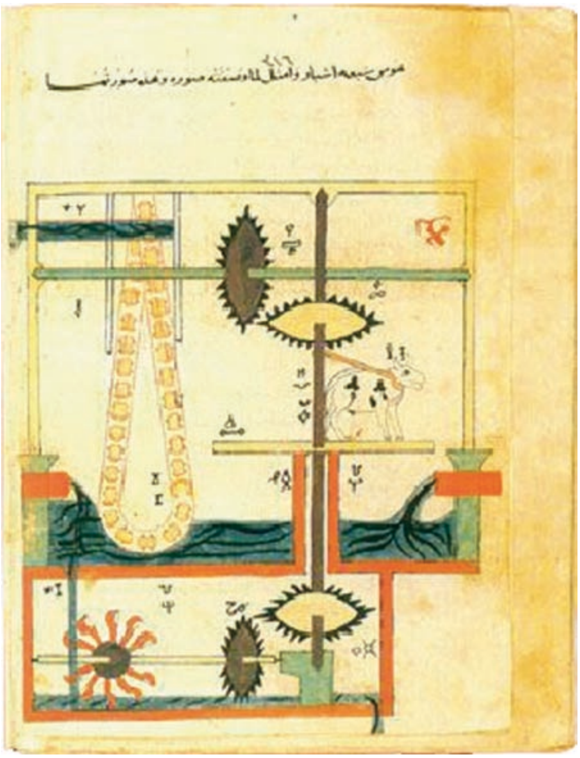

Fig. 3 Al-Jazari's water-powered Saqiya chain device (The Topkapi Palace Museum, Istanbul, N° A 3472)

machine. Indeed, one can notice that the gears, which are circular, are drawn as some sort of ellipses. Depending on the direction of the great axis of the ellipse, one can know the plane containing the gear. For example in Fig. 3 the gears with the vertical axis are drawn with "ellipses" with horizontal great axes and similarly for the horizontal axes gears. Moreover, the chain-like system of pots is represented skewed to show that it is contained in the vertical plane perpendicular to the one of the drawing, but still shows enough details. This representation is, indeed, one first attempt to use projection to represent 3D systems. Al-Jazari also used also letters and some special symbols to help him in the description of the system in very much the same way as in patents today.

The fourth machine used a flume beam (a hollow beam or a tube) and was animal powered. The tube oscillates back and forth thanks to a couple of gears driven by an animal and a crank-slider system. The scoop at the end of the tube is filled with water when it is at its lowest position and when it is raised, the water can flow inside the tube to the irrigation system. The idea of the tube here is very similar to the one used in the first two machines (Shadhuf). This shows how Al-Jazari is using modular designs and then improving on them each time, which attests to his practical sense of optimizing the design process. What is original, however, in this invention is his idea of converting a continuously rotating motion to an oscillating one using an inversion of the crank-slider mechanism. Several historians (Hill 1998; Bertrand 1969) considered this design as the first one to use a crank-slider mechanism in a machine. Indeed, even though the adopted solution is probably not the best, according to our contemporary knowledge, this design opened a whole era for more complex machines going up to the steam engine and the internal combustion engines. The idea of having a pin-in-a-slot type joint will be used again in his fifth invention (Fig. 4).

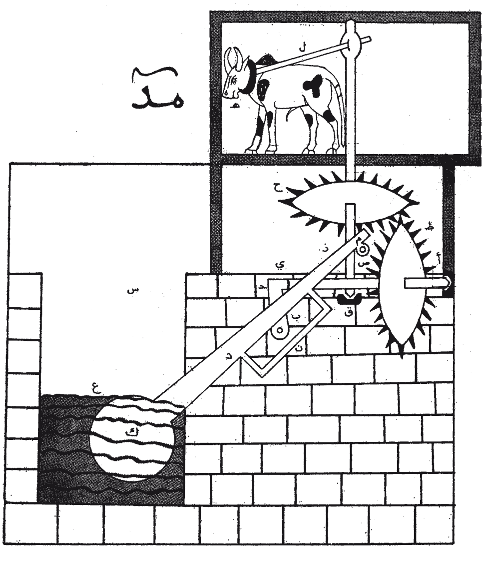

Fig. 4 Fourth water raising machine by Al-Jazari from Al-Jazari's manuscript

The fifth machine, presented by Al-Jazari, took this idea of converting different types of motion further by proposing what we nowadays call a piston pump. The translation motion of the piston is obtained by transforming a continuously rotating motion through a tricky system of gears and links.

This machine, a twin-cylinder, water-driven pump, represents the first attempt to use suction and discharge to lift water to a certain height. Up until that time (twelfth century), all the water-raising machines relied on filling some type of container and lifting it to empty it at the desired height. The machine proposed by Al-Jazari went away from this solution to try to force water through a pipe, which allowed him to lift water to heights never reached before with a relatively small-size machine. This invention contains the most features of relevance for the development of mechanical design, and is very similar to contemporary pumps (Fig. 5).

Three main novelties can be noted in this design. The first one, and probably the most important, is the use of eccentricity to convert the continuously rotating

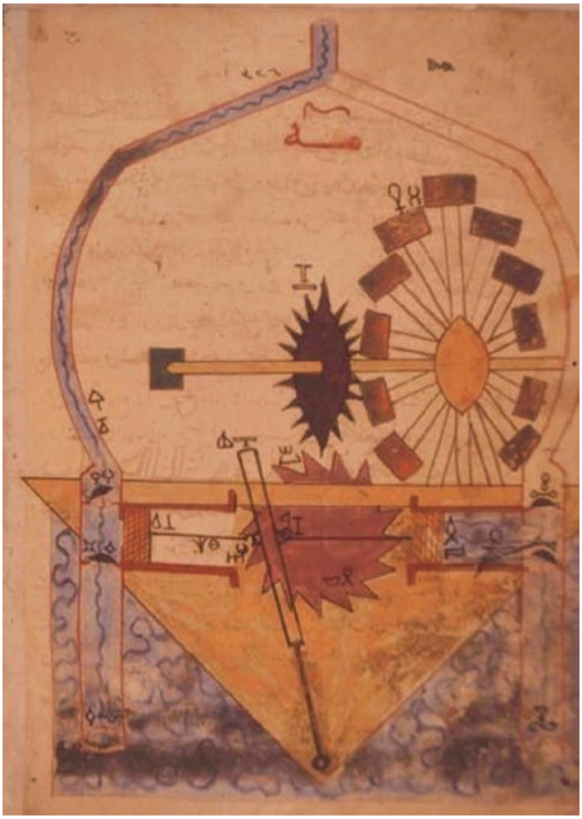

Fig. 5 The reciprocating pump from Al-Jazari's manuscript (Topkapi Palace Museum Library, Ahmet III 3472)

motion to an oscillating motion. Moreover, through a pin-in-slot type joint, Al-Jazari succeeded in getting the necessary reciprocating motion of the pistons.

The second novel aspect in this machine is the use of valves as a means to allow the suction and the discharge process in the reciprocating pump. Several contemporary machines are still using this design in controlling the suction and the discharge phases (steam engine, internal combustion engine, piston pumps…). All the historians agree that this invention was not known before by any of his predecessors.

The last aspect is the use of a large water wheel to make the system completely autonomous. Some historians mentioned that Al-Jazari also used animals to drive this machine, mainly during the drought seasons where the level of the water is low.

Clocks

Al-Jazari also mentioned many amusing, yet practical, devices, including several unusual clocks which were much more elaborate than those developed before. They were sometimes driven by weights. As the weight fell, it encountered resistance from a float riding in a water tank. Others involved a bucket that tipped over when filled with water, hitting a ratchet that moved the clock ahead (Fig. 6).

a

b

Translation: (a vertical pole) located between the two basins is used to sustain the horizontal tube in the middle. On top of the tube at the middle a funnel and the two ends of the tube are opened. At the bottom side of the tube, a small tube emerges from it and extends until it reaches the bucket. Also it gets out of the tube another small tube and it extends until it reaches the bucket. And I represent all in the figure.

Fig. 6 (**a**) Water clock by Al-Jazari (Süleymaniye library, Istanbul, Turkey), (**b**) translation of the text

Water clocks

This water clock uses two tipping buckets that are filled alternatively, making the horizontal tube tip from one side to the other. The flow of water is therefore switching from one tank to the other after a fixed period of time required to fill one bucket. A similar design was proposed by Al-Jazari as a musical instrument. The flow of water in the tank chases the air inside it and forces it to go through a whistle (Nadarajan 2007; Hill 1974).

The interesting idea in this design is the use of the small tubes to fill the two buckets. The oscillation of the tube triggers a system (not represented) to indicate the time at constant intervals. This clock can work as long as the water is flowing.

Candle Clocks

Al-Jazari also describes candle clocks which all worked in a similar manner. Each design specified a large candle with a uniform cross-section and known weight. The candle was installed inside a metal sheath, to which a cap was fitted. The cap had a hole in the centre, around which was an indentation on the upper side. The candle, whose rate of burning was known, had its wick going through the hole. The bottom of the candle rested in a shallow dish that had a ring on its side and was connected through pulleys to a counterweight. As the candle burned away, the weight pushed it upward at a constant speed. The automata are operated from the dish at the bottom of the candle by letting a small sphere drop in a container, which is suspended to the arm of the robot. Under the weight of the ball, the arm of the robot lowers, indicating the hour. The container descends until it hits the floor, which makes it to tip and to let the ball out (Fig. 7).

A second design is presented in Fig. 8, where the scribe sitting on the left is rotating as the candle goes up. A set of pulleys and a cable with a counterweight allows the transmission of the motion between the candle and the scribe. The tip of his pen indicates the hours and the minutes, which are engraved on a circular scale. The set of spheres on the right is made such that one sphere drops from the falcon's beak at the top of each hour.

Weight Clocks

The most famous of Al-Jazari's clocks is his three-meter-high elephant clock. Using weights dropped from its top at regular intervals, an intricate mechanism is triggered.

The clock features a perforated submersible bowl, a device that is at the heart of the clock mechanism. The small orifice in the submersible bowl is carefully

a

b

Translation:
The candle is attached by two strings through two pulleys to a weight. As the candle burns away it gets lighter and it lifts off under the effect of the weight, which lets one small ball to drop in a container suspended by a string to the arm of the robot. Under the weight of the ball, the arm of the robot lowers, indicating the hour. The container tips when it gets in contact with the floor and the ball rolls out of the mouth of the bird.

Fig. 7 (**a**) Candle clock of Al-Jazari (Smithsonian Institute), (**b**) translation of the text

Fig. 8 A candle clock from Al-Jazari's manuscript

calibrated to produce the correct rates of flow. This rate of flow determines the time at which the clock strikes at hourly intervals. As the bowl fills with water, it sinks and a set of pulleys and a cable with a counterweight allows the transmission of the motion to the scribe sitting on the back of the elephant. The tip of his pen indicates the hours and the minutes, which are engraved on a circular scale. When the bowl reaches the bottom, it releases a ball from the castle, which falls onto a channel mechanism that rotates a dial to reveal the time. The ball then travels to the falcon's beak and is then dropped into the mouth of a snake, which then swings due to the weight of the ball and drops the ball into a vase. The motion of the snake pulls on the bowl and empties it. The ball then disappears into the elephant's body and it activates the Mahout sitting on the head of the elephant to strike the cymbals. The snake swings back to his original position due a counterweight. At this time, the bowl is again floating and it starts to sink and the whole process repeats itself as long there are balls on top of the elephant (Fig. 9).

Fig. 9 Elephant clock (NY Metropolitan Museum)

Miscellaneous

Other chapters of Al-Jazari's work describe fountains and musical automata which are of interest mainly because the flow of water in them alternated from one large tank to another at hourly or half-hourly intervals. Several ingenious devices for hydraulic switching were used to achieve this operation (Rosheim 1994). These revolutionary machines owed him the title of the father of robotics (Chapius and Droz 1958; Nocks 2007).

One of Al-Jazari's machines was a boat with four automatic musicians that floated on a lake to entertain guests at royal drinking parties. It had two drummers, a harpist and a flautist (Fig. 10). The heart of the mechanism is a rotating cylindrical beam with pegs (cams) protruding from it. These just bump into little levers that operate the percussion. The point of the model is to demonstrate that the drummer can be made to play different rhythms and different drum patterns if the pegs are moved around (Fig. 11) (Ören 2001). Al-Jazari is also an inspiration for a musical robot live-coding system bearing his name, and his work is acknowledged in several contemporary books on robotics and mechanical design (Ceccarelli 2004; Dimargonas 2001).

Al-Jazari also noted a number of practical joke devices in his manuscript. Some were trick drinking vessels that appeared to contain water but could not be emptied. Others looked empty but produced water when tipped over.

In producing these not-so-useful inventions, Al-Jazari was typical of his age.

Fig. 10 Musical Automata from Al-Jazari's manuscript

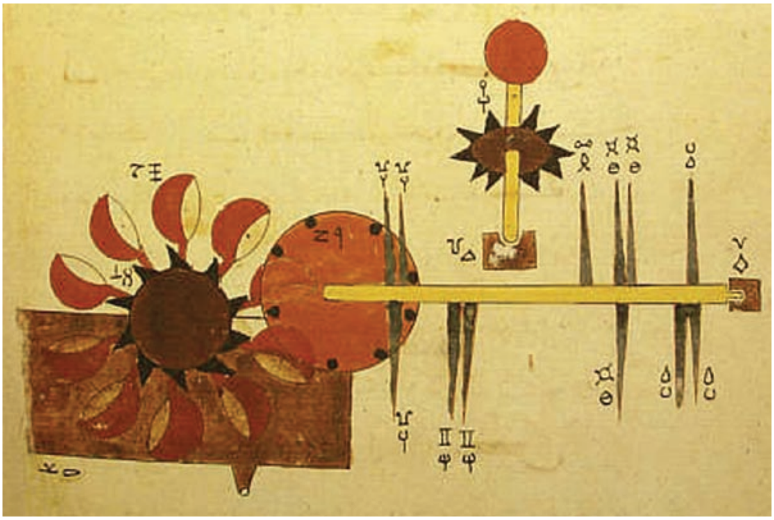

Fig. 11 Cam mechanism from Al-Jazari's manuscript

On the Circulation of his Work

Many copies of this book are conserved in a number of museums worldwide such as Top Kapi in Istanbul, and the Museum of Fine Arts in Boston, the museum of the Louvre in France and Oxford's Bodleian Library (Hill 1998).

British engineer Donald Hill, who has a special interest in Arab technology, writes: "It is impossible to over-emphasize the importance of Al-Jazari's work in the history of engineering; it provides a wealth of instructions for design, manufacture and assembly of machines" (Hill 1974).

About al-Jazari's book, Sarton says that "this treatise is the most elaborate of its kind and may be considered the climax of this line of Moslem achievement" (Sarton 1975).

Al-Jazari's book was translated into English by Hill (1974). It is a complete translation of his work, using mainly MS Graves 27 at the Bodleian Library, Oxford, UK (Hill 1998).

It is worth mentioning that the written Arabic heritage in mechanical technology began with the Banu Musa book, written in the nineth century. Banu Musa described a hundred ingenious devices. They have made contributions to technological refinements and new applications. However, Saliba (2007) compared the work of Al-Jazari and the work of Banu Musa and he concluded: ".... when their works (Banu Musa) are compared to the work of Al-Jazari, we note a remarkable maturity in the latter's work that is nowhere to be found in the works of Banu Musa. With Al-Jazari, we begin to notice discussions regarding the real function of mechanical devices, and real appreciation of their significance as tools that did not only fulfill daily functions for the society but that they were also tools that could demonstrate the way in which the natural physical principles worked" (Saliba 2007).

Many of the ideas employed in the construction of ingenious devices were useful in the later development of mechanical technology and they had a tremendous influence on the history of the mechanical design of machines. His utilitarian inventions were also used in the entire Arab world at that time and spread all the way to Spain. It is believed that the most likely location for the transfer of information between the East and the West was Spain where Muslims and Christians coexisted for eight centuries (Cigola and Gallozzi 2000; Cigola 2006). On the other hand, with the Crusades, the West met the East and the transfer of scientific and technical knowledge from the Eastern world was accentuated.

We can also note that Al-Jazari introduced several individual components like conical valves and locks. Conical valves appeared later in Leonard da Vinci's book (1495) and as a float-controlled regulator for steam boilers in England in 1784 (Mayer 1970).

Al-Jazari developed techniques to build his machines such as casting in closed mold boxes, which reappeared in Europe in 1500 (Smith 1968; Baer 1984).

In his book, Rosheim (2006) mentioned the book of Al-Jazari as one of the sources that might have influenced Leonardo da Vinci in building some of his clocks. This information was also reported in (Needham 1965) in his study on the influence of China and the Medieval Arabic civilization on the West.

Taqi Eddin, in the sixteenth century, also proposed a six-cylinder pump most likely inspired from the pump, which was invented by Al-Jazari 300 years before (Al-Hassan 1976).

Al-Jazari's third water-raising machine allowed lifting water higher by simply increasing the length of the chain and without drastic changes in the whole design. However, with classical designs of the "*Saqiya*", increasing the height requires changing the whole wheel for one having greater diameter, which is a much more difficult task.

One such machine was located on the River Yazid in Damascus (thirteenth century) (Fig. 12) and is thought to have supplied the water needs of a nearby hospital.

Several prototypes of Al-Jazari's machines have been built recently. During the Islam Festival in England in 1976, three of Al-Jazari's machines were shown. The first one was a monumental water clock, which is now exhibited in Asten in the Netherlands. Other prototypes can be seen in Frankfurt, Germany and in Aleppo, Syria. A full-scale prototype can also be seen in a mall in Dubai (Fig. 13) and a very elaborate simulation of the same system can be found on the web (Fig. 14).

In addition to the elaborate explanations and illustrations, Al Jaziri's book has an artistic and a historical value. All illustrations in the book are in color and they have great artistic merit. Historians believe that great artists lived at the court of the Artuqids who helped Al-Jazari in illustrating his book. These illustrations were also used by historians to study the clothing styles of men and women in Diyar Bikr in the thirteenth century (Akurgal and Hilber 1980; Raby 1985; Turner 1996).

Fig. 12 Vestige from a Saqiya in Damascus, Syria http://www.flickr.com/photos/damascene/80436428/

Fig. 13 Al-Jazari's clock at Dubai's Ibn Battuta Mall

Fig. 14 Simulation of the elephant clock (http://communication.ucsd.edu/aaytes/transliteracies/cezeri2.htm)

Modern Interpretation of Main Contributions

His inventions of water-raising machines have been in use since the thirteenth century. Indeed, the idea of having a chain of pots, in building the Saqiya, is still used nowadays in some Middle Eastern countries. Figure 15 shows a recent sketch of a Saqiya and the built system in the south of Egypt. We can notice that the use of two cogwheels with different diameters, as shown in Fig. 15, was not proposed by Al-Jazari.

In all his machines, Al-Jazari uses only cogwheels with identical diameters; hence we can conclude that gears are used in order to transmit movement between perpendicular axes rather than as a speed multiplier.

The fourth raising machine proposed by Al-Jazari (Fig. 4) is the first one made of only rigid bodies. The kinematic diagram of this machine is shown in Fig. 16. The dimensions are chosen as close as possible to the ones proposed in the manuscript. In Fig. 16a, we can see the lowest position of the tube where the bucket is being filled with water, and in Fig. 16b we have the second extreme position of the tube being emptied in the irrigation system. Figure 17 shows a planar kinematic

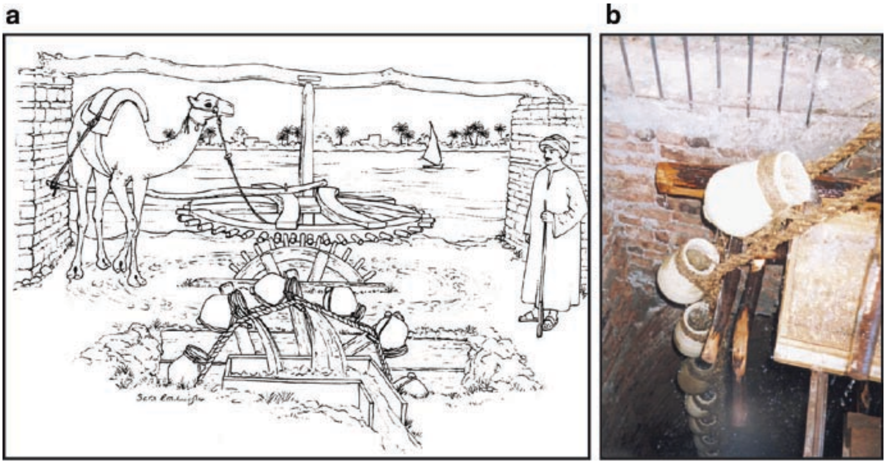

Fig. 15 (**a**) A recent sketch of a Saqiya as proposed by Al-Jazari, built in the south of Egypt, (**b**) the built system (http://www.saqiya-luxor.com/)

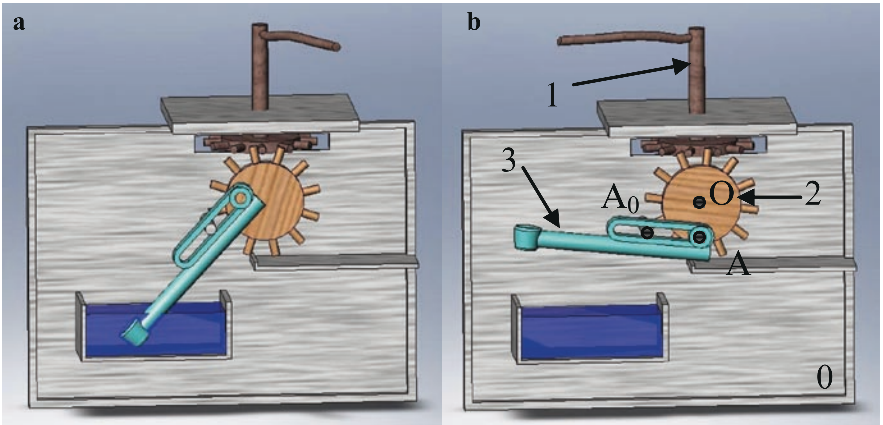

Fig. 16 a 3D CAD model of Al-Jazari's fourt water raising machine. (**a**) Lower position, (**b**) upper position

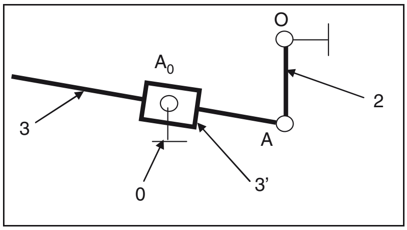

Fig. 17 A planar kinematic diagram of Al-Jazari's water-raising machine

diagram of the proposed machine. The pin-in-a-slot joint was replaced by two lower kinematic pairs. Therefore, the proposed mechanism is an inversion of the well-known crank-slider mechanism. Indeed, most historians agree that this is the first use of a crank-slider system in a machine and is probably the first use of the pin-in-a-slot joint also (Al-Hassan 1976; Teach and Ferguson 1994; Hill 1998; Bertrand 1969).

The drawback of this machine is its limited height to which it can lift water. This limitation inspired Al-Jazari to move away from the classical solution of raising the water and to invent the pumping solution. His fifth machine (Fig. 5) is a twin cylinder pump where the crank and the pin-in-a-slot joint are again used to build this system. Figure 18 shows a 3D CAD model of the system. The planar mechanism made of bodies 0-2-3-4 is the one transforming the continuous rotation into a reciprocating motion of the pistons (4). Figure 19a shows a kinematic diagram of the mechanism when the joint in B is modeled by a hinge joint.

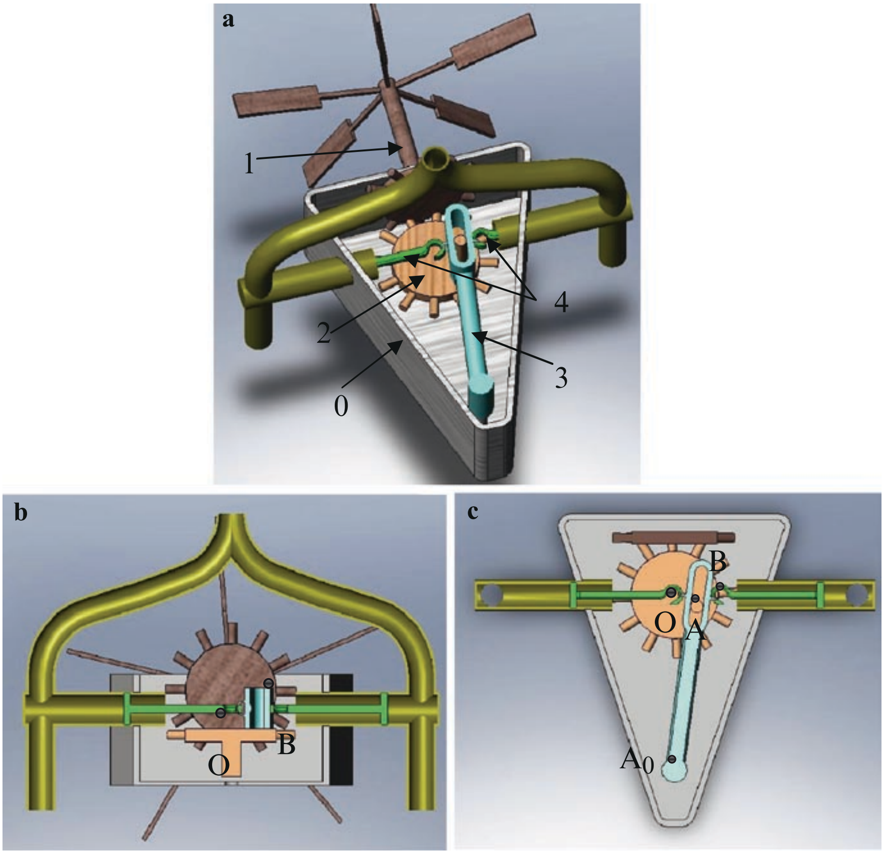

Fig. 18 (**a**) 3D CAD model of Al-Jazari's pump, (**b**) a vertical cut, (**c**) an horizontal cut

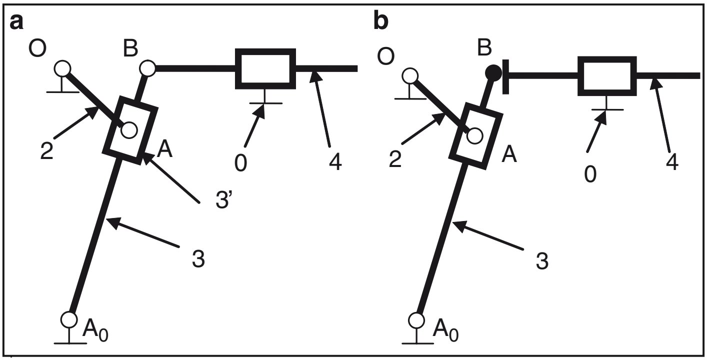

Fig. 19 A planar kinematic diagram of Al-Jazari's pump. (**a**) A hinged solution, (**b**) the adopted solution

One can see that the mobility of the system is 0 and no motion is allowed in this case. Al-Jazari was aware of this problem and proposed a unilateral joint made of a revolute joint but with an exaggerated clearance (Fig. 19). Therefore, this can be modeled by a point contact joint as shown in Fig. 19b. This practical solution allowed the system to work despite the existence of a backlash when inversing the direction of the motion of the pistons. Since the input speed is not important, the behavior of the system was deemed satisfactory by Al-Jazari. Nowadays, this mechanism has a connecting rod to allow the correct functioning.

This type of mechanisms is not far from a design point of view, from mechanisms taught at engineering schools nowadays, and its similarity with the quick-return mechanism is striking.

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Ivan Ivanovich Artobolevski (1905–1977)

Olga V. Egorova and Nikolai V. Umnov

Abstract Ivan Ivanovich Artobolevski devoted his life to the science of machines and to the creation of a theoretical base for the construction of modern and future machines which could improve man's work and release him from tiresome, monotonous and unhealthy operations. He received enormous respect and authority in his Motherland and great recognition abroad as a talented scientist, organizer and also as a statesman.

Biographical Notes

Ivan Ivanovich Artobolevski (Fig. 1) was born in Moscow on October 9, 1905 to the family of a faith teacher of Moscow Imperial Commercial School.

His father, Ivan Alexievich Artobolevski, was elected MA professor of theology at Moscow Agricultural Institute (Timiryazev Agricultural Academy nowadays). Artobolevski's house was always full of scientists and philosophers, and among them the elder friend of his father, the famous historian in Russia – Vasily O. Kluchevsky who, in those days, worked as a professor at Moscow State University named after Michael V. Lomonosov (MGU). The atmosphere of creative work and the relation with well-known natural scientists such as D.N. Prianishnikov, S.A. Zernov and N.A.Kulagin et al. couldn't but influence on the interest of Ivan Ivanovich towards the acquisition of knowledge, the learning of natural science and technology. Artobolevski passed his first examination in 1915 when he went on to

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Fig. 1 Ivan Ivanovich Artobolevski (1905–1977)

the Third Moscow Classical Gymnasium. Later, in 1921, under the influence of the outstanding teacher and professor A.F.Fortunov, who inculcated in his pupil love for mathematics, he went on to the faculty of mechanical engineering at the Timiriazev Agricultural Academy and successfully graduated from it in 1924.

It is interesting that his governess taught the little Ivan French and he advanced so much in his studies that, being a young boy, was able to read French books in their original form. This knowledge was useful to him in the future when he became a well-known scientist.

After the October revolution, in 1918 by reason of the separation of the church from the state and the extinction of the chair of theology, Artobolevski's father was dismissed and, in spite of being an excellent teacher and scientist, he was forced to accept the condition of a parson in a parochial church.

Naturally the family was in poverty and, besides, they had to quit their service apartment. The future scientist had to begin his labour activity combining studies with work as a librarian, a laboratory assistant, a preparer in the chair and a land surveyor's assistant.

The first and the main of I. Artobolevski's teachers were V.P. Goriachkin and N.I. Mertsalov. The founder of the new, for that time, science – "The agricultural mechanics", academician Goriachkin exerted great influence on further scientific activities of Ivan Ivanovich who worked under his leadership as a mechanics laboratory assistant, and obtained a lot of knowledge and experience in the field of the dynamics of machines and experimental investigations. Thanks to his chef, Professor Mertsalov, Artobolevski became interested in the theory of mechanisms, and studied projective geometry and spherical trigonometry.

According to his teachers' advice he attended a complete course at the physicomathematic faculty of Moscow State University.

It's not casual that after having obtained a ponderable stock of fundamental knowledge, even being very young he solved, a number of complicated problems in the field of the theory of flat and space mechanisms of agricultural machines.

Ivan Artobolevski was an excellent teacher. His lectures were always full of the latest information about the achievements in the international science and technology. He skilfully organized the educational process and promoted the introduction of modern methods of teaching. In 1940, he published a textbook for students, postgraduates and teachers of the mechanic- mathematical faculty of MGU, which became the basis of the university course "Theory of Mechanisms and Machines". Artobolevski constantly improved the courses he taught, and his textbooks gained international recognition and were repeatedly republished abroad.

Since he was young he had loved science, and in spite of his enormous lack of time, he always found time for literature, theatre, music and art. As a time cultured and educated person, he was keen on architecture, he collected books on art and painting. He preferred Russian artists and painters.

His acquaintance with one of the greatest intelligencia, A.V. Lunacharski, had influence on the development of young Ivan's artistic taste, because he visited his house and often met many outstanding personalities of literature, music and art there. One of his favourite writers was and continued to be up to his last days, the Russian writer Fedor M.Dostoevski. The scientist's wife, Olga Nikolaevna Artobolevski, being a pianist and singer (Fig. 2) promoted his approach to art personalities.

Fig. 2 Ivan I.Artobolevski and his wife Olga Nikolaevna

The most prominent Soviet and foreign scientists, musicians, artists could be seen with their hospitable family. They were friends with many opera singers and artists of drama theatres, painters, writers and sportsmen. They arranged home concerts with the participation of famous artists in their country house as well as in their apartment in Moscow. The great Russian tenor Ivan S. Kozlovski, being their friend, sang his arias and romances at these parties. It is not causal that the list of Artobolevski's friends mentioned in his autobiography, amazes by the abundance of known and unknown names.

All the colleagues and students noticed his remarkable self-control. Artobolevski never lowered himself to blasphemy, even in the circle of people sharing the same ideas, although sometimes the lack of a basis of the attacks of his detractors who insisted on trying to prove that a man with such origins (from the family of a theologist) he couldn't be a good mathematician, gave reason for this. What is this? Is it a character, an education and good breeding, or a strong part of Christian moral inculcated in his childhood? I think, all together.

One more fact in his biography arouses admiration. He voluntarily joined the army in 1941. Since the beginning of the Second World War all the collaborators of the Institute for Engineering Science (IMASH) had been evacuated to deepest Kazan (Russia), but the correspondent-member of the Academy of Sciences of the USSR Artobolevski, went to the war as a volunteer. Fortunately, he had been there only three weeks because, on the orders of the higher leadership of the country, all scientists, including him, were taken from the front. But the deed itself shows his immense conscience and patriotism, his true love to his Motherland.

In his mortal life, Artobolevski was a very interesting person, he liked classical music, art, read a lot, was fond of sports, played tennis, cultivated flowers and loved animals. He lived an interesting but sometimes uneasy life, especially in his youth because of his social origin. But he continued working and believed that the awful injustices towards him would stop one day. And so it happened.

His multiphase scientific activity was highly appreciated by the Academy of Sciences of the USSR. In 1936 he had a scientific degree of Doctor in engineering science conferred on him; in 1939 he was elected a correspondent-member of the Academy and in 1946, at the age of 40, an academician on mechanics. Due to his great services in the development of national science and social activity, Artobolevski was awarded with the highest title of the Soviet Union – the Hero of Socialist Labour and the highest award – the Lenin Order (during his life he had been awarded this six times!). He achieved a lot and all his achievements received the highest assessment in his Motherland.

The academician also gained enormous recognition abroad. In 1967, the Institute for Mechanical Engineering of Great Britain awarded him James Watt Gold Medal (Fig. 3) – the highest award in the world given to engineers. Earlier this award was conferred on the greatest mechanics and engineers of the world – G.Ford, A.Stodol, and G.Taylor.

Artobolevski dedicated a lot of his efforts and energy to the integrity of the specialists of different countries, who worked in the field of the theory of machines, and to the International Federation on Theory of Machines and Mechanisms

Fig. 3 Ivan I.Artobolevski in London being awarded with the James Watt Gold Medal

(IFToMM), as he understood perfectly well the importance of international contacts for Soviet and world science.

This Federation was founded in 1969 and Ivan I.Artobolevski was unanimously elected its first President. He held the post for two periods and then became its past-president up to his final days. This is the greatest international recognition of a man who had dedicated all his life to chosen science.

As his President, he directed the work of the sessions of general assemblies, the meetings of their execution councils, participated in the work of organizing committees of the international magazine IFToMM, drawing more and more Soviet and foreign specialists into the work of the Federation. It is here where he used the French language which he spoke to perfection.

Artobolevski also carried out much work for the International Organization of Scientific Workers (IOSW) and he was elected its vice-president in 1965. This organization was founded in 1945 by the great French man, Frederick Jolio Curie, who could direct the efforts of scientists towards the struggle for the peace and happiness of all people, against nuclear war and the use of other means of mass destruction. In 1959 Ivan Artobolevski was awarded the Jolio Curie Silver Anniversary, medal by the International Peace Council.

Aacademies of science of many countries elected Artobolevski as a honorary academician and honorary doctor. He was awarded many local and international honours.

Artobolevski's life is a vivid example of the untiring scientific, social and state activity of a scientist who did a lot to promote scientific, technological and engineering programs and the flourishing of mankind. And he achieved everything through his work and talent.

A Brief History of IFToMM

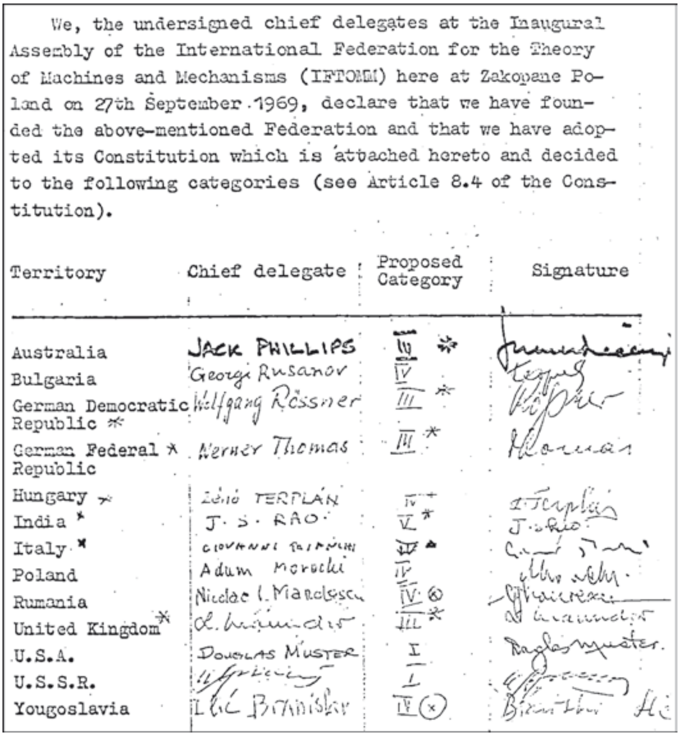
IFToMM was founded as the International Federation on Theory of Machines and Mechanisms in Zakopane, Poland, on September 29, 1969, during the Second World Congress on the Theory of Machines and Mechanisms (TMM) (Fig. 4).

The main promoters of the IFToMM World Federation were Academician Ivan I.Artobolevski (USSR) and Prof. Erskine F.R.Crossley (USA), whose principal aim was to overcome the obstacles of the time of the Cold War by developing international collaboration on TMM science for the benefit of the world.

IFToMM started as a family of TMM scientists among whom we may identify the IFToMM founding fathers who signed or contributed to the foundation act (Fig. 5), with the initial 13 Member Organizations (countries), in the persons of: Academician Ivan I. Artobolevski (USSR), Prof. Erskine F.R. Crossley (USA), Prof. Michael S. Konstantinov (Bulgaria), Dr. Werner Thomas (GFR), Prof. B.M. Belgaumkar (India), Prof. Kenneth H. Hunt (Australia), Prof. J. Oderfeld (Poland), Prof. Jack Phillips (Australia), Prof. George Rusanov (Bulgaria), Prof. Wolfgang Rössner (GDR), Prof. Zènò Terplàn (Hungary), Prof. Jammi S. Rao (India), Prof. Giovanni Bianchi (Italy), Prof. Adam Morecki (Poland), Nicolae I. Manolescu (Rumania), Leonard Maunder (UK), Douglas Muster (USA), Ilic Branisky (Yugoslavia).

The foundation of IFToMM was the result of the intense activity in stimulating and promoting international collaboration, more that never in the past, as started in the late 1950s, as is documented by several letters that are stored in the IFToMM Archive.

Fig. 4 1969 IFToMM Congress (IFToMM Archive)



We, the undersigned chief delegates at the Inaugural Assembly of the International Federation for the Theory of Machines and Mechanisms (IFTOMM) here at Zakopane Poland on 27th September 1969, declare that we have founded the above-mentioned Federation and that we have adopted its Constitution which is attached hereto and decided to the following categories (see Article 8.4 of the Constitution).

Territory	Chief delegate	Proposed Category	Signature
Australia	JACK PHILLIPS	III *	
Bulgaria	Georgi Rusanov	IV	
German Democratic Republic *	Wolfgang Rössner	III *	
German Federal * Republic	Werner Thomas	III *	
Hungary *	Zoltó Terplán	IV *	
India *	J. S. RAO	V *	
Italy *	[illegible]	IV *	
Poland	Adam Morecki	IV	
Rumania	Nicolae I. Manolescu	IV ⊗	
United Kingdom *	[illegible]	III *	
U.S.A.	DOUGLAS MUSTER	I	
U.S.S.R.	[illegible]	I	
Yougoslavia	Ilić Branislav	IV ⊗	

Fig. 5 IFToMM Foundation Act, 1969 (IFToMM Archive)

The first World Congress was held in 1965 in Varna, Bulgaria, during which the foundation of IFToMM was planned and it was later agreed to during the Second World Congress on TMM in Zakopane, Poland. The Congress series was immediately recognized as the IFToMM World Congress and in 2007 there were celebrations of the 12th anniversary with the participation of the 48 Member Organizations.

The IFToMM community has continuously grown over time and the TMM has evolved to large engineering science, including new disciplines. This has brought, in 2000, to the amendment of the name of the IFToMM Federation to the IFToMM International Federation for the Promotion of Mechanism and Machine Science and a change in the name of TMM to MMS (Mechanism and Machine Science), in order to emphasize the modern mission of the IFToMM community.

IFToMM activity has grown in many aspects and nowadays there are 13 Technical Committees, five Permanent Committees, five Journals and one affiliated journal "Mechanism and Machine Theory".

The IFToMM community evolved from a purely family character of a few beginners and founders to a worldwide scientific community through the following generations:

- 1950s–1979 First generation: founding fathers and their friendly colleagues up to the fourth IFToMM World Congress in Newcastle upon Tyne in 1975 with Prof. Maunder as Congress Chair
- 1980–1995 Second Generation: pupils and people educated by the founding fathers and their friendly colleagues; up to the ninth World Congress in Milan in 1995 with Prof. Rovetta as Congress Chair
- 1996–today Third Generation: educated people within the framework of the IFToMM and within IFToMM activity with 48 national organizations as IFToMM members

Knowing the History of IFToMM[1] can also promotea greater awareness of community identity and significance. More information on the IFToMM and its activities can be found on the website: http://www.iftomm.org.

List of Main Works of Ivan Artobolevski

Bibliography includes more than 1,000 published works. The main are:

– "On the Structure of Space Mechanisms" (1935)
– "Theory of Space Mechanisms" (1937)
– "The Experiment of Structural Analysis of Mechanisms" (1939)
– "Fundamentals of Unique Classification of Mechanisms" (1939)
– "Synthesis of Mechanisms" (1944)
– "Acoustic Dynamics of Machines" (1969)
– "Machines of 20th century" (1974)
– "The Mechanisms in Modern Engineering Design" (1970–1975)
– Main Textbooks for institutions of higher education: "Theory of Mechanisms and Machines" (1940), "Theory of Mechanisms" (1940, 1945, 1952, 1953, 1965, 1967, 1975, 1988 editions)

A Review of Main Works by Ivan Artobolevski

The circle of Artobolevski's interests was very wide. He worked in the field of the structure and kinematics of plane and space mechanisms, was engaged to the analysis of force, the theory of balancing of machines, the investigation of the movement of mechanisms, the calculation of mass of fly-wheels. He also wrote works on an approximate and exact synthesis of mechanisms and, together with his colleagues, he elaborated on the basis for automatic machines.

[1] Details on the History of IFToMM can be found in the first chapter of the Proceedings of the first International Symposium on the History of Machines and Mechanisms HMM2000 (published by Kluwer) in which all the past IFToMM Presidents have outlined their historical perspective of IFToMM in contributed papers with references.

Fig. 6 Title pages of the works by Ivan Artobolevski

Several 1,000 printed works belong to his pen (Fig. 6), among which, the most important are "Theory of Space Mechanisms" (1937), "Structure, Kinematics and Kinetostatics of Multilinking Plane Mechanisms" (1939), "Theory of Mechanisms and Machines" (1940), "Synthesis of Mechanisms" (1944), a reference book in four volumes "Mechanisms" (1947–1951), "Theory of Mechanisms for Reproduction of Plane Curves" (1959), "Synthesis of Plane Mechanisms" (1959), "Theory of Mechanisms and Machines" (1975) and an edition in five volumes "The Mechanisms in Modern Engineering Design" (1970–1975) which is considered as the encyclopaedia of all ancient and modern mechanisms and includes the description, systematization, classification and the main properties of about 5,000 mechanisms of different types and purposes.

Structure and Classification of Mechanisms

In 1939, Artobolevski's investigations in the field of structure and classification of mechanisms finished with the publication of the monograph "Fundamentals of Unique Classification of Mechanisms". This work gave wide possibilities for the further development of the theory of machines and mechanisms because it made the construction of the methods of the kinematic and kinetostatic analysis of mechanisms considerably easier. Thus, the problem concerning the investigation of the mechanism of any complexity comes down to the analysis of separate groups from which the mechanism is composed. In the presence of a strict scientific classification, the projection of the mechanism becomes easier.

Besides the structural classification of mechanisms, Ivan Artobolevski suggested a functional classification in which the mechanisms are divided into uniform groups which depend on the functions performed by them in machines and devices (for example, the mechanism of clamps, feed, regulators, brakes, etc.) and also the structure-constructive classification of the mechanisms on types of links and kinematic pairs (of lever, tooth, friction, shaft and others). Both classifications are stated in a multivolume reference book which represents a systematic collection of descriptions of mechanisms applied in different branches of machine and device engineering. The reference book had several editions and was widely used by designers while projecting machine and devices.

Kinematics and Kinetostatics of Plane Mechanisms

In 1939 Artobolevski finished his investigations in the field of kinematic, and kinetostatics with the publication of the monograph “Structure, Kinematics and Kinetostatics of Multilinking Plane Mechanisms”. Later on, he carried out additional investigations on kinematics and managed to set up some new loci peculiar to plane mechanisms that have a great significance. Two of these new loci, relating to the definition of velocities and accelerations of plane mechanisms, were named by him as analogues to the circles of Bress and Jagir. In the article “Geometrical Methods of Solution of Some Problems on Theory of Mechanisms” (1947), he showed that all the problems bound up with the definition of acceleration could be solved with the help of the construction of the plans of velocities only.

Space Mechanisms

The results of Artobolevski’s investigations on the theory of space mechanisms are summarized in the monograph “Theory of Space Mechanisms” (1937). In this monograph, Ivanovich examined the problems of the kinematics of a solid body during the different tasks of its motion, gave the axoid theory and, finally, exposed the methods of kinematic analysis of space mechanisms according to his own classification. This work is built up on the principles of geometrical school with wide utilization of the method of right-angled projections.

Dynamics of Mechanisms

One of the first works of Artobolevski on dynamics is dedicated to the solution of the problem of the motion of mechanisms under the influence of set forces when these forces are the functions of the arrangement of the links. For the first time this problem was solved by Ivanovich with the help of the method proposed by him which led him to determine the velocities and accelerations of the links of a mechanism which is under the influence of set forces. The problem on the motion of mechanisms is closely related to the problem of the calculation of fly masses for machine units which are under the influence of constantly changing forces. He managed to show that the approximate method of calculation of fly masses proposed by Radinger has some essential deficiencies and it gave serious deviations in the dimensions of the calculated fly masses. Using Lagrange's second-order equation, Artobolevski proposed a geometrical method of determination of derivatives from masses reduced to the functions of a turn angle. Further investigations on questions about the motion of a machine unit under the influence of set forces, are related to the creation of experimental methods of determining the mechanical parameters of a machine. At the Institute for Engineering Science of the AS of USSR (now RAS), Artobolevski created the Laboratory of Machine Dynamics where he worked out not only the recommended methods of experimental investigation of machines, but also many original means of registration and calculation of mechanical parameters of machines. Artobolevski also paid great attention to another highly important problem of the dynamics of machines, the balancing of the mechanism on the base. He solved the problem of balancing of mechanisms with complex kinematic diagrams. While solving it, he proposed some original methods of balancing four-bar chain mechanisms with the help of counterbalances and also of complex mechanisms with the help of additional toothed gearing which equilibrate the forces of inertia of different orders.

During the last years of Artobolevski's direct participation, one more trend appeared in the modern machine dynamics. The methods of acoustic dynamics of machines allowed him to solve problems on elimination of harmful high-frequency vibrations and lowering the level of noise. Nowadays, the acoustic dynamics of machines has developed into a huge scientific program which has not only scientific-engineering significance but also social significance as well. The level of vibrations and the noise in machines characterizes not only the dynamic tension of the machines but also the work conditions in the everyday life. Artobolevski was far-sighted here giving enormous support to some scientists who had been working on this problem.

Synthesis of Mechanisms

In the field of projection of plane mechanism, Artobolevski suggested geometric methods of synthesis with the help of centroid and interrounded curves for the most general cases of the task of plane motion. The result of these investigations is published in the monograph "Synthesis of Plane Mechanisms" (1939) and in the book "Synthesis of Mechanisms" (1944). In the monograph "Theory of Mechanisms for the Reproducing of Algebraic Curves" (1959), some methods were showed that made possible the synthesis of mechanisms for drawing and rounding not only conic sections but also other spreading curves. This work is the first big generalization in the world literature in the so-called theory of exact synthesis of mechanisms.

All the achievements of the synthesis of mechanisms were summed up in the book "Synthesis of Plane Mechanisms" (1959) which he wrote together with some of his colleagues. This book widely covers the different methods of synthesis of mechanisms that it can be considered, by right, as a work of an encyclopaedic nature.

Theory of Automatic Machines

As far back as in the thirties, Artobolevski, together with a group of scientists, began working on a summary monography dedicated to the general theory of automatic machines. The first two volumes were published under the title "Methods of Analysis of Automatic Machines" (1945, 1949). The methods of structural, kinematic and kinetostatic analysis of automatic machines and the method of their power valuation are stated in the book. The elaborated methods of projection of complex systems of machines of automatic operation which include technological machines and apparatus transporting and informative machines, engines and also auto-operators and industrial robots, obtained a scientific base.

Manipulators, Robots and Walking Machines

Artobolevski was one of the first in the Soviet Union to attract the attention of specialists to the problems of robots, manipulators and walking machines. In his works with his students, not only the basis of the theory of mechanic systems of manipulators were laid but also possibilities were shown for their further development. Artobolevski made much of the development of this problem in the USSR, formulating the most important scientific problems in that field. He, together with his pupils, worked out the methods of kinematic and dynamic analysis of executive organs (grips) of manipulators and robots, which possess high mobility and suggested criteria for integral valuation of their geometry and kinematics. Problems were discussed on the development of investigations directed towards the creation of robots with elements of artificial intellect.

History of Science and Technology

Artobolevski paid much attention to the questions of the history of science and technology. Fighting for the historical justice in world science, he defended, with arguments, the priority of Russian scientists. His works are interesting and instructive, dedicated to the analysis of the scientific legacy of Mikhail V. Lomonosov, Ivan P. Kulibin, P.L. Chebyshev, N.E. Zhukovski, L.V. Assur, S.I. Vavilov and also of his teachers I.P. Goryachkin and N.I. Mertzalov. At the same time, he always underlined the valuable contribution made by Russian scientists Chebyshev, Vishnegradski, Petrov and others to the formation of a scientific school on machines and its influence on the development of a world scientific school on the theory of machines and mechanisms.

He also carried out a very detailed investigation dedicated to Leonardo da Vinci's legacy. He showed how closely the works on physics and mechanics of this genius were related to the theory of different mechanisms and machines, devices and their use in practice. Leonardo da Vinci, in his works, appears before us as a theoretic scientist, an outstanding engineer, constructor and innovator, the one who worked out theories of transmission and projected hydro-technical constructions, built excavating machines, weaving-looms and different mechanisms for military affairs, invented devices of different types to polish the lens of optic devices and many other things. It is not casual that in 1968, Artobolevski was elected a honourable member of the International Academy of History of Sciences (Paris).

During the last years, together with Alexei N.Bogoljubov, he wrote a capital work "Leonid Vladimirovich Assur" in which it was proved that some questions on the structure of mechanisms were worked out by Assur more wider and deeper in comparison to the works of Burmester and Grubler.

A great number of Artobolevski's scientific books and articles are translated into many languages and are published in dozens of countries. This testifies to perpetuate his memory not only in Russia but far across its boundaries as well.

On the Circulation of Works

Among the personalities of science and engineering who greatly contributed to the scientific and engineering progress in the world, academician Ivan Ivanovich Artobolevski played a very important role. He founded the Soviet (Russian) school on the theory of machines and mechanisms, made great generalizations in the theory of machines and left a rich legacy: monographies, reference books, textbooks, scientific and publicistic articles in magazines and newspapers.

Artobolevski came to the conclusion which he later elaborated on, that a harmonious system for the classification of mechanisms existed, the beginnings of which he discovered in the works of Assur. This classification permitted him to create a strict scientific base for the theory of machines and mechanisms and it made considerably easier the elaboration of the general methods of calculation of mechanisms. This theory also became the base of the fundamental course "Theory of Machines and Mechanisms" (1940) distinguished by the strictness and harmony of the exposition of material. Afterwards, this work, with some changes and supplements, was republished repeatedly in the Soviet Union and abroad and was a great success. Artobolevski was constantly engaged to the development of the science "Theory of Machines and Mechanisms" (TMM) and wrote not only a new chapter of science important for some branches of industry but also became the main ideologist of new tendencies.

Knowing perfectly well the international literature on the TMM, he kept up a wide correspondence with the greatest scientists of different countries and even knew some of them personally, having met with them abroad.

In his letters to his colleagues, he exchanged some new scientific ideas on the science of machines and mechanisms. Such communication turned out to be very fruitful and on this basis scientific seminars on TMM appeared in different cities of the Soviet Union, such as Leningrad (now Saint Petersburg), Kiev, Odessa, Tbilisi, Kaunas, Alma-Ata and also in some fraternal countries such as Bulgaria, Poland and Czechoslovakia.

Being a scientist and statesman, Ivan Artobolevski had to travel much and he gave lectures for the common people. He always took an active part in the organization by holding seminars, discussions, conferences, symposiums and congresses in the field of TMM, being at the head of scientific councils and a member of the editing and publishing councils.

The scientific activity of Artobolevski is indissolubly connected with teaching. Yet being a student of Timiryazev Academy, he began teaching at the chair of agricultural machines. In 1929 he was elected professor and obtained the Chair of Technological Mechanics at the Moscow Chemical and Technological Institute named after Dmitry Mendeleev. Later he gave lectures at the Moscow Institute for Chemical and Mechanical Engineering, Air-Military Academy named after N.E.Zukovski, Moscow State University, and became at the chair of the "Theory of Machines and Mechanisms" Department at the Moscow Aviation Institute (Fig. 7).

At different periods of time, he gave courses on TMM, the balance of air and sea engines, the theory of agricultural machines, the theory of Space mechanisms, the

Fig. 7 A group of professors of "Theory of machines and mechanisms" department, Moscow Aviation Institute, 1948

basis of the theory of automatic machines, the theory and calculation of mill machines and the theory of revolving vibrations of the shafts of engines.

Artobolevski was an excellent lecturer, he gave lectures with inspiration and it seemed that he enjoyed them. He always had a great audience and his lectures were attended not only by students but also by teachers.

He helped young scientist in their investigation, and he did that with pleasure and consideration. About 100 scientific workers defended their candidate thesis under his leadership and 30 pupils became Doctors of Science and professors.

Modern Interpretation of Main Contributions to Mechanism Design by Ivan Artobolevski

Ivan I.Artobolevski wrote a great four-volume work "Mechanisms" which he had been working on for 10 years. The first edition, which was published in 1947–1952, contained a description of about 4,000 mechanisms applied by modern science, and was then the most complete directory. Engineers, thus received a theoretical basis for designing machines.

In 1808, the "Course of Construction of Machines" ('Essai sur la composition des machines') by Lanz and Betancourt was published – one of the first history textbooks of engineering and machines. It has a table where the authors included all known mechanisms at the end of the eighteenth – the beginnings of nineteenth. For one and a half centuries the quantity of mechanisms has increased almost 30 times! At the end of the 1960s, Artobolevski started to work on a new edition of the directory. Its first two volumes named "Mechanisms in Modern Engineering Design" (Fig. 6), were published in 1970 and 1971, contained 2,228 lever mechanisms, and in the second volume there appeared a description of 123 mechanisms made by Artobolevski himself: for example, a link-lever ellipsograph, the mechanism for plotting and rounding of ellipses and a hyperboloid, a link-lever hyperbolograph. The experience creating of these mechanisms allowed Artobolevski to later develop on the general theory of their synthesis. Such mechanisms have found application at processing surfaces of the second level, including surfaces of cylinders having in sections, curves of the second order. In 1937, the Commission for Engineering Science in the Academy of Sciences of the USSR was created, transformed then into the USSR Academy of Science Institute for Engineering Science (now RAS Institute for Engineering Science, named after A.A.Blagonravov), where Artobolevski created a number of laboratories and supervised the Department of "Theory of Machines and Mechanisms", and later the Department of "Mechanics of Machines". Here, in that Institute, Ivan Ivanovich concentrated the basic scientific activity during his lifetime.

As time passed, a number of problems appeared which earlier didn't ever enter the theory of mechanisms and machines: vibrating, vibrating-percussive systems, the theory of machines with variable structure and parameters, account of elasticity of parts and backlashes in kinematic pairs, the theory of systems of automatic machines, etc. These problems are actual today. They have not only scientific and technical, but also social values connected with studying complex system "man–machine–environment". Not casually, Artobolevski always spoke about two aspects of vibration: on the one hand it is necessary to escape from fluctuations and to achieve their elimination, and on the other hand, fluctuations in machines can be useful and could be used for conducting various technological processes. Under his initiative and under his management in RAS Institute for Engineering Science, named after A.A.Blagonravov a conference was held on vibrating machines with the purpose of attracting the attention of scientists and engineers to this problem. Since the 1950s of the twentieth century and until today a lot of new offers have appeared on use of a vibrating principle by means of which such technological operations as condensation, separation and crushing of materials, drilling of rocks and removal of pressure casting are carried out, sorting and transportation of fine details and many other things. Artobolevski was never a scientist of one idea. He took great interest in everything new and constantly put new tasks before his pupils and colleagues and actively developed new sections of the Theory of Machines, such as acoustic dynamics of machines; the theory of walking machines; the theory of automatic systems; and also synthesis multiple parameter, multicriterial systems in general. It is an important merit that Artobolevski was the first to restore the seditious word "Robot" after a very long-term prohibition of cybernetics in the Soviet Union. During his direct participation in the Institute of Surgery named after A.V.Vishnevski, the laboratory of medical cybernetics was created, successfully solving problems of the diagnosis of various diseases. Together with A.E.Kobrinski, he gave a lecture "Some problems of construction of systems known as robots" at a conference on the basic problems of theory of machines and mechanisms.

Under Artobolevski's initiative with the 1967 All-Union, symposiums concerning the theory and principles of mechanisms of robots and manipulators on which possible directions of their further development were discussed, were also started on a regular basis. He was the first to show the huge value of these machines in the future not only from the scientific and technical point of view, but also from the social and humanistic point of view. Artobolevski spoke of robotics as being one of the advanced directions of progress. "It is very important, that these systems", – he wrote, "allow the release of human beings from the work in zones of raised radioactivity, harmful and dangerous to health, from dust content, gassed conditions, zones of heat and pressure". His words were prophetical. It is expected, that the robots of the subsequent generations possessing elements of an artificial intellect, can replace man in extreme situations: in space, under water at greater depths, under the ground, in the struggle against terrorism, having left for man only the functions of supervision, management and introduction a complex system. Under Artobolevski's initiative, a Scientific Council on the theory and principles of mechanisms of robots and manipulators was also created, and he was its chairman from 1973 to 1977. He attached huge significance to the coordination of scientific activity of scientists, engineers, teachers, to collective discussion of achievements of a science and its prospects since 1937 and up to the end of his life he had been a permanent head of the seminar on theory of machines and mechanisms, and the editor-in-chief of works of this seminar (160 collections have been published).

Mechanics of machines was the first applied science, as the result of the industrial revolution of the eighteenth century. The two following centuries brought with them a stream of information and duplication of sciences, and a number of sciences about machines in particular, and at the present time has reached a three-value figure. But, until mankind uses machines, the theory of machines and mechanisms (TMM) in the sum of human knowledge will play one of the most important roles. In one of the publicistic clauses, addressed to the youth, Artobolevski wrote: "Most important in the education of scientific youth is the development of independence and creative ideas. To learn and learn creativity – it is possible. Most important for a creative person is his skill to observe a natural phenomenon, to know the mechanism of processes, and to transfer this knowledge to the world of techniques".[2]

During his last years, Artobolevski wrote one of his greatest works: "Successes of the Soviet school on theory of machines and mechanisms", (Fig. 8), in which he

К 60-летию ВЕЛИКОЙ ОКТЯБРЬСКОЙ СОЦИАЛИСТИЧЕСКОЙ РЕВОЛЮЦИИ

академик

И. И. АРТОБОЛЕВСКИЙ

УСПЕХИ СОВЕТСКОЙ ШКОЛЫ ТЕОРИИ МАШИН И МЕХАНИЗМОВ

АЛМА-АТА
ММ 77
ВСЕСОЮЗНЫЙ СЪЕЗД

ВСЕСОЮЗНЫЙ СЪЕЗД
по теории машин
и механизмов
сентябрь 20—24, 1977 г.
г. Алма-Ата

Москва — 1977

Fig. 8 Title page of the last (life time) publication of Ivan Artobolevski: "Successes of the Soviet school on theory of machines and mechanisms"

[2]Artobolevski I.I. "Be not afraid to dare", "The Komsomolskaya Pravda" (the newspaper), 11 May 1974.

summed up the activity of all Soviet schools on the theory of machines actually created by him. It was his last publication. His scientific ideas and the published works help acceleration of scientific and technical progress. His life deserves to be studied in detail and to become an example for new generations of modern engineers and scientists.

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Ludwig Burmester (1840–1927)

Teun Koetsier

Abstract Ludwig Burmester was a nineteenth century German mathematician. His *Lehrbuch der Kinematik, Erster Band, Die ebene Bewegung* (Textbook of Kinematics, First Volume, Planar Motion), of 1888, contains the first far-reaching attempt at a synthesis of theoretical kinematics and kinematics of mechanisms. His most influential technical contribution is the Burmester theory which deals with four or five discrete positions of a moving plane. The goal of the Burmester theory is the synthesis of mechanisms. In the present paper, Burmester's work is discussed against the background of the development of the theory of machines and mechanisms in the nineteenth century.

Biographical Notes

Ludwig Ernst Hans Burmester, Fig. 1, was born on May 5, 1840, as son of a gardener in the village of Othmarschen near Hamburg in Germany. He died on April 20, 1927, as a respected professor emeritus of Descriptive Geometry and Kinematics at the University of Munich and a member of the Bavarian Academy of Sciences. Between these dates lies a rich and varied professional life dominated by Geometry and Kinematics.

At the age of 14, Burmester became an apprentice in the workshop of a Hamburg precision mechanic. He was allowed to go to the Polytechnical Preparatory School in Hamburg run by Otto Jensen. Jensen was an excellent man who was not only a great teacher of mathematics but good at convincing rich citizens of the city of Hamburg to support talented children like Ludwig Burmester. Because Burmester thought that there was a good future in telegraph machines, he left Hamburg and went to Berlin where Siemens & Halske were building such machines. Yet, in the end his desire to study prevailed.

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Fig. 1 Ludwig Burmester (1840–1927) when he was a professor in Dresden (Courtesy of Dr. Klaus Mauersberger, T. H. Dresden)

In 1862 he enrolled at the Polytechnical School in Dresden in the department for future teachers of mathematics, science and technology. He attended the classes of Oskar Schlömilch on several areas of mathematics. It is remarkable that he seems to have acquired a considerable knowledge of geometry that later dominated his activities, all by himself. In 1864, Burmester received his diploma in Dresden with honours.

In the next years, Burmester studied in Göttingen where he obtained his doctor's degree in 1865.

In 1868, Burmester married Gabriele Schallowetz (August 4, 1848–November 15, 1919). Out of the marriage a daughter, who died very early and three sons were born. After 1865, Burmester worked for 4 years as a secondary school teacher in Lodz in Russian Poland.

In 1870, Burmester had to leave Lodz after the Russians had closed down the secondary school he was teaching in. In 1872, Burmester's luck changed, he became professor of descriptive and synthetic geometry in Dresden, where he had become Privatdozent after his Habilitation in 1871. In 1875, he started teaching projective geometry and in 1879 he started to teach kinematics. Much of his work in this period is related to kinematics. One of his earliest publications after his appointment in Dresden in 1873 combines a growing interest in kinematics with geometrical questions concerning projection and shadows. On 1 October 1887, Burmester was appointed to the chair of descriptive geometry and kinematics in Munich. For the events leading to his appointment, see Hashagen (2003, pp. 500–506). In Munich, where he lived in the Kaulbachstraβe 83, Burmester was highly respected. In 1905, he became a member of the Bavarian Academy of Sciences. In the last years of his life he developed a great interest in the mechanical engineering side of cinematography. He lectured on this subject and he studied different methods for guiding film in a projector.

Burmester died in 1927 of a heart attack. He was buried next to his wife in the cemetery of Kreuth near Lake Tegernsee. The grave is still there. Two necrologies appeared, written by Finsterwalder (1927) and Müller (1930). They show that one of the giants of nineteenth century German kinematics had died.

Burmester's Work

Burmester's Göttingen thesis is titled *Ueber die Elemente einer Theorie der Isophoten* (About the elements of a theory of isophotes). It deals with the representation of lighted surfaces in three-dimensional space. Isophotes on a surface are lines of constant light intensity: they are the sets of points for which the cosine of the angle between the light direction and the surface normal has a constant value. It is remarkable that Burmester's treatment of the subject is entirely analytical. The contrast with Burmester's later works, in which his method is more and more synthetic, is considerable.

In 1871, his first book appeared in Leipzig: the *Theorie und Darstellung gesetzmäßig gestalteter Flächen* (Theory and representation of well-defined surfaces). It was reprinted in 1875. The book is about the subject of his dissertation, the theory of isophotes.

Interesting is Burmester's distinction between lines of "true light intensity", the isophotes, and lines of "observed light intensity", which he called isophengs. They are the sets of points for which the product of, on the one hand, the cosine of the angle between the light direction and the surface normal, and, on the other hand, the cosine of the angle between the direction of the eye and the surface normal, has a constant value. Figure 2 is an example taken from (Burmester 1871).

Burmester was interested in all aspects of the theory of perspective as well. In 1883, in Leipzig he published his book *Grundzüge der Reliefperspective* (The Main Features of Relief Perspective), dealing with the principles of relief perspective. In ordinary perspective, a half space is mapped on one plane of projection; in relief perspective, a half space is mapped on the space between two parallel planes. Burmester built several models in order to demonstrate the effect of his theory (See Fig. 3).

In 1884, Burmester published *Grundlehren der Theaterperspective* (Foundations of Theater Perspective). It is said that he was involved in the design of the decor for some of Wagner's opera's.[1]

It is remarkable that both the subject of isophotes and the subject of relief perspective have recently attracted interest in the area of computer aided geometric design (Lordick, 2005).

[1]Cf. http://www.mathematik.tu-muenchen.de/~kaplan/fakul/node16.html. I have not been able to check this. Wagner died in 1883, before Burmester came to München. Yet the Germans took theatrical design very seriously and it is quite possible that during Wagner's last years or after his death, Burmester was involved in the scenography in Bayreuth.

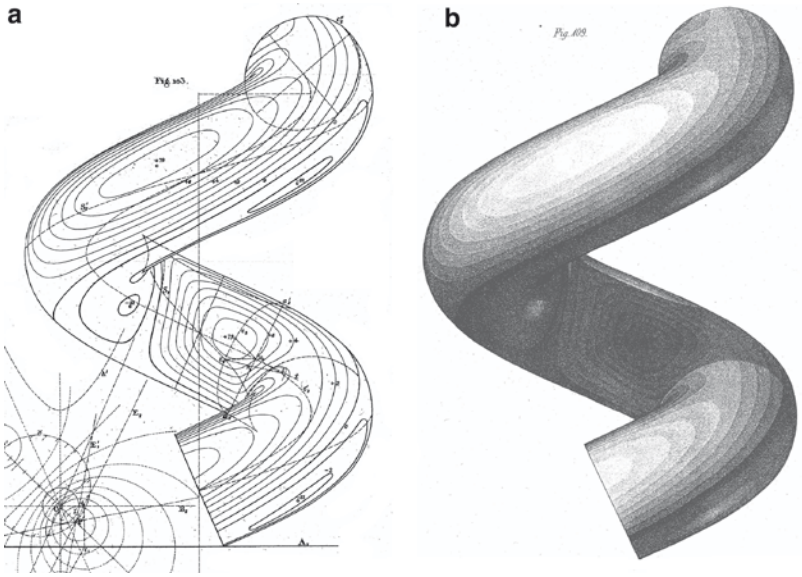


Fig. 2 Figures from Burmester's book on isophotes: (**a**) lines of equal light intensity; (**b**) a shadow representation

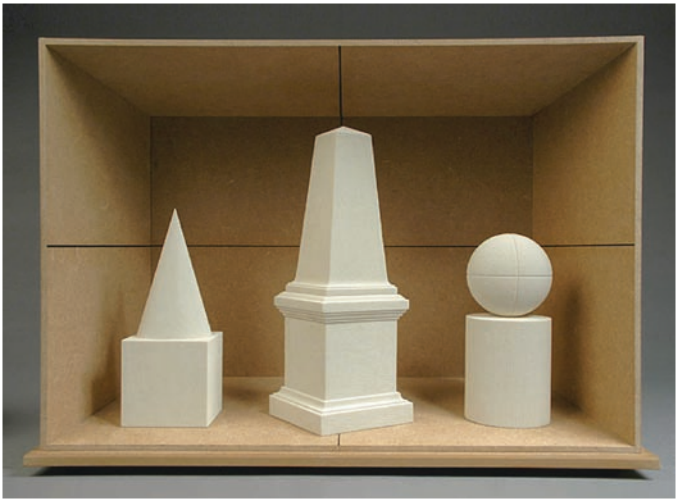
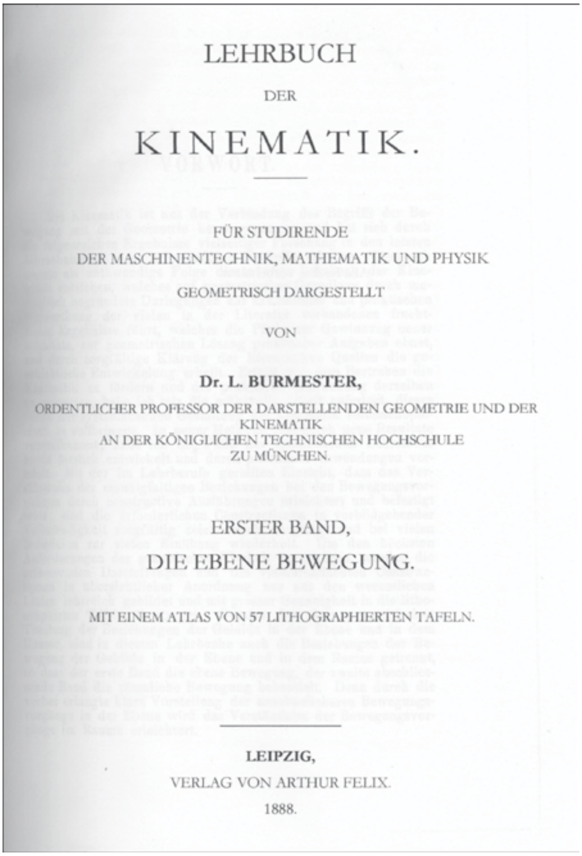


Fig. 3 A reconstruction by Dr. Daniel Lordick (TU Dresden) of one of Burmester's relief perspective models (Lordick 2005) (Courtesy of Dr. Lordick)

The turn to kinematics was crucial in Burmester's life. Before the 1960s of the nineteenth century, kinematics of mechanisms was hardly a coherent discipline and results from theoretical kinematics were not applied systematically to the kinematics of mechanisms. In the second half of the nineteenth century, things changed.

Kinematics enjoyed great popularity among both mechanical engineers and mathematicians. The work of the German engineer Franz Reuleaux (1829–1905) was in particular very influential. Reuleaux's *Theoretische Kinematik* (a theoretical treatise on kinematics of mechanisms, in spite of its title. See below), published in book form in 1875, paved the way for further mathematization of kinematics of mechanisms. On the other hand mathematicians also played an essential role. Ludwig Burmester was a prominent example.

Burmester's most important contribution to kinematics is undoubtedly his *Lehrbuch der Kinematik, Erster Band, Die ebene Bewegung* (Textbook of Kinematics, First Volume, Planar Motion). It was originally published in three installments; the first two installments appeared in 1886 in one volume of 560 pages and the last installment appeared at the end of 1887. In 1888 the three installments appeared in one volume. In 941 pages accompanied by an atlas with 863 figures presented Burmester gave a survey of everything he knew about planar kinematics, which included many of his own results (Fig. 4).


LEHRBUCH

DER

KINEMATIK.

FÜR STUDIRENDE
DER MASCHINENTECHNIK, MATHEMATIK UND PHYSIK
GEOMETRISCH DARGESTELLT

VON

Dr. L. BURMESTER,

ORDENTLICHER PROFESSOR DER DARSTELLENDEN GEOMETRIE UND DER KINEMATIK
AN DER KÖNIGLICHEN TECHNISCHEN HOCHSCHULE
ZU MÜNCHEN.

ERSTER BAND,
DIE EBENE BEWEGUNG.

MIT EINEM ATLAS VON 57 LITHOGRAPHIERTEN TAFELN.

LEIPZIG,
VERLAG VON ARTHUR FELIX.
1888.

Fig. 4 Title page of Burmester's *Lehrbuch der Kinematik* (1888)

In 1890, he and the other mathematicians from München were involved in the foundation of the *Deutsche Mathematiker-Vereinigung* (Association of German Mathematicians).

Review of Main Work Related to Mechanism Design

The Background

With the completely new classification of mechanisms by means of kinematical chains in the 1860s, Reuleaux had introduced a very abstract point of view in kinematics of mechanisms. For a mathematician, this boiled down to viewing a planar mechanism as a collection of coinciding Euclidean planes all moving (with one degree of freedom) with respect to each other. This was a major and not trivial step forward which helped to turn kinematics of mechanisms into a more coherent discipline. It involves two related elements: considering the frame of a mechanism as a link and, moreover, abstraction from the particular shape of the links in a mechanism and concentration on the way in which the links are connected. Without mentioning Reuleaux, Sylvester wrote in 1875:

> The true view of the theory of linkages is to consider every link as carrying with it an indefinitely extended plane and to look upon the question as one of relative motion [...] Fix any of these planes and the linkage becomes a link-work [...]. (Sylvester, 1875)

In the investigation of bar-mechanisms, Sylvester attributed the extension of the consideration to the planes connected with bars to Samuel Roberts. Yet the priority belongs to Reuleaux who developed his ideas at least 5 years before Roberts turned to kinematics at the end of the 1860s.

Burmester's turn to kinematics in Dresden is related in different ways to Reuleaux' influence. Undoubtedly, the abstract point of view introduced by Reuleaux in the theory of mechanisms combined with Burmester's great interest in the recently developed geometrical theories enabled Burmester to do his kinematical work. As for geometry, Theodor Reye's *Geometrie der Lage* (Projective geometry) of 1866, revised and reprinted several times, is representative of the geometrical background of Burmester's work in kinematics). It seems to have been Rittershaus who stimulated Burmester to do kinematics. Trajan Rittershaus (1843–1899), professor of kinematics and electro-technical machines in Dresden, had been Reuleaux' student in Zürich and his assistant in Berlin.

The Lehrbuch der Kinematik: A Characterization

Nowadays it is not uncommon to distinguish between *theoretical kinematics* dealing primarily with the general properties of motion and *kinematics of mechanisms* which concentrates on the kinematical properties of (classes of) specific mechanisms. As we will see below, Reuleaux used the term kinematics in a different way. We will use the modern terminology. Burmester's *Lehrbuch der Kinematik* contains the first far-reaching attempt at a synthesis of theoretical kinematics and kinematics of mechanisms. The planned second volume on spatial kinematics was never written. The content of the kinematical papers that Burmester wrote before the publication of his book, are all included in the book. In 1874 and 1875, he published on affine and equiform kinematics: the moving plane moves and is subjected to affine or equiform transformations as well, while the fixed plane remains Euclidean. The results return in the twelfth chapter of the *Lehrbuch der Kinematik*. In 1876 and 1877, he wrote two very original papers on what would later be called the *Burmester theory*. The Burmester theory returns in the ninth chapter of the book. In 1880 he published a systematic investigation of the instantaneous velocities of n rigid systems moving with respect to each other in the plane. Aronhold had discovered the three centers theorem when he prepared a course on theoretical kinematics in Berlin, which took place in 1866–67. Twenty years later, Kennedy would independently discover the same theorem. In Burmester's 1880, paper the full potential of the theorem in velocity analysis became clear. The results return in the seventh chapter of the book. It is remarkable that this paper exerted some influence in civil engineering. The results were used for the calculation of forces in a framework by means of the principle of virtual displacements (Kurrer 2002, pp. 521–525). After 1888, Burmester continued to publish on kinematics. In 1893, he thoroughly investigated a class of overconstrained mechanisms introduced by Kempe in 1878. He returned to affine kinematics, this was in 1902, a subject that he had studied in 1874 and 1875. In 1911 and in 1925, he published on acceleration in planar motion. The *Lehrbuch der Kinematik* consists of 12 chapters. It is a compilation of almost everything that was known on planar kinematics at that time. On the one hand, Burmester gave a survey of the results from theoretical planar kinematics. On the other hand, he systematically studied their application to practically all planar mechanisms that had been identified at the time. Examples of figures from the atlas are given in Figs. 5 and 6.

The Lehrbuch der Kinematik: Its Contents

Let us consider the structure of the *Lehrbuch der Kinematik* in more detail. The first chapter is devoted to the general properties of planar motion: velocity, the instantaneous center of rotation (the pole), the polhodes, the motion of three coinciding planes with respect to each other, construction of tangents and centers of curvature, with many examples of special motions.

Chapter two concerns the different cycloids and their properties.

Chapter three deals with cylindrical gears, cycloid gearing, involute gearing.

Chapter four deals with the gear in internal gear pumps (*Kapselraeder*). In this chapter, Burmester discusses all existing types of such pumps.

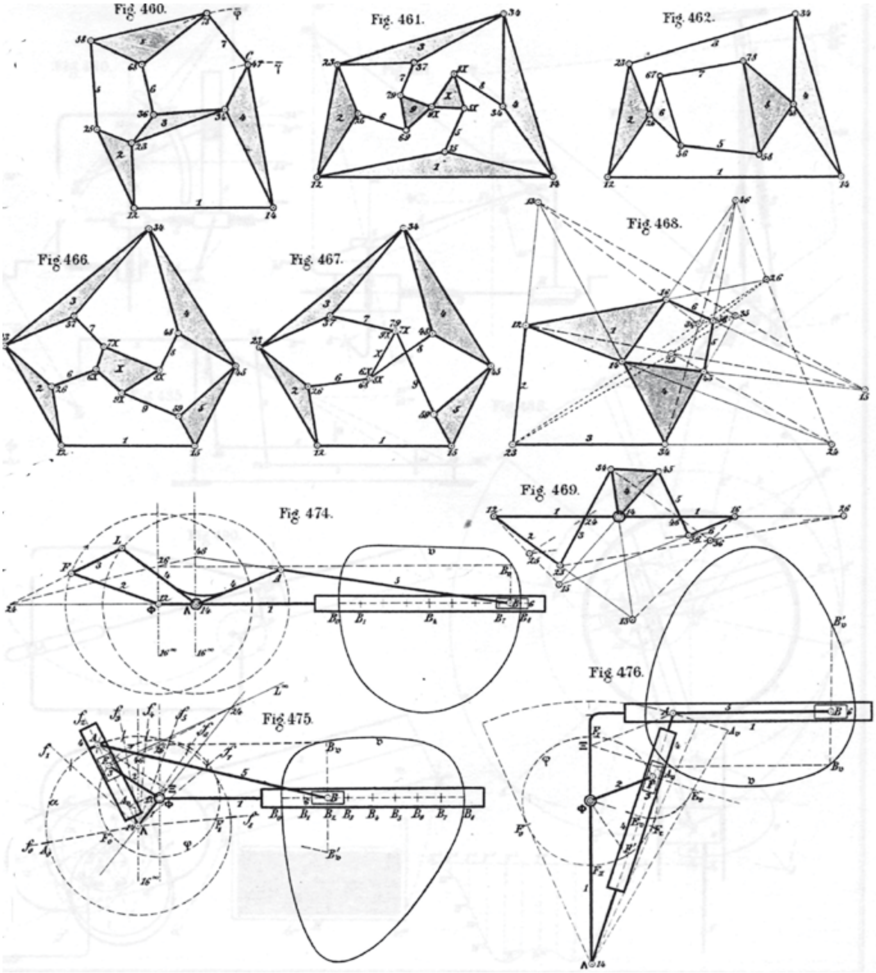


Fig. 5 Figures accompanying Burmester's seventh chapter of the *Lehrbuch der Kinematik* on compound planar mechanisms

He always moves from the very general to the specific. The theories given in the first chapter are applied in chapters two to four. In the fifth chapter, Burmester again starts from very general considerations, which are applied in chapters six and seven.

In the fifth chapter, he deals with the general theory of constraints (*Zwanglauf*): restrictions on the motion of a system. The final goal of this theory, which was defined by Reuleaux, is to determine the most favorable ways to realize a particular one-degree-of-freedom constrained motion. Reuleaux' notions of kinematic pair (consisting of two elements that constrain each other's motion) and kinematic chain

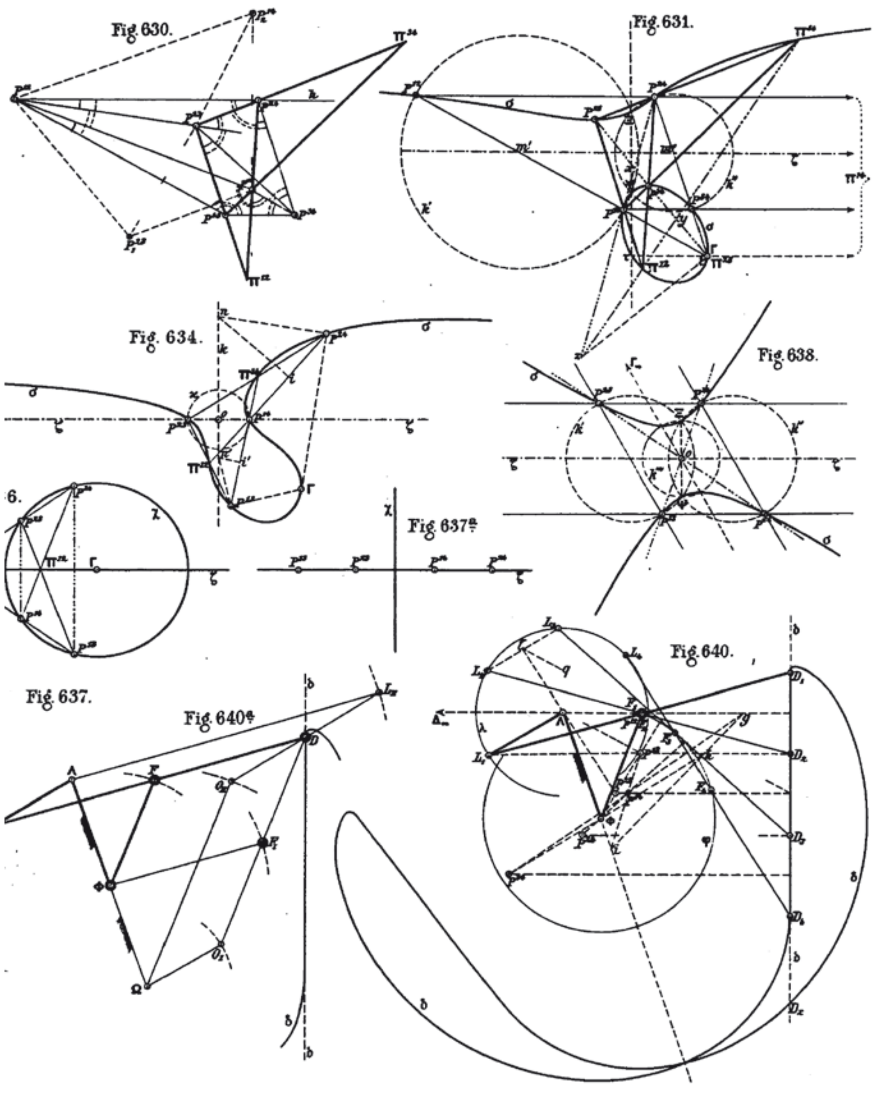


Fig. 6 Figures accompanying the treatment of the Burmester theory in the ninth chapter of the *Lehrbuch der Kinematik*. The curve σ in Fig. 634 is the centre point curve. In Fig. 638, σ consists of the line at infinity and a hyperbola

are the basic notions. There are, however, some terminological differences between Burmester and Reuleaux. Instead of Reuleaux' word 'kinematic chain', for example, Burmester uses the word 'mechanism', something Reuleaux would later interpret as an insult that revealed that Burmester had not understood the significance of Reuleaux' kinematics at all. For more details see the section on the reception of Burmester's work below.

The sixth chapter is very long, 122 pages. It deals with *simple planar mechanisms*. When the links (or elements including the one that is fixed, the frame) of a mechanism form a closed sequence and all elements execute a one-degree-of-freedom constrained motion with respect to each other, the mechanism is by definition a simple mechanism. First Burmester discusses the different planar four-bar linkages, Robert's theorem and the graphical velocity analysis of a planar four-bar linkage. Then he discusses special cases like the slider–crank mechanism and the Scotch-yoke mechanism with the graphical velocity analysis. He treats simple mechanisms with cams, with non-circular gear wheels and simple belt-driven mechanisms. There is also a section on locking and switching devices.

Burmester then proceeds in the seventh long chapter of 143 pages to compound planar mechanisms. In such mechanisms there will be at least one element that is connected through closure to more than two others. At the beginning of the chapter, Burmester discusses Grübler's results concerning constraints and results concerning the configuration of poles at a particular instant in the case of several coinciding moving planes. Then he turns to the discussion of all the compound mechanisms that he was familiar with. Wherever possible, Burmester applied the pertinent theoretical results to the many special mechanisms that he discusses. Watt's mechanism, Stephenson's mechanism and many others are treated. Figure 5 gives an idea of the variety of mechanisms that Burmester studied.

In the eighth chapter, Burmester deals with what he calls "guided mechanisms", like the pantograph. A one-degree-of-freedom kinematic chain is attached to the fixed plane by means of only one hinge. Then if we guide a point of one of the other links along a curve, we have a guided mechanism. In the same chapter, he discusses overconstrained mechanisms.

In the ninth chapter he deals with straight-line mechanisms. Also, here he develops a very general theory before it is applied. This time it is quite new: it is the theory nowadays called Burmester's Theory. Burmester's *Lehrbuch der Kinematik* is the culmination of a long development and is frequently based on papers that Burmester had written earlier. The treatment of the Burmester theory is based on the content of two papers from 1876 and 1877. Below, we will look at these papers in some detail.

In the twentieth chapter, of the *Lehrbuch der Kinematik*, he discusses slider controls for locomotives like Stephenson's control or Heusinger von Waldegg's control. In the eleventh chapter of 122 pages, Burmester gives an extensive theory of acceleration with applications to many simple and compound mechanisms. Also, here Burmester starts from the general theory and only then considers its applications. Finally in the twelfth chapter, Burmester deals with equiform and affine kinematics.

The Burmester Theory and the Burmester Points

The 1876 paper, which clearly represents Burmester's growing interest in applications of kinematics in mechanical engineering, consists of three parts. The paper is on the design of four-bar straight-line mechanisms taking into consideration the discrete positions of a moving plane. In 1876, Burmester first considered three discrete positions S_1, S_2 and S_3 of a moving plane and determined the points in the moving plane that are in those positions on a straight line. Right from the start, Burmester attacked the problem by means of projective geometry. By considering projective pencils of points and lines, he proved that the set of all points in S_2 that are in the three positions on a straight line, is a conic section. Because the circle points I and J are on it, it is a circle C_2 in S_2. This result was already known; it had been published without proof by Grouard in 1870. In his 1876 paper, Burmester went on to four positions, although he restricted himself to a proof of the theorem which says that, in general, precisely one point is in the four positions on a straight line.

In the 1877 paper, Burmester attacked the more general problem of the loci of points that are in a number of discrete positions on a circle. First he considered three positions and proved that the locus of the centers of the circles that are determined by triples of homologous points on three homologous lines is a conic section through the three poles. This theorem immediately yields: There exist either one or three circles that go through four homologous points on four homologous lines. The circles correspond to real points of the intersection of conic sections. By applying this theorem to the homologous lines of a pencil, the locus of centers of quadruples of four homologous points turns out to consist of the points of intersection of corresponding elements of two pencils of conic sections. Burmester analytically proved (the methods in the rest of the paper are synthetic) that this *Mittelpunktskurve* (centre point curve) is a circular curve of third degree. He also shows that it is a so-called focal curve, which is the locus of the foci of all conic sections that touch four given straight lines. Burmester then showed that the locus of points that are in four positions on a circle is also a focal curve, which he calls the *Angelpunktkurve* (pivotal point curve). In his book, he called this curve the "circle point curve". From the text of the 1877 paper, it is clear that Burmester's ideas were still being developed. For example, Burmester identifies the fixed plane with position 1, which means that he did not seem to realize that by considering the situation from the point of view of the moving plane, we are also dealing with four positions of the fixed plane with respect to the moving one and it is because of that the *Angelpunktkurve* must be of the same nature as the "centre point curve".

Finally, Burmester considered five positions and he found the points that are all five positions on a circle by intersecting two focal curves. Because from the nine points of intersection the circle points and three poles must be subtracted, he easily proved the existence of the four points that were later called the *Burmester points* by R. Müller.

One of the admirable characteristics of Burmester's work is the fact that he combined a great interest in theoretical results with an interest in applications. His 1877 paper on discrete position theory is no exception. The Burmester theory is immediately applied to Stephenson's link mechanism for controlling the steam valve of a locomotive.

Kempe's Focal Mechanism

In 1878, Alfred Bray Kempe published a paper which contains a remarkable over-constrained linkage (see Fig. 7). ABCD is a four-bar mechanism. If we choose arbitrary points S, R, V and U on the bars and connect them with bars of a fixed length to a joint P, we create, in general, a rigid structure. Kempe showed that P can be chosen in such a way that quadrilateral ASPV is similar to quadrilateral PRCU and quadrilateral BSPU is similar to quadrilateral PRDV. He, moreover, showed that for such points P, the mechanism has one degree of freedom. Obviously P moves in a circle with respect to AB. Kempe also showed that if the centers of this circle moves to infinity (on the extension of AB) and we remove the bars PR and PS (one has to remove them in fact, because their lengths become infinite), the mechanism becomes the straight-line linkage that Hart had found a year earlier.

It is easy to show that the similarity of the quadrilaterals implies that for the point P inside the quadrilateral we have:

$$\measuredangle APB = \pi - \measuredangle CPD.$$

In other words, P is a point from which opposite sides of the quadrilateral AB and CD are seen under angles that are each other's complement. Moreover, the converse holds as well: for all such points we can determine points S, U, R and V such that we get an over-constrained linkage consisting of a four-bar linkage divided into two pairs of similar quadrilaterals.

In 1893, Burmester wrote a long and very thorough paper about the mechanism. He showed that for a given quadrilateral, the locus of all points P that yield an over-constrained mechanism of this type is a circular curve of the third degree. Moreover, such points P are always the focus of a conic section that touches the sides of the quadrilateral. In other words, the third-degree curve is the set of all foci of the conic sections to which the four sides of the quadrilateral or their extension are tangent. Burmester introduced the term *focal mechanism* for this mechanism because, during the motion of the mechanism, the point P is always the focus of a

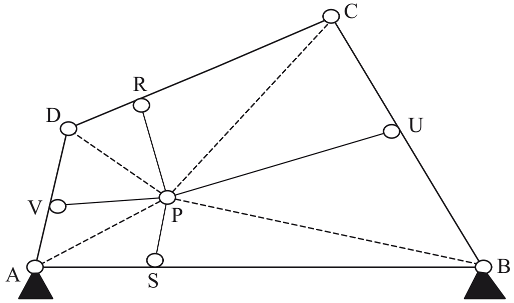


Fig. 7 Kempe's focal mechanism

conic section (changing during the motion) that touches the sides (or their extension) of the four-bar linkage.

Although beyond any doubt, Kempe discovered the mechanism, Wunderlich wrote a paper in 1968 in which he called it "Burmester's focal mechanism" without mentioning Kempe. Dijksman noticed Wunderlich's oversight and called the mechanism *Kempe's focal mechanism*. I prefer that name. The mechanism is also called the Kempe-Burmester focal mechanism (cf. Mallik et al. 1994, p. 121)

On the Reception of His Work

Background

Burmester's book is part of the development of scientific mechanical engineering in the nineteenth century. Before the nineteenth century machines had been studied traditionally in mechanics. When in the eighteenth century, rational mechanics was created, the investigation of machines had become an application of rational mechanics. Because of the difficulties involved, the results were limited. In the nineteenth century, it became clear that the geometrical aspect of machines and mechanisms could be investigated very successfully. Yet the investigation of machines remained applied mathematics or applied mechanics. There was no independent science of machines with a status comparable to the status of the established disciplines. Moreover, in the nineteenth century, the theory of machines was taught on the European continent at polytechnical schools, which in general, had a lower status than universities.

Scientific mechanical engineering was not born easily. For example, in 1877, J. Lüders wrote a booklet of 88 pages with the title *Wider Herrn Reuleaux* (Against Mr. Reuleaux) in which he described Reuleaux' *Theoretische Kinematik* as a book without any value, not written for the specialist but meant to impress the public at large. Others criticized Reuleaux as well because they failed to see the value of his work for mechanical engineering in practice.

In the second half of the nineteenth century, one can distinguish three different views of technology in Germany (Hensel et al. 1989, p. 167). The first view, represented by Franz Grashof (1826–1893), for a long time chairman of the Association of German Engineers (Verein Deutscher Ingenieure), defines technology in the tradition of French positivism: technology is applied natural science and applied mathematics. Burmester must have shared this view. In the second view, represented by Reuleaux, the machine is in the development of mankind, the essential element that determines man's relation with nature. Reuleaux can indeed be seen as one of the first philosophers of technology, who attempted to characterize the general development of mankind on the basis of the fundamental notion of machine. As a result of this position, he emphasized the need for an independent, unified theory of the machine. This theory would reserve a precise place for its application. The third view, represented by Alois Riedler (1850–1936), is opposed to the dominance of theory in the first two views. For Riedler, technology is more a socio-economic system of which theory is only one of the components. “Knowledge is a daughter of application, not the other way around”, Riedler wrote (Hensel et al. 1989, p. 180). Words like ‘reality’, ‘organisation’ and ‘labour’ frequently occurred in his writings. He also opposed the specialization that resulted in curricula at technological universities that consisted of completely separate courses.

What Grashof, Burmester and also Reuleaux, however, had in common was the belief in the value of theoretical considerations and in deduction from the general to the particular. The difference was that Reuleaux defended a general theory of machines, independent of natural science and mathematics. Riedler was sceptical of all general theory. Another representative in Germany of the latter view was Th. Beck (1839–1917), factory owner and engineer from Darmstadt. Reuleaux had written (1875, p. 586): “What has ‘advantage’ to do with science?” Beck argued that the main task of mechanical engineering is to understand how to build a machine in such a way that it yields the greatest advantage (Hensel et al. 1989, p. 199).

When Reuleaux and Burmester wrote their books, the gap between the theory of machines and the practice of building, using and maintaining machines was still considerable. This created tensions and Reuleaux felt under attack from Riedler for not being practical enough, while, on the other hand, he felt that his work was not taken seriously enough by people like Grashof and Burmester. In this particular position, Reuleaux was unable to appreciate the value of Burmester’s book.

Reuleaux’ Severe Criticism of Burmester

In general, Burmester’s book was well received. For example, in 1886, Schumann wrote a very positive review of the first two installments in the *Jahrbuch für die Fortschritte der Mathematik* and in 1887 he repeated his positive opinion with respect to the third installment. There was, however, one remarkable exception. In 1889 Reuleaux wrote:

> His [Burmester’s – T. K.] book represents a phenomenon that probably has not yet occurred in our literature. As the main result of my investigation I must point out that *the book does not contain one new thought, not even a small one, in the area covered by the title of the book*. Yes, in order to honor the truth I must say that none of the laws of kinematics is treated completely correctly. Mr. Burmester turns out to be an amateur in kinematics (1894, p. LIII, italics are mine- T. K.).

This quotation is preceded by almost 20 (sic!) pages of severe criticism. Some of the criticism is undoubtedly justified. Wherever Burmester saw a possibility to apply his general theoretical considerations to a particular mechanism he did so, even if such an application seemed miles away from the practice of machine building. In this respect, Burmester’s book was written clearly by a mathematician and not by an engineer. However, Reuleaux mainly criticized Burmester for using the word kinematics in an improper way. The above quotation in fact says: “the book does not contain any new contribution in the area of knowledge that I, Reuleaux, call kinematics; it may contain many new thoughts concerning other areas of knowledge”.

Burmester defined kinematics in 1886 when he announced his book as follows:

> Kinematics, which encompasses the geometrical theory of motion and its application to machines, was born from the connection of geometry with the notion of motion. (Quoted by Reuleaux 1894, p. XXXII)

Reuleaux had defined kinematics as *Zwanglauflehre*, which can be translated as "the theory of constrained motion". Kinematics was, from Reuleaux' point of view, identical with the theory of mechanisms. Reauleux wrote that kinematics is

> The science that deals with the question how a machine should be composed such that the movements, i.e. changes of position, of the parts with respect to each other are completely determined (Reuleaux 1894, p. XVI)

The basic notions in kinematics are "kinematical pair", "kinematical chain" and "mechanism". In a kinematical pair, two elements are connected in such a way that the motion of two elements with respect to each other is constrained but keeps at least one degree of freedom. In a closed kinematical chain kinematical pairs are connected in such a way that one degree of freedom is left in the chain. By fixing one of the elements of a closed kinematical chain we obtain a mechanism. The mechanism becomes a machine when we use it to force the forces of nature do work by means of precisely defined movements.

Reuleaux distinguished between *theoretical and applied kinematics*. Applied kinematics dealt with the design of machinery in practice on the basis of theoretical kinematics.

It is clear that Reuleaux had defined kinematics as the core discipline in the new emerging science of machines that he envisaged. In Reuleaux' view of kinematics, the geometry of motion was most useful but it played only a supporting role in kinematics. Kinematics encompassed in this view much more than geometrical considerations.

Reuleaux' goal in life was the creation of a science of machines with a status comparable to the other sciences. That is why he gave his *Theoretische Kinematik* a deductive structure; he had tried to make the science of machines with kinematics at its heart as rigid as Euclid's *Elements*. In Reuleaux' perspective, Burmester did not simply use the word kinematics in a different way. No, Reuleaux saw Burmester's book as an attempt to reduce the science of machines to merely applied mathematics. In 1890 he wrote about Burmester and others:

> At the same time geometry imagined, that is its self-appointed imperialist protagonists imagined, to easily unharness the numerous recently derived kinematical theorems with the right of the conqueror and drive them like patient lambs into their sheepcote. (Reuleaux 1890, p. 248)

Reuleaux felt he had to defend the science of machines against enemies like Burmester. It seems that Reuleaux sent his criticism to the Rector and the Senate of the Technische Hochschule in Munich and later he even sent a copy of his 20-page criticism of Burmester's book to the Royal Bavarian Ministery of Education in Munich (Königliche Bayrische Kultusministerium) so that the ministry would see how incompetent a professor they had on their payroll. Burmester, well-positioned in Munich, Fig. 8, reacted to this with a public defense, which obviously did not satisfy Reuleaux. Actually, Burmester was not the real enemy. When he criticized Burmester, Reuleaux was professor in Berlin at the Technische Hochschule and he was at the top of his power. In 1890–1891, he was even rector of the Hochschule. In 1888, however, Alois Riedler had become professor at the Hochschule. Riedler had completely different views for mechanical engineering. He defended a curriculum with much less theory and more practical exercises. Riedler was a formidable opponent who clashed vehemently with Reuleaux. In the end, Riedler won. He succeeded in drastically reducing the number of classes devoted to mathematics and other theoretical subjects. In 1896 Reuleaux retired and soon kinematics was no longer an obligatory subject in Berlin.

H.–J. Braun characterized the situation in mechanical engineering in late nineteenth century Germany as a conflict about the correct method. That is what it was. Yet, one gets the impression that Reuleaux' self-image included infallibility which, in combination with his overambitious theoretical program and his willingness to fight his opponents any time anywhere at great lengths, turned the opposition between points of view into real battles. In particular, in Berlin the clash was very serious. Elsewhere things developed differently, as we will see below.

The Development in Dresden

It is interesting to compare the dramatic developments in Berlin with the situation in Dresden in the same period (Mauersberger 2001). Kinematics classes started in Dresden in 1870. They were given by Ernst Hartig (1836–1900) who was a specialist and pioneer with respect to measurement and test engineering. As we have seen, Burmester became professor for descriptive geometry in Dresden in 1872. In 1874, Reuleaux' pupil Trajan Rittershaus became professor of kinematics and electrotechnical machines. In the same period, Otto Mohr (1835–1918), specialist in graphical methods in statics and strength of materials, was professor of technical mechanics for the civil engineers. Moreover, in 1873, Gustav Zeuner (1828–1907) had become director of the Polytechicum in Dresden. Instead of fighting each other, these men stimulated each other in different ways. Although, in the course of time, the subject played a lesser role in the curriculum, for example, because dynamical aspects of machines became more important, in Dresden kinematics continued to be an important discipline. In 1894, Mohr had succeeded Zeuner, who had returned to teaching, as professor of technical mechanics. In 1900, the successor of Otto Mohr was Martin Grübler (1851–1935), famous for his contributions to the theory of constraints. A younger representative of the kinematical tradition in Dresden is Hermann Alt (1889–1945) who worked on the Burmester theory, as we will see below.

The Long-Term Reception of Burmester's Work

As for the long term reception of Burmester's work and in particular the Burmester theory, I will restrict myself. In the twentieth century, his work and the elaborations by others became an established part of modern kinematics. I will restrict myself to remarks about Italy, Germany and the United States.

Lorenzo Alievi (1856–1941) wrote his treatise *Cinematica della Biella Piana* (Kinematics of the plane coupler) in Rome in 1892. He published the book in Naples in 1895. It deals with the higher-order properties of the curvature of the four-bar coupler curve. Allievi was familiar with Burmester's *Lehrbuch der Kinematik* and with Schoenflies' *Geometrie der Bewegung* of 1886. Schoenflies had pointed out that Burmester's discrete position theory implied analogous, elegant results in instantaneous kinematics, for example, points of stationary curvature are on a curve of the third degree, the instantaneous analogue of Burmester's circle point curves. Moreover, the analytical methods of the differential calculus can be applied in instantaneous kinematics. Allievi drew the conclusion that the higher-order properties of the curvature of the four-bar coupler curve ought to be accessible to an analytical investigation. He started at the second-order level with the Euler-Savary equation and by differentiating, he reached higher-order results. This was a good idea. Half a century later, A. E. Richard de Jonge rightly praised Allievi's book (De Jonge 1943, p. 667).

In 1930, the German Rudolf Beyer published his *Technische Kinematik* (Technical Kinematics). Beyer starts his preface, next to a picture of Reuleaux, with the statement:

> In the spirit of Franz Reuleaux,
>
> with Burmester in mind,
>
> in the footsteps of Ferdinand Wittenbauer.

The first 147 pages are devoted to Reuleaux' theory of constraints in the spirit of the great man. The next 280 pages are written with Burmester in mind and the last 63 pages are devoted to dynamics in the footsteps of Wittenbauer. In the 1930s, Rudolph Beyer was the spokesman of the German kinematicians (Kerle 2007, p. 184) and the situation is perfectly clear. The quarrels of the second half of the nineteenth century were forgotten and Reuleaux and Burmester were both celebrated as great kinematicians. Reuleaux' lasting contribution turned out to have been his abstract approach of the machine: look at mechanisms and the problem of their classification in terms of kinematical pairs and kinematical chains. The bulk of the theory, however, at the time turned out to be, with Burmester in mind, the development of the general kinematical properties of motion in combination with their application to specific mechanisms.

The first half of the twentieth century is exactly the period in which kinematics was really applied in practice. In the 1990s, Riedler had been right: much of the theory that was taught at the Technische Hochschulen was not applied in practice. This had changed drastically in the 1930s. The nineteenth century graphical methods were really applied both in the analysis and the synthesis of mechanisms. Moreover, there were new developments. Worth mentioning is the fact that Herman Alt (1889–1954), professor in Dresden, further developed the Burmester theory (Mauersberger 2006).

In 1942 and 1943, A. E. Richard de Jonge wrote two papers in which he introduced the kinematics that had been developed in Europe to the American study of Mechanical Engineers in the United States. Writing about the US, De Jonge called “kinematic synthesis” the least known but most interesting branch of kinematics. The Burmester theory gets much attention in De Jonge’s description. The author’s intention was to wake up the Americans by pointing out that in Europe, in particular in Germany, but elsewhere as well, important work in kinematics had been done. In America hardly any published work existed. In the author’s closure, he expressed his disappointment at the lack of interest for his papers.

However, the man who most successfully introduced modern kinematics in America was Ferdinand Freudenstein (1926–2006). When de Jonge published his papers on kinematics, he was adjunct professor at the Polytechnic Institute of Brooklyn. In 1954, he worked for the Reeves Instrument Corporation in New York. Freudenstein was enthusiastic about De Jonge’s papers. He wrote:

> The greatest benefit of the use of the author’s method is obtained when computing machines can be utilized. (Roth 2007, p. 242)

Through Freudenstein and his pupils, modern kinematics, including many of Burmester’s ideas, conquered America. Roth (2007) contains Freudenstein’s academic family tree at the time of his death. It consisted of 500 members. Worth mentioning in this context is a 1959 paper written by Freudenstein and Sandor in which he started an important series of papers on the vector-loop methods in synthesis and the modern development of the classical Burmester theory (Roth 2007, p. 175).

In 1954, De Jonge saw what was coming. In the course of the years the graphical methods were replaced by analytical methods and the solutions were calculated by means of computers.

Spherical and spatial analogues of the planar Burmester theory have been developed. In a good modern textbook like McCarthy’s 2000 the theorem

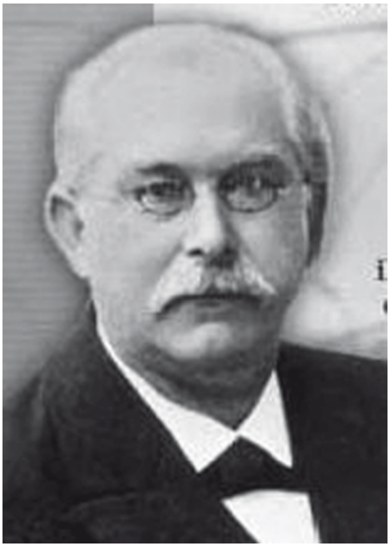


Fig. 8 Ludwig Burmester when he was professor in Munich

that makes it possible to easily find the center points of RR-chains that correspond to four given positions of a body in the plane, is called *Burmester's theorem* (see p. 60). In 1967, Bernard Roth derived the spherical analogue of this theorem. McCarthy calls it the *Burmester-Roth theorem* (see p. 176). As for space, given five positions of a moving body, there are six fixed axes that can serve as central axes of CC-chains that can guide the body through given positions. McCarthy calls these lines the Burmester lines (p. 244).

The Burmester Curves

In German, *French curves* are called *Burmester curves*. A French curve is a template made out of wood or plastic composed of different curves. It is used in manual drafting to get smooth curves. It is not known exactly how the German Burmester sets that consist of three templates acquired this name. Yet it seems very probable that it was indeed Ludwig Burmester whose name was given to the templates because, in his *Grundzüge der Reliefperspective* (The Main Features of Relief Perspective) of 1883, Burmester remarked in a footnote:

> For exact mathematical drawings the suitably formed curved ruler is a useful aid like the circle and can be much recommended; because in a drawing made with ruler and compass the curves drawn by hand form an ugly contrast which greatly influences the beauty and the homogeneity of the drawing. [...] Experience teaches that three suitably formed curved rulers are sufficient for drawing curves in almost all cases. (1883, p. 17)

Burmester made many drawings. The experience he mentioned must have been his own experience. The T.U. Dresden possesses a considerable collection of "Burmester curves" (See Fig. 9).

Fig. 9 Burmester curves (Courtesy of Dr. Klaus Mauersberger)

Fig. 10 A commercial set of Burmester templates (Courtesy of Faber-Castell)

It is possible that someone in Dresden or Munich took the set that Burmester used and started to produce it and sell it under the name *Burmester curves* (Fig. 10).

Acknowledgements I am very grateful to Frau Judith Winkler (Kreuth beim Tegernsee, the village where Burmester was buried) for her help and to Dr. Klaus Mauersberger (T.U. Dresden) for critically commenting on an earlier version of this paper.

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Henry George (Harry) Ferguson (1884–1960)

Gordon R. Pennock

Abstract This article reviews the life and significant contributions of Henry George (Harry) Ferguson, the pioneer of a system of farm mechanization which helped to revolutionize agriculture. Ferguson, see Fig. 1, was the inventor of the tractor that bears his name and which led to a partnership with Henry Ford and eventually to the Massey-Ferguson tractor. Ferguson was a philanthropist with a single-focus mission, the aim of which was agricultural production. During his lifetime it was this production which controlled the cost of living. As an employee of the Irish Department of Agriculture, during World War I, he supervised the operation and maintenance of the small number of tractors that were then in use. He came to the realization that efficient agriculture based on mechanization was the only solution to the problems of the world's food supply. He devoted his time and energy to the development of equipment which he believed would reduce the cost of food production and the cost of living. His passion to mechanize farming to the highest degree, occupied most of his working life. He was a man with a never-let-up personal drive and had a love for building and tinkering with machines. Ferguson received some 100 patents on improvements in carburetors for internal combustion engines, improvements relating to tractor plows, and the means for coupling agricultural implements to tractors. He was a brilliant engineer who brought about a major change in tractor design with his revolutionary linkage, the three point hitch, that allowed both tractor and implement to work as an integrated unit. Today, virtually all tractors are based in some manner on the unique ideas of Ferguson.

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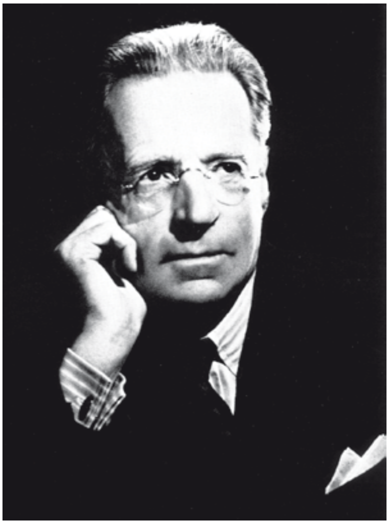
Fig. 1 Henry George (Harry) Ferguson (*c*.1930)



Biographical Notes

James Ferguson married Mary (Minnie) Bell on July 1, 1879, and over the next 24 years, 11 children were born into the family; namely, Joseph Bell Ferguson, James Patterson, Margaret Elizabeth, Henry George, Mary Agnes, Norman Priestly, William Edwin Persis, Sarah Ludley Agnew, John Victor Stanley, Edgar McKnight, and Hugh Fisher (www.proni.gov.uk). The children were born on their father's farm at Growell, in the parish of Dromore, 5 miles from Hillsborough, in County Down. Growell, a townland of scattered farmsteads and cottages, is some 15 miles south of the city of Belfast, the capitol of Northern Ireland. The Ferguson family were members of the Brethren, or Plymouth Brethren, and attended the Growell Gospel Hall. So Henry George, or Harry as he was always called, grew up under the teachings of the Holy Bible. However, he was to turn his back on this Christian influence and later in life he would acknowledge that he was, in fact, an agnostic.

It is interesting to note that Ferguson was born just a few months before Gottlieb Daimler received a patent for his motor-cycle and Karl Benz received a patent for his motor-car (Wymer 1961). By the time Harry was 1 year old, the Daimler motor-cycle and the Benz motor-car were the only petrol driven vehicles on the roads throughout Europe. Ferguson left school at the age of 15 and began working full-time with his father on the farm. His light build, however, proved most unsuitable for the heavy farm labor. In truth, he had no interest in the work. By the age of 17, he was preparing to immigrate to Canada. By most accounts he had the necessary paper work in his possession when the oldest brother Joe offered him the opportunity to serve an apprenticeship in his new business (Fraser 1972, 1973). Joe also had no interest in farm work and had started an apprenticeship, at the age of 15, as a maintenance mechanic with the firm of Combe Barbour, general engineers, making linen machines and other factory machines. Then in 1901, Joe joined with two other ex-apprentices from Combe Barbour, Stewart Hamilton and James Alexander McKee, to form the Stewart Partnership on the Shankill Road in North Belfast. This started as a small engineering business but soon concentrated on automobile and motorcycle repairs and, in fact, this was one of the first garages in the city of Belfast. A short time later, Joe opened his own garage on Little Donegall Street in Belfast and called his business, J.B. Ferguson and Company, Automobile Engineers. Later in life he was to own a car dealership in New York.

Belfast (from the Gallic, or Irish language – *Béal Feirste* – meaning sandy ford at river mouth) was originally a town in County Antrim (http://en.wikipedia.org./wiki/belfast). The County Borough of Belfast was created when it was granted city status in 1888 by Queen Victoria. The population within the city limits at that time, according to the 1881 census, was 208,122 (www.nirsa.gov.uk). The city is situated on the eastern coast and is flanked to the northwest by a series of hills, including the Cavehill which is thought to be the inspiration for Gulliver's Travels, a novel by the Irish writer Jonathan Swift. Belfast is a port city, located at the western end of Belfast Lough at the mouth of the River Lagan, making it an ideal location for the shipbuilding industry that once made it famous. When the Titanic was built there in 1912, Harland and Wolff was the largest shipyard in the world. This shipyard with its giant cranes, which could be seen from most parts of the city, is renowned for building many famous ships. The Olympic-class ocean liners which were a trio of the largest and most luxurious ocean liners of their time (namely the RMS Titanic, RMS Olympic and HMHS Britannic) were built there between 1908 and 1914. During and immediately after the Second World War, Belfast was an industrial city known around the world not only for the building of large ships, but for aircraft manufacture, the linen industry, and rope manufacturing. Not far from the shipyard is the aircraft factory, Short Brothers and Harland, which is renowned for the building of freight, and small passenger, aircraft. In the early 1960s, the factory would gain notoriety for its pioneering work with a vertical take-off and landing (VTOL) research aircraft known as the SC1. The Rolls-Royce Flying Bedstead proved the vertical lift capabilities of the RB108 engines, but only flew in England. Belfast is also the birthplace of many famous engineers and mathematicians, including, William Thomson, perhaps better known as Lord Kelvin (1824–1907), Osborne Reynolds (1842–1912), John Greenlees Semple (1904–1985), and John Stewart Bell (1928–1990).

So it was in this city, in the year 1901, that Harry Ferguson joined his brother as an apprentice mechanic in the car and cycle repair shop. They were very successful in both motor-cycle and car racing and established what was described by many as the best garage business of its kind within the city limits. Harry showed he had a natural gift for mechanics and engineering. In 1903, he built a motor-cycle to his own design and won a hill test to determine how its performance would compare with factory production motor-cycles. He also won several road races and trials. Then in 1907, he built and raced his own car. For most of his life, Harry promoted motor-cycle and car racing. His efforts led to the Stormont Road Races Act of 1932, which made possible the first Ulster Grand Prix on the roads of Northern Ireland. He also lobbied the Royal Automobile Club (RAC) to organize the famous Tourist Trophy (TT) motor cycle races (1928–1936). In later life, Harry would apply himself to the design of four-wheel drive cars. He designed the Ferguson Formula car which could transmit traction and braking torque equally to all four wheels. This resulted in the four-wheel drive, using controlled differentials to govern the speeds of the individual wheels. The differential had a limited range of motion only, the front wheels could travel up to 15% faster than the rear wheels (which is a condition required when turning a circle at maximum lock). The rear wheels could turn 5% faster than the front wheels, which was the margin to allow for deflation of a rear tyre. If there was a tendency for greater speed variations than these values, then the differential would lock and all four wheels would be driven at the same speed. The master differential allowed the use of the Maxaret anti-lock brake system that was developed by Dunlop, initially for aircraft wheels. Ferguson developed the first Formula 1 racing car with all wheel drive, the car was the Ferguson P99 (http://en.wikipedia.org./wiki/ferguson), the system included viscous coupling and the anti-lock braking system. The British race car driver Stirling Moss raced a car of this design in the 1960 and 1961 Formula 1 World Championships. Moss, one of the most successful Formula 1 racing car drivers until he was forced to retire in 1962, won the Gold Cup at Oulton Park with the P99. This, of course, was before four-wheel drive cars were excluded from the racing circuit. The P99 also won the British Hill Climb Championship on two occasions. The system, designed by Ferguson was later used in the Jensen FF car. This car had a four-wheel drive system with unequal front/rear torque splitting, a self-locking center differential, and the Maxaret anti-lock brake unit.

By the age of 25, Ferguson had designed and flown a monoplane (http://www.uftm.org.uk). Apparently his initial interest in aviation was galvanized by the excitement generated over Bleriot's crossing of the English Channel in July 1909. He attended the flying meetings at Rheims in August of that year and the Paris Air Exhibition in September. He started to build his first aeroplane immediately upon his return. Although Harry's main expertise was in the building and tuning of engines, he had studied all the aircraft on display in France in great detail, and this enabled him to mastermind the construction of the aircraft on the premises of J. B. Ferguson and Company Ltd., while his brother Joe was in America on motor-related business. Ferguson was the first Briton to build and successfully fly a powered aeroplane in Ireland, this was only 6 years after the pioneering flight of the Wright brothers. While early attempts to get airborne were unsuccessful, he did manage his first flight of this small monoplane on December 31, 1909, at Hillsborough. Ferguson faced the aeroplane into the wind, and with the power of an eight-cylinder engine, raised the aeroplane into the air to a height of about 12 ft. Apparently the aeroplane traveled a total distance of about 130 yards before Ferguson brought it back to earth for a safe landing. Ferguson also flew the monoplane at Magilligan Strand, County Londonderry. His flight at Dundrum Bay, just north-east of Newcastle, County Down, in August 1910, was officially recognized by the Aeroplane Club. He won a cash prize of £100 offered for a 2 miles flight, although Harry flew closer to 3 miles. A man who claimed to have helped Ferguson construct the monoplane was William John Sands (Flackes 1960) who lived on the Old Hillsborough Road, Lisburn, County Down. Due to his age at that time, however, it appears unlikely that Sands worked on the early version of the Ferguson aeroplane. Two friends, Joseph Martin and John L. Williams, however, were prominent throughout the design, building and flight testing of the aircraft. Joe lived in Dromore, County Down, and worked for J.B. Ferguson. He was an expert in building spoked wheels for motor cars. Sands was about 19 years old when he was employed by Ferguson, after serving an apprenticeship in the maintenance of machinery for the linen industry. He also operated a small car repair business on the Lisburn Road. Sands would end up working for Ferguson for more than 35 years, and their association would cover almost 50 years. They had a friendship which survived some very sharp disagreements. In fact, Sands would testify against Ferguson during the infamous lawsuit filed by Ferguson in January 1948 against the Ford Motor Company. Sands had come to believe that he was the true inventor of the Ferguson System (see the following section) and while Sands was an engineering genius in his own right, he was a designer and not an inventor. In the lawsuit against the Ford Motor Company, Ferguson was seeking damages in excess of $250 million on the grounds that Ford had conspired to destroy the Ferguson business and for alleged infringement of several Ferguson patents. The lawsuit was finally settled out of court some 4 years later, in April 1952, for less than $10 million in damages to Ferguson in payment of royalties on patented devices used by Ford after the break-up with Ferguson. These devices comprised, in large part, the Ferguson System.

Harry opened his own motor repair business in Belfast, in 1911, which he called the May Street Motor Company, Limited. Harry would eventually move the business to Lower Donegall Street East. Joe Martin went with Harry to May Street and John Williams also worked for Harry up to the time of his untimely death in 1940. Two other gentlemen who worked for Ferguson were Hugh Reid, who joined the company as a journeyman draughtsman in 1918, and Joseph Thompson, who started as an apprentice and, for many years, was manager of Harry Ferguson (Motors) Limited in Belfast. Subsequently, Thompson bought the business and it was renamed Thompson-Reid Limited. It is interesting to note that the internal combustion engine which was to play such an integral part in the automobile industry, in general, and tractors, in particular, was invented in 1885, just a few months after Harry was born. In 1913, Ferguson married a local girl called Maureen Watson in a registry office in Newry, County Down. The following year, as a loyalist, he was involved in gun running for the Ulster Volunteer Force. Then when the First World War broke out, the Irish Department of Agriculture offered him a wartime Governmental post. At this time, Harry was the agent for a 20 horse power American tractor, called the Overtime. The department asked Ferguson to supervise the operation and maintenance of the small number of tractors that were in use at that time to increase domestic food production. This could be described as the turning point in the life of Harry Ferguson. It was his introduction to the mechanization of agriculture, and the beginning of his focus on plow design. He came to the conclusion that efficient agriculture based on mechanization was the only solution to the problems of food supply around the world. He put all his energy into the development of equipment which he believed would bring down the cost of food production and the cost of living. William J. Sands was with Ferguson during the campaign to increase tractor usage and food production in Ireland during the First World War. He provided a clue to the origin of Ferguson's obsession with agricultural production in pointing out that Ferguson consulted with Dr. Wibberley of Queen's University, Belfast, who had written a book on farming along factory lines (Flackes 1960).

The Overtime tractor was a very heavy machine (it weighed over 2 tons) and dangerous to operate. Ferguson was of the opinion that only a tractor of his own design would do justice to his new plow. He came to the conclusion that the whole idea of making a tractor as one unit, and the implement as another, was entirely wrong. Ferguson designed and built a plow in 1917 which would increase efficiency in food production. His plow was to be coupled to the tractor by a three point linkage, that is, the three-point hitch (Rae 1980). It is interesting to note that Henry Ford began to work on developing a light, cheap and durable tractor as early as 1907, but did not arrive at a satisfactory design until about 1915. As fate would have it, the first Henry Ford tractor (named the Fordson) went into production in 1917. The plow that Ferguson developed, commonly referred to as the "Belfast plough", was first linked to the Model T Ford but was then designed specifically for the Fordson tractor. The man who translated Ferguson's plow ideas into metal was William John Sands. The new two-furrow implement was presented to the farming public at a demonstration in Coleraine, County Antrim. However, in 1918, the Ferguson plow was not at the level of perfection to which the designer aspired. He patented the duplex hitch in that year. However, patents were typically sacrificed because there was not enough money to keep them alive. Also, in that year of 1918, Harry and Maureen had a daughter Elizabeth (Betty). She was to be their only child. Betty would marry Anthony J. Sheldon, an employee in the Ferguson Company. They would have a daughter Sally (she would marry and become Mrs. Sally Fleming), and a son Jamie. The Ferguson Family Museum is currently operated by Jamie on the Isle of Wight (www.ferguson-museum.co.uk).

By 1920, the British farmer had still not decided that the tractor had come to stay. Ferguson and Sands traveled to the United States to visit Henry Ford and show him their, still from perfect, design. Ford offered Ferguson a position in his organization to develop the plow further but refused to provide him with manufacturing facilities. Preferring to remain independent, Ferguson refused the offer. The story of Ferguson's struggle throughout the 1920s and much of the 1930s is one of never giving up in face of repeated frustrations. Fortunately, he had the support of some fine men during this time, many of whom he had first met while taking technical courses at the Belfast Technological College. These men included Captain John L. Williams, Joseph Thompson, Ernest Hamilton Browne, Trevor Knox, Archibald Greer, John Chambers, and T. MacGregor Greer. In 1921, Ferguson took his plow to the Fordson tractor plant in Cork, Ireland, to carry out further tests with some of the Ford staff. The Fordson, as previously mentioned, was a light tractor with many of the same faults as the other light tractors of that period. However, little came from this interaction and Ferguson continued to focus on the development of his plow. He made an arrangement with the Shunk Company, Bucyrus, Ohio to manufacture the plow (Neufeld 1969). Then the business was shifted to Indiana and the Ferguson-Sherman Corporation of Indiana was formed in the town of Evansville, in the southern part of the state. This company was a sales organization which sold thousands of his hand-lift plows with automatic depth control. Some of the components for the Ferguson plow were manufactured at the near-by Vulcan Plow Company.

List of Main Works

During his life time, Ferguson would compile over 100 patents (http://www.google.com/patents; http://ep.espacenet.com) beginning in 1912, with improvements in and relating to carburetors for internal combustion engines, and continuing up through 1950. Most of the patents after 1915 would relate to improvements in the tractor, the plow and agricultural implements, for example, GB119883: Improvements relating to tractor ploughs; GB122703: Improvements relating to ploughs; CA200513: Plough; FR527705: Perfectionnements aux moyens d'accouplement des instruments aratoires; US1379399: Means for coupling agricultural machinery; CA207827: Plough; US1464130: Means for coupling agricultural implements; CA234363: Means of coupling agricultural implements to tractors; CA233226: Agricultural implement; US1501652: Agricultural implement; US1501651: Agricultural implement; CA236960: Agricultural implement; US1526972: Plow; and US1529425: Plow. However, the patents that would revolutionize farming were the patents for the Ferguson system, or the Ferguson hydraulic draft control system. The system was covered by numerous patents which dated from 1917 to 1939. Many of these patents owed a great deal to various members of the Ferguson team. However, it was Ferguson's vision which directed them towards specific solutions to the engineering problems.

Review of Main Works on Mechanism Design

The master patent, filed by Ferguson in 1925, was GB253566 and incorporated the principal of draft control whereby the depth of a ground-engaging implement is automatically controlled by reference to the effort, or draft, required to pull it. The movement of the linkage could be controlled by an electric, mechanical, or hydraulic device. This patent also covered draft control by means of the transmission torque of the tractor. Taken from this patent is Fig. 2 which is a schematic diagram of a disk harrow coupled to the hydraulic mechanism in conjunction with the draft control for angling the disks automatically.

The frame (46) is attached to the disk gangs by means of ball joints (47) and, at the forward end, is pivotally attached to the rocker (9). The rods (48), connected to the disk gangs and to the bell crank (49), serve to regulate the angle of the disk

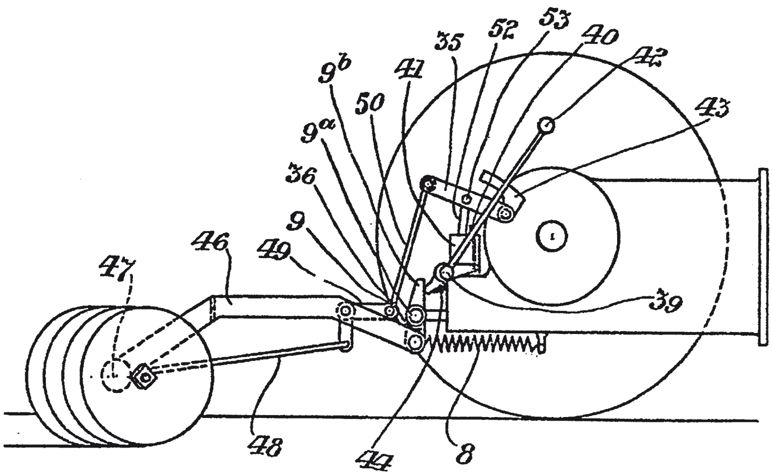


Fig. 2 A schematic diagram of a disk harrow with draft control

gangs. The bell crank is also coupled to the duplex links (35) by means of a rod (50). The duplex links, pivoted on the tractor, are actuated by the piston of the arm cylinder (41) through the piston rod (52) and the crossbar (53). The hand control lever (42) rotates the eccentric shaft (39) on which is mounted a bell crank, which is coupled to the valve (40). A quadrant (43) is provided to retain the hand control lever in any pre-determined position in order to adjust the working depth of the implement. The spring (8) is attached to the rocker (9) and the tractor frame and takes the pull of the implement. Any variation in the pull produces a movement of the rocker which is communicated to the bell crank (pivoted on the eccentric shaft (39) for hand control) which operates a valve (40) and in turn controls the pressure of the oil in the cylinder (41).

The Ferguson system was a system for the mechanization of agricultural operations with the aim and objective of enabling increased production of food and other farm commodities easily, economically and profitably, so that farm products could reach all the people at prices they could afford. The system was a combination of a mechanical linkage and a hydraulic mechanism for controlling the operation of farm implements. The original version of the Ferguson system is shown in Fig. 3 where A denotes the neutral position, B denotes the raised position, and C denotes the lowered position (Morling 1979). The essential features of the system are: (a) integration of the implements with the tractor; (b) hitch geometry to keep the front end of the tractor on the ground (i.e., weight transfer from the implement to the rear wheels of the tractor); (c) traction without excessive tractor weight (i.e., implement penetration without excessive implement weight); (d) continuous automatic control of the implement in the soil; (e) quick and simple attachment and detachment of the implements to and from the tractor; (f) protection of the implement from all normal hazards of operation (such as hitting rocks and other hidden obstructions); and (g) finger-tip and automatic hydraulic control and operation of the tractor and the

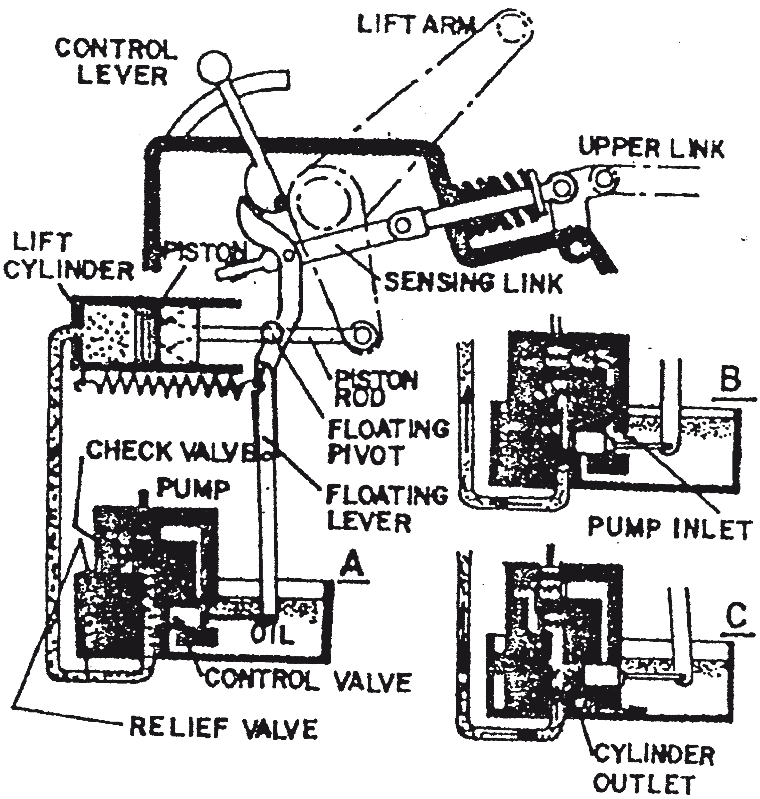


Fig. 3 The original Ferguson draft control hydraulic system

implements. These features were realized with the development of a suitable linkage arrangement between the tractor and the implement, a system of hydraulic controls, and an appropriate tractor. The linkage system, referred to as "the three-point linkage" or "the three-point hitch" was designed with two links at the bottom to pull the implement and one link at the top. It is interesting to note that the original design had two links at the top and one link at the bottom (www.ferguson-museum.co.uk). However, Ferguson quickly realized that this arrangement would not work. The top link served two purposes; namely (a) it served as a rigid restraining brace between the tractor and the implement which prevented the front end of the tractor from rearing backwards off the ground; and (b) as the implement pulled back on the bottom two links (when in the ground), it pushed the top link forward which in turn activated a hydraulic mechanism that tended to exert a lifting force on the implement.

The lifting tendency added weight to the rear wheels and increased traction. It also acted as a counterweight to the front end, shifting front weight to the rear wheels and providing useful traction. Due to the implement reaction forces, the Ferguson tractor could be made lighter and smaller while actually gaining increased stability. This was one of the key features of the Ferguson system. Another important aspect was the method for lifting and lowering the implement and for controlling the depth of the implement in the soil. This was provided by a hydraulic mechanism that was built into the tractor and could be controlled either manually or automatically. Manual control was furnished by a small lever which caused the built-in hydraulic mechanism to lift, lower and adjust the working depth. Automatic control utilized the resistance of the soil as the implement was pulled forward, to activate a control spring through the pushing or compression forces set up in the top link. The control spring in turn governed the hydraulic mechanism, causing it to react automatically, and so govern the working depth of the implement as preset manually. In this manner, an increase in the soil resistance would not stop the progress of the tractor. Rather, it would push the top link forward which, in turn, would cause the hydraulic mechanism to exert a lifting tendency on the implement. This, in turn, would increase the tractive weight on the rear wheels, thereby adding to the pulling ability of the tractor. Furthermore, to the extent that the implement was momentarily lifted out of the soil, allowed the tractor to move forward even under hard-pulling conditions. The implement in the two extreme positions is shown in Fig. 4 (Fraser 1973).

A tractor with the Ferguson system was light, maneuverable, ideally suited for small fields and was applicable to a wide variety of farming implements. The single upper link had improved the draft control but problems remained caused by the continuous pumping of oil under pressure and the tendency to heat and aerate it. In some cases, the problem was so severe that after some 30 min of work, the hydraulic system would airlock. The solution that was proposed by Ferguson was to put the hydraulic control valve on the suction side of the pump. This, in effect, cut off the supply of oil to the pump when no oil under pressure was required to raise the implement. The pump and the control valve had to be submerged in oil. However, Ferguson could foresee no real problems with this arrangement. The control valve, which would be

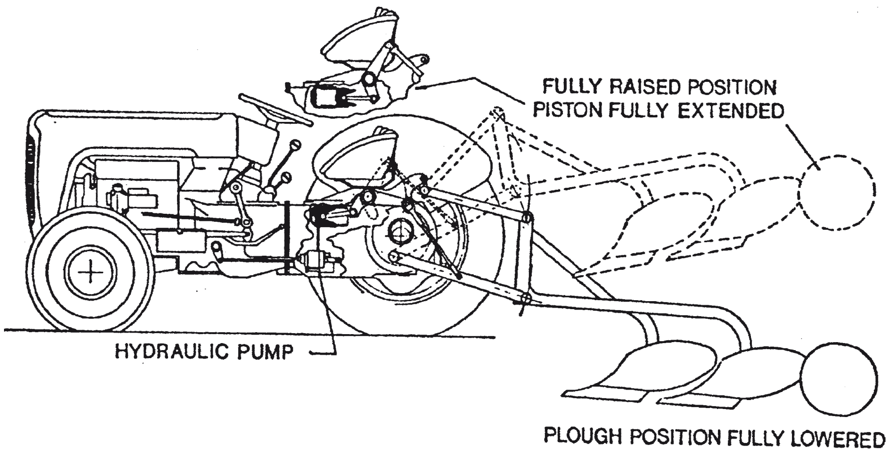


Fig. 4 The implement in the two extreme positions

actuated by the draft forces in the upper link, would be a sleeve running in a housing which was part of the pump. In the housing there would be two ports or openings (an inlet port and an outlet port). When the sleeve valve was centrally located it would block off both ports, thereby retaining the oil in the ram cylinder and holding the lower links at their actual height. If there was an increase in draft as the implement went deeper, the extra compression load in the upper link would slide the valve one way to uncover the inlet port and allow the pump to suck in oil and raise the implement back to the pre-set depth of work. If there was a decrease in draft, the valve would slide the opposite way to uncover the outlet port and allow the oil to escape from the ram cylinder back into the sump, thus lowering the implement.

The automatic mechanism actuated through draft forces in the upper link could, of course, be over-ridden by the lever next to the driver's seat when the driver wanted to raise or lower the implement on the headland or make an adjustment in the working depth. This solution was referred to as suction side control and turned out to be the basic answer to the problem. However, some mild tendency towards bobbing of the implements under certain conditions was to remain for several years. It was finally eliminated by detail changes to the control valve design. Suction side cut-off was the last breakthrough needed to make hydraulic draft control a completely sound and practical proposition. A detailed illustration of the design of the Ferguson system is shown in Fig. 5 (Morling 1979).

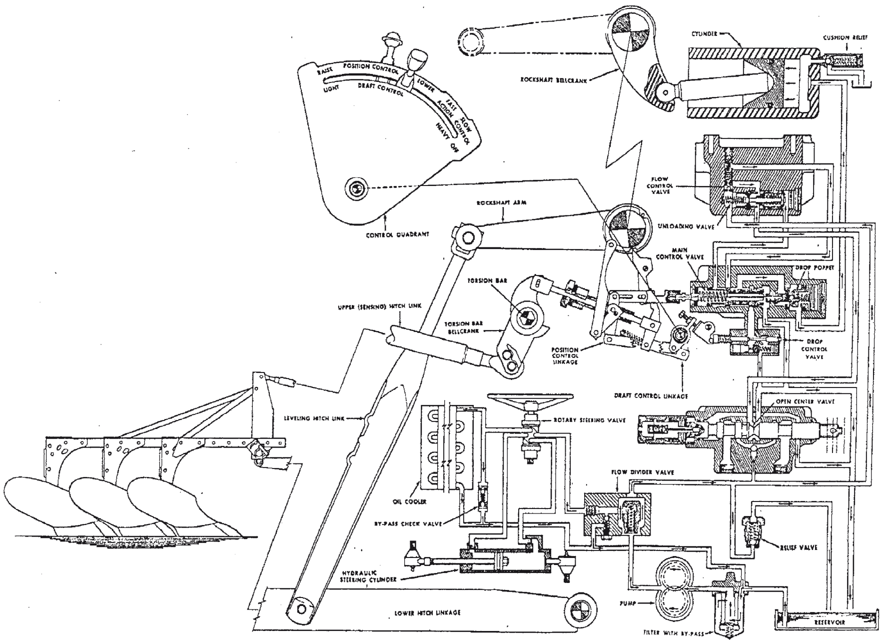


Fig. 5 The design of the Ferguson system

On the Circulation of Works

In 1929, Ferguson claimed to have solved the power farming problem and, in 1930, a demonstration of the tractor system was scheduled for the Northern Ireland government at Andersonstown, on the outskirts of Belfast. However, there were technical details that needed to be resolved and there was the problem of finding the capitol for large-scale production. He asked the Government of Northern Ireland for money to establish his tractor production in Ulster. Lord Craigavon had suggested that financial support would be made available, but nothing happened. The first Ferguson prototype tractor was ready in 1933. The tractor weighed only 16 cwt, compared to the 30 cwt of the lightest tractor then in production. Most of these tractors were built in Belfast and had steel wheels, before tractors had pneumatic tyres. In 1935 after much experiment and engineering development, Ferguson finally claimed to have perfected the Ferguson System. It had taken him almost 16 years to bring the application of hydraulics to mounting implements behind the tractor to what he regarded as a commercially viable platform. This may seem an exceptionally long period of time but it should be remembered that the pumps, control valves, and hydraulic cylinders that he required for the tractor application all had to be designed and developed with no apriori knowledge. The Brown-Ferguson Company was formed about this time and produced the 1354 Model A tractor. The tractors were manufactured in Huddersfield, England, by the David Brown Company. Since the name “Brown” was better known than the name “Ferguson,” the tractors were named the Brown-Ferguson tractors and were introduced in 1936.

Then in 1939, Ferguson entered into a partnership with Henry Ford to sell tractors that incorporated the Ferguson System. This led to the Ford-Ferguson tractor (or the Ford tractor – Ferguson system). More than 300,000 of these tractors were manufactured and sold around the world between 1939 and 1947. It is interesting to note that Ford had never considered entering into any form of a partnership with Ferguson. However, he knew if he was to do business with him, he would have to break his golden rule. They never signed a formal contract, their word was their bond, and they sealed their bargain simply by the shaking of hands. Ford was so impressed with the Ferguson system that he told him “This machine is a work of genius…you have put yourself on a plane with such inventors as the Wright Brothers, Marconi, Edison, and Bell… You will make history!” (Wymer 1961). Soon after World War II, Ferguson and Sir John Black of the Standard Motor Company, Coventry, began manufacturing the Ferguson tractor. The Ferguson TE-20 model (TE referred to Tractor England, there was also a TO model where TO referred to Tractor Overseas) a light-weight tractor was one of the models. It was Ferguson’s most successful design, commonly known as the Little Grey Fergie (or Wee Fergie). Approximately 500,000 of these tractors were manufactured at the Banner Lane plant in Coventry between 1946 and 1954. Hundreds of thousands of successor models were built at this plant for some 50 years until it closed in 2002. The TE-20 was a small but effective design and is a popular collectors’ item for enthusiasts today (Condie 2001).

In 1947, Ford's family (in particular Henry Ford II) reneged on the Ford-Ferguson contract. So in 1948, 9 years after the partnership was formed, Ferguson brought a lawsuit against the Ford Motor Company. The lawsuit was settled in 1952 with Ferguson receiving an estimated 3.3 million pounds sterling (approximately 9.25 million US dollars) in royalties. Ferguson's costs alone were thought to have been in the region of one million pounds sterling. It is important to note that the court refused to renew Ferguson's patent citing its major importance to agriculture and all tractor manufacturers. Surely this was a lasting testament to the engineering ability and ingenuity of Ferguson. In 1953, the Ferguson organization and the Massey-Harris Company, Toronto, amalgamated to form the Massey-Harris-Ferguson Company (later renamed as the Massey-Ferguson Company). The Massey-Harris company was responsible for producing the world's first commercially successful self-propelled combine in 1938. The merger brought together their twin skills in harvesting machinery and tractor design to produce one of the world's most powerful forces in farm equipment. In fact, the merger created a corporation with the second highest sales of farm machinery in the world (Neufeld 1969). However, it was another stormy partnership and in 1954, Ferguson resigned his office in the company. In 1995, the Massey-Ferguson company was purchased by the US-based AGCO Corporation.

Modern Interpretation of the Main Contributions

This section presents a kinematic and dynamic force analysis of the three-point hitch mechanism (Hain 1953, 1955, 1956, 1959, 1973; Hain and Skalweit 1957; Thaer 1956; Phillips 1958; Brock 1954). The method of kinematic coefficients is used to provide geometric insight into the kinematic analysis and the Newton-Euler technique, which also provides physical insight, is used for the dynamic force analysis (Uicker et al. 2003).

(a) Kinematic Analysis. A simple model of the hitch is obtained by assuming that it is symmetrical about the longitudinal axis of the tractor. In this case, each side mechanism (Brock 1954) can be modeled by a planar six-bar mechanism (see Fig. 6). The mechanism is essentially two four-bar linkages coupled by link 3. The input link 2 is actuated by a hydraulic actuator which causes the blade (link 6), in general, and blade point P, in particular, to lift out of and lower into the soil. The blade is attached to the tractor by a lower lift arm (link 4) and an upper link (link 5).

The vectors required for the kinematic analysis are shown in Fig. 6. There are two independent vector loops; namely: the vector loop for links 1, 2, 3 and 4; and the vector loop for links 1, 4, 5 and 6. The first vector loop equation can be written as

$$\overset{\surd I}{\bar{R}_2} + \overset{\surd ?}{\bar{R}_3} - \overset{\surd ?}{\bar{R}_4} - \overset{\surd \surd}{\bar{R}_1} = 0 \qquad (1)$$

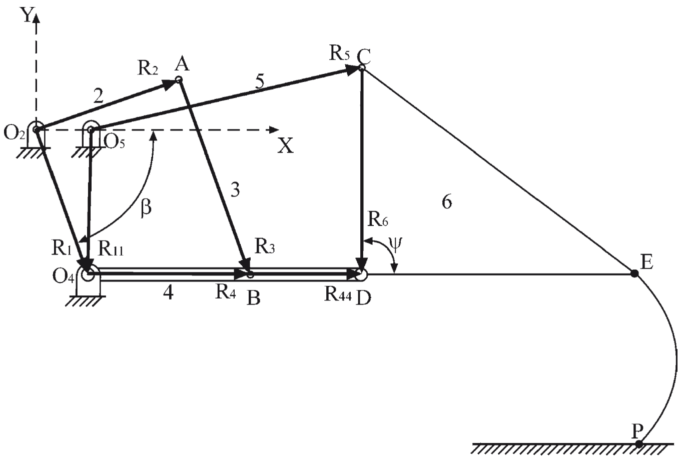


Fig. 6 The three point hitch and the vectors for the mechanism

where the first symbol above each vector indicates the magnitude and the second symbol indicates the direction of the vector with respect to the fixed X-axis. The known quantities are denoted by √, the unknown variables are denoted by ?, and the independent variable (or input θ_2) is denoted by I. For a given position of the input link, the position of links 3 and 4 can be obtained by several techniques, such as trigonometry, or a numerical method, for example, the Newton-Raphson iterative technique (Phillips 1958). Differentiating the X and Y components of Eq. (1) with respect to the input position and writing the resulting equations in matrix form, gives

$$\begin{bmatrix} -R_3 \sin\theta_3 & R_4 \sin\theta_4 \\ R_3 \cos\theta_3 & -R_4 \cos\theta_4 \end{bmatrix} \begin{bmatrix} \theta_3' \\ \theta_4' \end{bmatrix} = \begin{bmatrix} R_2 \sin\theta_2 \\ -R_2 \cos\theta_2 \end{bmatrix} \tag{2}$$

where θ_3' and θ_4' are referred to as the first-order kinematic coefficients of links 3 and 4, respectively (Uicker et al. 2003). Using Cramer's rule, these kinematic coefficients are

$$\theta_3' = \frac{R_2 R_4 \sin(\theta_4 - \theta_2)}{\text{DET}} \quad \text{and} \quad \theta_4' = \frac{R_2 R_3 \sin(\theta_3 - \theta_2)}{\text{DET}} \tag{3a}$$

where the determinant of the coefficient matrix in Eq. (2) can be written as

$$\text{DET} = R_3 R_4 \sin(\theta_3 - \theta_4) \tag{3b}$$

Differentiating the X and Y components of Eq. (1) twice with respect to the input position and writing the resulting equations in matrix form, gives

$$\begin{bmatrix} -R_3 \sin\theta_3 & R_4 \sin\theta_4 \\ R_3 \cos\theta_3 & -R_4 \cos\theta_4 \end{bmatrix} \begin{bmatrix} \theta''_3 \\ \theta''_4 \end{bmatrix} = \begin{bmatrix} R_2 \cos\theta_2 + R_3 \cos\theta_3\, \theta'^2_3 - R_4 \cos\theta_4\, \theta'^2_4 \\ R_2 \sin\theta_2 + R_3 \sin\theta_3\, \theta'^2_3 - R_4 \sin\theta_4\, \theta'^2_4 \end{bmatrix} \tag{4}$$

where θ''_3 and θ''_4 are referred to as the second-order kinematic coefficients of links 3 and 4, respectively. Using Cramer's rule, these kinematic coefficients can be written as

$$\theta''_3 = \frac{-R_2 R_4 \cos(\theta_2 - \theta_4) - R_3 R_4 \cos(\theta_3 - \theta_4)\theta'^2_3 + R_4^2 \theta'^2_4}{\text{DET}} \tag{5a}$$

and

$$\theta''_4 = \frac{-R_2 R_3 \cos(\theta_2 - \theta_3) - R_3^2 \theta'^2_3 + R_3 R_4 \cos(\theta_3 - \theta_4)\theta'^2_4}{\text{DET}} \tag{5b}$$

where the determinant is given by Eq. (3b).

The second vector loop equation can be written as

$$\overset{\surd?}{\underline{R}}_5 + \overset{\surd?}{\underline{R}}_6 - \overset{\surd?}{\underline{R}}_{44} - \overset{\surd\surd}{\underline{R}}_{11} = 0. \tag{6}$$

Differentiating the X and Y components of this equation with respect to the input position gives

$$-R_5 \sin\theta_5\, \theta'_5 - R_6 \sin\theta_6\, \theta'_6 + R_{44} \sin\theta_4\, \theta'_4 = 0 \tag{7a}$$

and

$$R_5 \cos\theta_5\, \theta'_5 + R_6 \cos\theta_6\, \theta'_6 - R_{44} \cos\theta_4\, \theta'_4 = 0. \tag{7b}$$

Then writing these two equations in matrix form gives

$$\begin{bmatrix} -R_5 \sin\theta_5 & -R_6 \sin\theta_6 \\ R_5 \cos\theta_5 & R_6 \cos\theta_6 \end{bmatrix} \begin{bmatrix} \theta'_5 \\ \theta'_6 \end{bmatrix} = \begin{bmatrix} -R_{44} \sin\theta_4\, \theta'_4 \\ R_{44} \cos\theta_4\, \theta'_4 \end{bmatrix}. \tag{8}$$

Using Cramer's rule, the first-order kinematic coefficients of links 5 and 6 can be written as

$$\theta'_5 = \frac{R_{44} R_6 \sin(\theta_6 - \theta_4)\theta'_4}{\text{DET}} \quad \text{and} \quad \theta'_6 = \frac{R_{44} R_5 \sin(\theta_4 - \theta_5)\theta'_4}{\text{DET}} \tag{9}$$

where the determinant of the coefficient matrix in Eq. (8) is

$$\text{DET} = R_5 R_6 \sin(\theta_6 - \theta_5). \tag{10}$$

Differentiating the X and Y components of Eq. (6) twice with respect to the input position and writing the answers in matrix form, gives

$$\begin{bmatrix} -R_5\sin\theta_5 & -R_6\sin\theta_6 \\ R_5\cos\theta_5 & R_6\cos\theta_6 \end{bmatrix}\begin{bmatrix} \theta_5'' \\ \theta_6'' \end{bmatrix} = \begin{bmatrix} R_5\cos\theta_5\,\theta_5'^2 + R_6\cos\theta_6\,\theta_6'^2 - R_{44}\cos\theta_4\,\theta_4'^2 - R_{44}\sin\theta_4\,\theta_4'' \\ R_5\sin\theta_5\,\theta_5'^2 + R_6\sin\theta_6\,\theta_6'^2 - R_{44}\sin\theta_4\,\theta_4'^2 + R_{44}\cos\theta_4\,\theta_4'' \end{bmatrix} \tag{11}$$

Using Cramer's rule, the second-order kinematic coefficients of links 5 and 6 can be written as

$$\theta_5'' = \frac{R_6^2\theta_6'^2 + R_5R_6\cos(\theta_5-\theta_6)\theta_5'^2 - R_6R_{44}\cos(\theta_4-\theta_6)\theta_4'^2 - R_6R_{44}\sin(\theta_4-\theta_6)\theta_4''}{DET} \tag{12a}$$

and

$$\theta_6'' = \frac{-R_5^2\theta_5'^2 - R_5R_6\cos(\theta_6-\theta_5)\theta_6'^2 - R_5R_{44}\cos(\theta_4-\theta_5)\theta_4'^2 - R_5R_{44}\sin(\theta_4-\theta_5)\theta_4''}{DET} \tag{12b}$$

where the determinant is given by Eq. (10).

Using the chain rule, the angular velocity and acceleration of link j (= 3, 4, 5 and 6) can be written, respectively, as

$$\omega_j = \theta_j'\,\omega_2 \quad \text{and} \quad \alpha_j = \theta_j''\,\omega_2^2 + \theta_j'\,\alpha_2. \tag{13}$$

Now that the angular velocities and accelerations of the links are known, the kinematics of the blade point P can be investigated. The vector equation for point P, see Fig. 6, can be written as

$$\underset{R_P}{??} = \underset{R_1}{\surd\surd} + \underset{R_{44}}{\surd\surd} + \underset{R_{66}}{\surd\surd} + \underset{R_{67}}{\surd\surd} \tag{14}$$

where $\overline{R}_{66}$ is the vector from pin D to point E and $\overline{R}_{67}$ is the vector from point E to point P. Differentiating the X and Y components of this equation with respect to the input position, the first-order kinematic coefficients of point P are

$$X'_P = -R_{44}\sin\theta_{44}\theta_4' - R_{66}\sin(\theta_6+\psi)\theta'_6 - R_{67}\sin\theta_6\theta_6' \tag{15a}$$

and

$$Y'_P = R_{44}\cos\theta_{44}\theta_4' + R_{66}\cos(\theta_6+\psi)\theta'_6 + R_{67}\cos\theta_6\theta_6'. \tag{15b}$$

Then differentiating these equations with respect to the input position, the second-order kinematic coefficients of point P are

$$\begin{aligned} X''_P = &-R_{44}\cos\theta_{44}\theta_4'^2 - R_{44}\sin\theta_4\theta_4'' - R_{66}\cos(\theta_6+\psi)\theta_6'^2 \\ &- R_{66}\sin(\theta_6+\psi)\theta_6'' - R_{67}\cos\theta_6\theta_6'^2 - R_{67}\sin\theta_6\theta_6'' \end{aligned} \tag{16a}$$

and

$$Y''_P = -R_{44}\sin\theta_{44}\theta_4'^2 + R_{44}\cos\theta_4\theta_4'' - R_{66}\sin(\theta_6+\psi)\theta_6'^2 + R_{66}\cos(\theta_6+\psi)\theta_6'' - R_{67}\sin\theta_6\theta_6'^2 + R_{67}\cos\theta_6\theta_6'' \tag{16b}$$

Finally, the velocity and the acceleration of point P can be written, respectively, as

$$\bar{V}_P = (X'_P\,\hat{i} + Y'_P\,\hat{j})\,\omega_2 \tag{17a}$$

and

$$\bar{A}_P = (X''_P\,\hat{i} + Y''_P\,\hat{j})\,\omega_2^2 + (X'_P\,\hat{i} + Y'_P\,\hat{j})\,\alpha_2. \tag{17b}$$

The geometry of the path of point P can also be expressed in terms of kinematic coefficients. The unit tangent and unit normal vectors to the path of point P are defined, respectively, as

$$\hat{u}^t = \frac{X'_P\,\hat{i} + Y'_P\,\hat{j}}{R'_P} \quad \text{and} \quad \hat{u}^n = \hat{k}\times\hat{u}^t = \frac{-Y'_P\,\hat{i} + X'_P\,\hat{j}}{R'_P}, \tag{18a}$$

where

$$R'_P = \pm\sqrt{\left(X'_P\right)^2 + \left(Y'_P\right)^2}. \tag{18b}$$

The positive sign is chosen if the change in the input position is positive, that is counterclockwise, and the negative sign is chosen if the change in the input position is negative, that is, clockwise.

The radius of the curvature of the path of point P can be written as (Uicker et al. 2003)

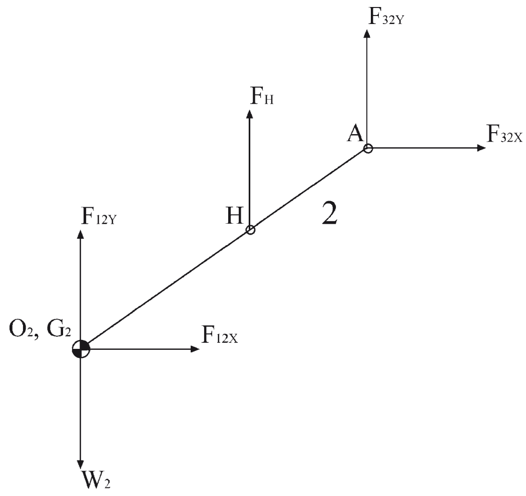
$$\rho_P = \frac{R_P'^{\,3}}{X'_P Y''_P - Y'_P X''_P} \tag{19}$$

where the first and second-order kinematic coefficients of point P are given by Eqs. (15) and (16), respectively. The X and Y coordinates of the center of the curvature of path of point P can be written, respectively, as

$$X_{CC} = X_P - \rho_P\left[\frac{Y'_P}{R'_P}\right] \quad \text{and} \quad Y_{CC} = Y_P + \rho_P\left[\frac{X'_P}{R'_P}\right]. \tag{20}$$

In the design of a three point hitch, the length of link 2 and the range of motion of this link are predefined by the hitch itself (Ambike and Schmiedeler 2007). The length of link 4 (the rocker) is variable, and the designer can select the length of the coupler to produce the desired path, or orientation, for the implement. The desired performance, however, is not defined by traditional motion generation task

Fig. 7 The free body diagram of link 2



requirements (Kinzel et al. 2006). Rather, the typical design goals are to locate the instant center of the coupler (Uicker et al. 2003) (also referred to as the pitch point) in a desirable location, to provide the necessary ground clearance for the implement when it is not in use and to allow for some elevation of the implement without significant change in its orientation.

(b) Dynamic Force Analysis. For convenience, the centers of mass of links 2, 4, and 5 are assumed coincident with the ground pivots O_2, O_4, and O_5, respectively, and the centers of mass of links 3 and 6 are assumed coincident with points B and E, respectively. The actuating force, denoted as $\bar{F}_H$, is provided by a hydraulic actuator which is assumed to act vertically upward at point H, see the free body diagram of link 2 shown in Fig. 7.

From Newton's second law, the sum of the external forces in the X and Y directions can be written, respectively, as

$$F_{12X} + F_{32X} = m_2 A_{G_{2X}} = 0 \tag{21a}$$

and

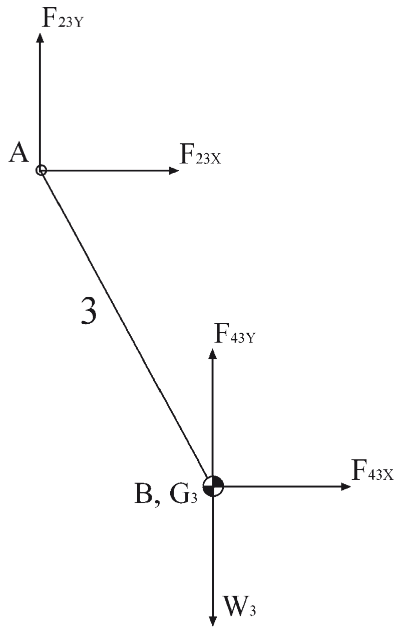
$$F_{12Y} + F_{32Y} + F_H - W_2 = m_2 A_{G_{2Y}} = 0, \tag{21b}$$

where F_{12X}, F_{12Y}, F_{32X}, and F_{32Y}, are the X and Y components of the internal reaction forces at pins O_2 and A, respectively, and W_2 is the weight of the link. From Euler's equation, the sum of the external moments about the mass center of link 2 can be written as

$$R_{22} \cos\theta_2 F_H + (R_2 \cos\theta_2 F_{32Y} - R_2 \sin\theta_2 F_{32X}) = 0. \tag{22}$$

The free body diagram of link 3 is shown in Fig. 8.

Fig. 8 The free body diagram of link 3



The sum of the external forces in the X and Y directions can be written, respectively, as

$$F_{23X} + F_{43X} = m_3 A_{G_{3X}} \tag{23a}$$

and

$$F_{23Y} + F_{43Y} - W_3 = m_3 A_{G_{3Y}}. \tag{23b}$$

The sum of the external moments about point A can be written as

$$(R_3 \cos\theta_3 F_{43Y} - R_3 \sin\theta_3 F_{43X}) - R_3 \cos\theta_3\, W_3 = I_{G_3}\bar{\alpha}_3 + m_3\, \bar{R}_3 \times \bar{A}_{G_3} \tag{24}$$

where the acceleration of the mass center of link 3 (which is coincident with pin B) is obtained from a kinematic analysis. The vector equation for point B can be written as

$$\bar{R}_B = \bar{R}_1 + \bar{R}_4. \tag{25}$$

Differentiating the X and Y components of this equation with respect to the input position, the first and second-order kinematic coefficients of point B, respectively, are

$$X_B' = -R_4 \sin\theta_4 \theta_4' \tag{26a}$$

$$Y_B' = -R_4 \cos\theta_4 \theta_4' \tag{26b}$$

$$Y_B'' = -R_4 \sin\theta_4 \theta_4'' - R_4 \cos\theta_4 \theta_4'^2 \tag{26c}$$

and

$$Y_B'' = R_4 \cos\theta_4 \theta_4'' - R_4 \sin\theta_4 \theta_4'^2. \tag{26d}$$

The X and Y components of the acceleration of point B can then be obtained from the relationships

$$A_{BX} = X_B' \alpha_2 + X_B'' \omega_2^2 \qquad \text{and} \qquad A_{BY} = Y'_B \alpha_2 + Y_B'' \omega_2^2. \tag{27}$$

The free body diagram of link 4 is shown in Fig. 9. The sum of the external forces in the X and Y directions can be written, respectively, as

$$F_{14X} + F_{34X} + F_{64X} = m_4 A_{G_{4X}} = 0 \tag{28a}$$

and

$$F_{14Y} + F_{34Y} + F_{64Y} - W_4 = m_4 A_{G_{4Y}} = 0. \tag{28b}$$

The sum of the external moments about the mass center of link 4 can be written as

$$(R_4 \cos\theta_4 F_{34Y} - R_4 \sin\theta_4 F_{34X}) + (R_{44} \cos\theta_4 F_{64Y} - R_{44} \sin\theta_4 F_{64X}) = I_{G_4} \alpha_4. \tag{29}$$

The free body diagram of link 5 is shown in Fig. 10. The sum of the external forces in the X and Y directions can be written, respectively, as

$$F_{15X} + F_{65X} = m_5 A_{G_{5X}} = 0 \tag{30a}$$

and

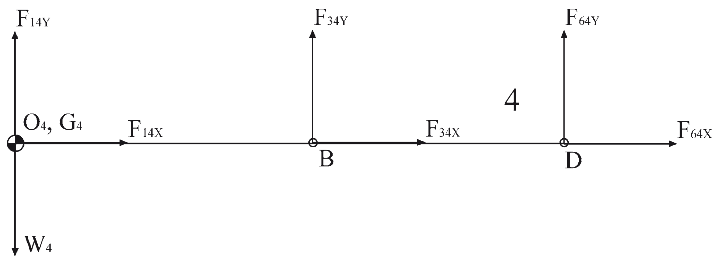


Fig. 9 The free body diagram of link 4

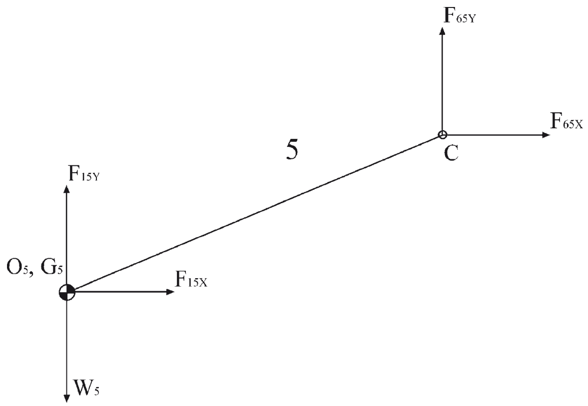


Fig. 10 The free body diagram of link 5

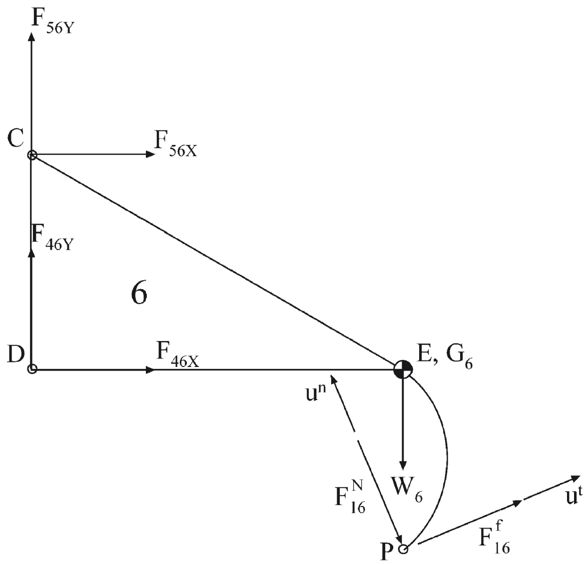


Fig. 11 The free body diagram of link 6

$$F_{15Y} + F_{65Y} - W_5 = m_5 A_{G_{5Y}} = 0. \tag{30b}$$

The sum of the external moments about the mass center of link 5 can be written as

$$R_5 \cos\theta_5 F_{65Y} - R_5 \sin\theta_5 F_{65X} = I_{G_5} \alpha_5. \tag{31}$$

The free body diagram of link 6 is shown in Fig. 11. The contact force between the ground and the blade point P is assumed to be known and the normal force is assumed to be acting downward, that is, in the opposite direction to the unit normal vector.

Also, the friction force opposes the velocity of point P, that is, the friction force is in the opposite direction to the unit tangent vector and can be written as

$$F_{16}^{f} = \mu \, F_{16}^{N} \tag{32}$$

where μ is the coefficient of friction. The sum of the external forces in the X and Y directions can be written, respectively, as

$$F_{56X} + F_{46X} - (F_{16}^{f})_P u^{tx} - (F_{16}^{N})_P u^{nx} = m_6 A_{G_{6X}} \tag{33a}$$

and

$$F_{56Y} + F_{46Y} - W_6 - (F_{16}^{f})_P u^{ty} - (F_{16}^{N})_P u^{ny} = m_6 A_{G_{6Y}} \tag{33b}$$

where u^{tx}, u^{ty}, u^{nx}, and u^{ny} are given by Eq. (18a). The sum of the external moments about point D can be written as

$$R_{DCX}F_{56Y} - R_{DCY}F_{56X} - R_{DEX}W_6 + \overline{R}_{DP} \times (-\overline{F}_{16}^{f} \bullet \hat{u}^{t} - \overline{F}_{16}^{N} \bullet \hat{u}^{n}) = I_{G_6}\overline{\alpha}_6 + m_6 \, \overline{R}_{DE} \times \overline{A}_{G_6}. \tag{34}$$

The vector equation for the mass center of link 6 (which is coincident with point E) can be written as

$$\overline{R}_E = \overline{R}_1 + \overline{R}_{44} + \overline{R}_{66}. \tag{35}$$

Differentiating the X and Y components of this equation with respect to the input position, the first and second-order kinematic coefficients of point E are

$$X_E' = -R_4 \sin\theta_4\theta_4' - R_{66}\sin(\theta_6 + 180 - \Psi)\theta_6' \tag{36a}$$

$$Y_4' = R_4 \cos\theta_4\theta_4' + R_{66}\cos(\theta_6 + 180 - \psi)\theta_6' \tag{36b}$$

$$\begin{aligned} X_E'' = & -R_4 \sin\theta_4\theta_4'' - R_4\cos\theta_4\theta_4'^2 - R_{66}\sin(\theta_6 + 180 - \psi)\theta_6'' \\ & - R_{66}\cos(\theta_6 + 180 - \psi)\theta_6'^2 \end{aligned} \tag{36c}$$

and

$$\begin{aligned} Y_E'' = & R_4 \cos\theta_4\theta_4'' - R_4\sin\theta_4\theta_4'^2 + R_{66}\cos(\theta_6 + 180 - \Psi)\theta_6'' \\ & - R_{66}\sin(\theta_6 + 180 - \Psi)\theta_6'^2. \end{aligned} \tag{36d}$$

The X and Y components of the acceleration of point E can then be obtained from relationships similar to Eq. (27).

The total number of unknown variables for the dynamic force analysis is 15, and there are 15 equations, see Eqs. (21)–(24), (28)–(31), (33) and (34). The solution can be obtained by writing the equations in matrix form and taking the inverse of the 15 × 15 coefficient matrix. However, to provide insight into the analysis, and as a check of the matrix inversion, the solution can be obtained from an inspection of the 15 equations. A possible rocedure is to solve Eqs. (31) and (34) for the internal reaction forces F_{56X} and F_{56Y}, Eq. (33a) for the internal reaction forces F_{46X}, Eq. (33b) for the internal reaction force F_{46Y}, Eq. (30a) for the internal reaction force F_{15X}, Eq. (30b) for the internal reaction force F_{15Y}, Eqs. (24) and (29) for the internal reaction forces F_{34X} and F_{34Y}, Eq. (28a) for the internal reaction force F_{14X}, Eq. (28b) for the internal reaction force F_{14Y}, Eq. (23a) for the internal reaction force F_{23X}, Eq. (23b) for the internal reaction force F_{23Y}, Eq. (22) for the hydraulic actuator force F_H, Eq. (21a) for the internal reaction force F_{12X} and Eq. (21b) for the internal reaction force F_{12Y}.

To illustrate the numerical procedure, consider $O_2 O_4$ = 34.0 cm, O_2A = 34.0 cm, O_4B = 36.0 cm, AB = 46.0 cm, O_4D = 61.0 cm, O_2O_5 = 11.5 cm, O_5C = 62.5 cm, CD = 46.0 cm, DE = 61.0 cm, EP = 38.0 cm, $\beta = 70^o$, $\psi = 90^o$ and the line EP is parallel to the line CD. The input link is rotating counter-clockwise from an initial position $\theta_2 = -10^o$ to a final position $\theta_2 = +20^o$, with an angular velocity and acceleration as shown in Figs. 12a and b, respectively. For the specified range of motion, the X and Y coordinates of the path of point P, obtained from Eq. (14), and the radius of curvature of the path, see Eq. (19), are as shown in Figs. 13a and b, respectively.

The velocity and acceleration of point P versus the input position are as shown in Figs. 14a and b, respectively.

The masses of the links are m_2 = 1.5 kg, m_3 = 2 kg, m_4} = 4 kg, m_5 = 2.5 kg, and m_6 = 25 kg and the mass moments of inertia of the links, about their respective centers of mass, are I_{G2} = 0.030 N m-s^2, I_{G3} = 0.045 N m-s^2 and I_{G4} = 0.075 N m-s^2 I_{G5} = 0.095 N m-s^2, and I_{G6} = 0.250 N m-s^2. When the blade is in the soil, that is, – 85 cm $\geq Y_P \geq$ – 115 cm, the coefficient of friction and the friction force at point P are assumed to be $\mu = 0.30$ and F_P^f = 100 N respectively.

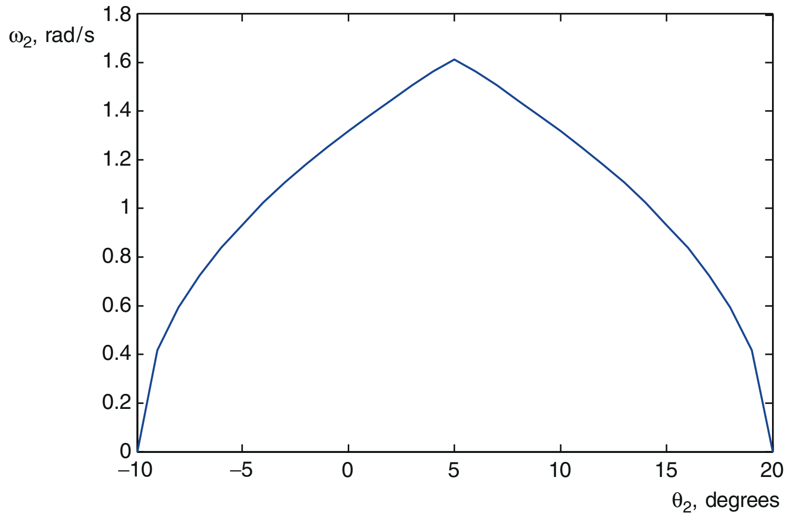


Fig. 12 (**a**) The angular velocity of the input link 2. (**b**) The angular acceleration of the input link 2

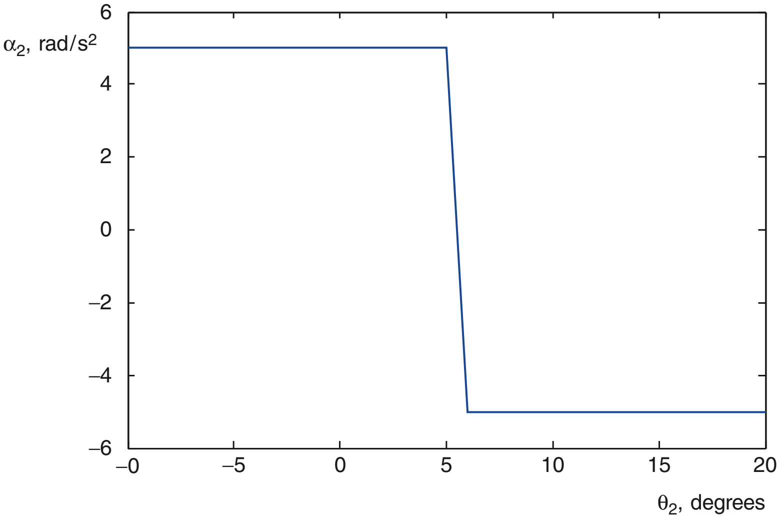


Fig. 12 (continued)

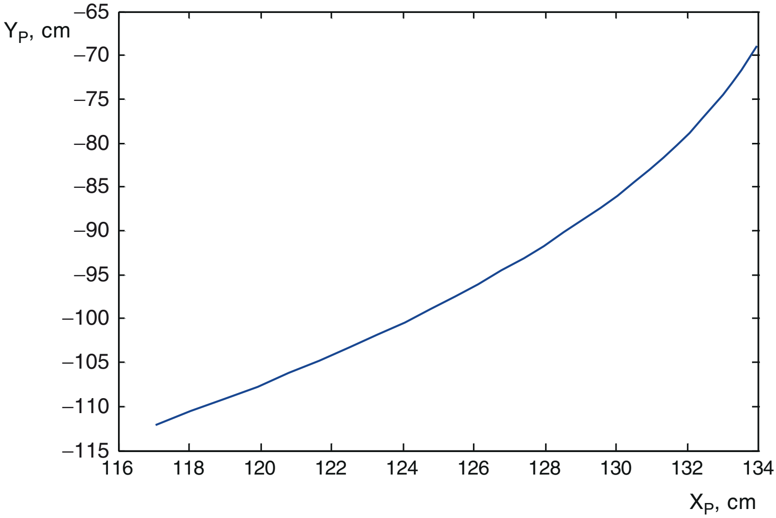


Fig. 13 (**a**) The X and Y coordinates of the path of point P. (**b**) The radius of curvature of the path of point P

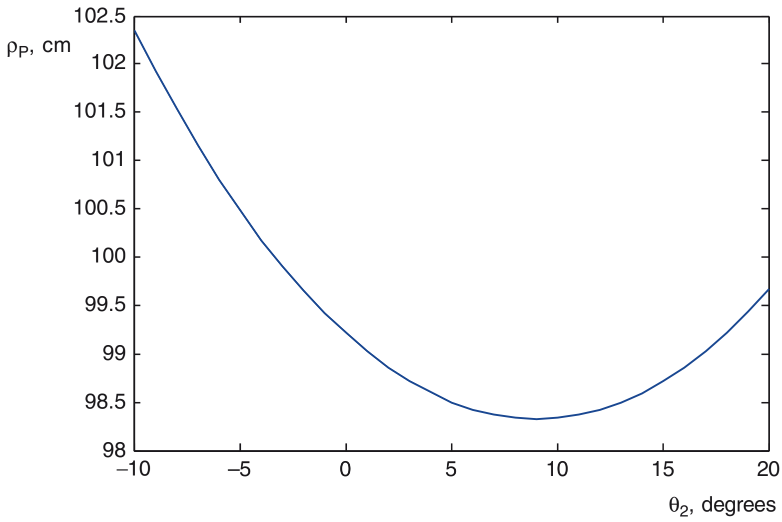


Fig. 13 (continued)

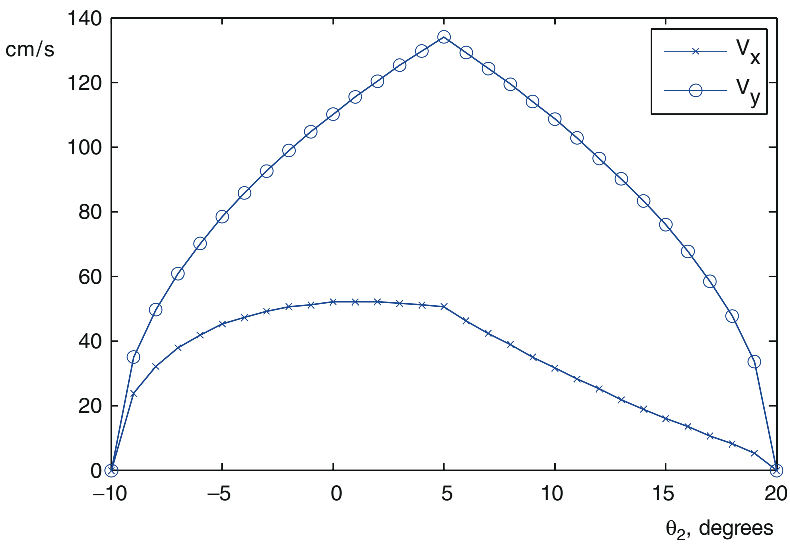


Fig. 14 (**a**) The velocity of point P versus the input position. (**b**) The acceleration of point P versus the input position

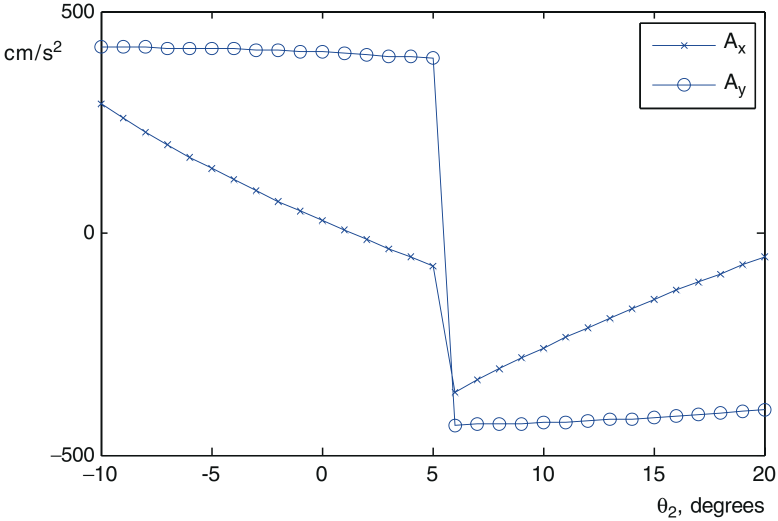


Fig. 14 (continued)

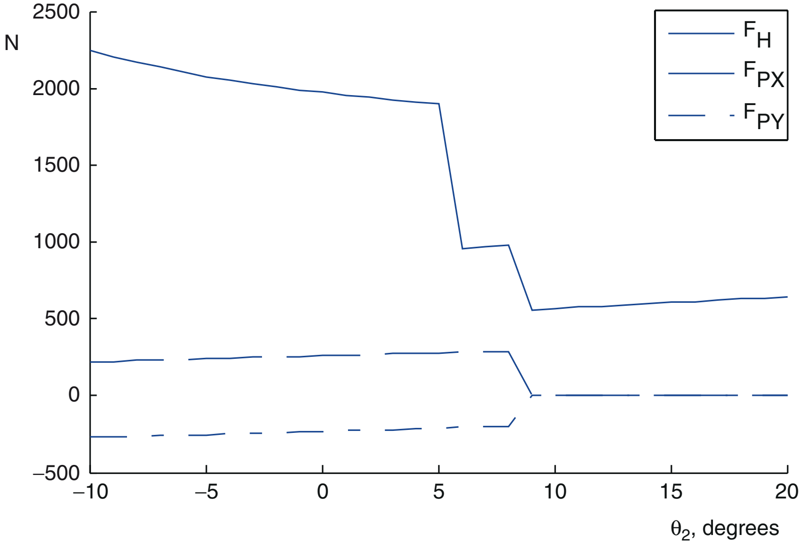


Fig. 15 The X and Y components of F_P and F_H

Due to space considerations, a complete set of numerical results for the dynamic force analysis will not be presented here. However, for illustration purposes, consider the force that is required by the hydraulic actuator to overcome the contact force on the blade at point P. The X and Y components of this force against the position of link 2 are as shown in Fig. 15. From the solution to the dynamic force analysis, a plot of the corresponding hydraulic actuator force against the position of the input link is also shown on the figure. It is worth noting that the numerical results of the force analysis can be used, for example, to demonstrate the influence of the link dimensions on the loads acting on the links of the three-point hitch and on the tractor. The results can also be used by the designer to optimize the link dimensions and to investigate the dimensions proposed by Ferguson in his original design. Also, the hydraulic actuator can be sized based on the maximum contact force that is expected at P.

Concluding Remarks

Henry George (Harry) Ferguson died at Abbotswood, Stow-on-the-Wold, Gloucestershire, in his bath about 8:30 am, Tuesday, October 25, 1960 (10 days before his 76th birthday). He had been suffering from a manic depressive condition and, over the years, this condition had become more severe. The doctor attending Ferguson said that in July, 1959, Ferguson was found in similar circumstances in his bath. On that particular occasion, the doctor had come to the conclusion that Ferguson was suffering from an overdose of barbiturate tablets. The pathologist and the coroner at Ferguson's inquest indicated that Ferguson had died from an overdose of barbiturate tablets but that there was no evidence to show whether the tablets were self-administered or ingested accidentally. Ferguson was cremated 3 days after his death on Friday, October 28.

Even in the last few months of his life, Ferguson was planning a new venture in tractor distribution in his native Northern Ireland. He saw the exploitation of land resources as the way to prosperity and lower prices. He had even argued in pre-World War II days that Nazism might have been contained by intensive cultivation of German soil. During his last few months, all his activities were centered on his car project which he regarded to be of fundamental importance. This project received tremendous publicity but remained shrouded in secrecy. One prominent motoring correspondent spoke of Ferguson as the man behind the car that never was. One of Ferguson's business associates said at the time that the car was a tremendous technical advance on anything seen so far and should be put on the market at the earliest opportunity. A motoring correspondent of a large newspaper said that competent observers had stated that Ferguson's car design secrets did indeed spell of unheard of efficiency.

In spite of his great gifts and rare personal qualities, Ferguson would not have been an easy partner to work with. In fact, he was an extremely difficult man. He had a fanatical attention to detail and insisted, for example, that his employees wear clean boiler suites and display white handkerchiefs. When Harry stumbled upon an idea, he had the vision and the tenacity to pursue it over many decades. He sought out people to pursue his ideas with him and he had the ability to inspire them to make contributions beyond their own talents. In most cases, he won from them uncompromising and long-lasting loyalty. It will never be known, however, how much his own intense individualism frustrated agreement with those in government circles who wanted to collaborate with him. Ferguson held very strange views on economics, believing very passionately in reducing prices so as to widen the market that he continued to do so regardless of the general inflation forces affecting his costs (Neufeld 1969). Negotiating for sales of his assets with Massey-Ferguson, on one occasion in 1953, he agreed to the toss of a coin to settle the difference between $16 million and $17 million. Alas, he called tails and lost the $1 million. Later he was presented with a cigar box with the tossed coin fixed on top and the engraving, "To our friend and partner Harry Ferguson, A gallant sportsman". His inventions, especially the three-point hitch, and his dedication to an affordable tractor, had a great influence on the agricultural economies of the world. His economic philosophy was guided by the belief that the best way to improve the total economy was through cutting the costs of production of agricultural products which control the cost of living. The measure of his success can be gauged by the fact that over 85% of all wheeled farm tractors produced in the 1960s were based on the Ferguson system or derivations of this system (Feilden 1970).

It is unfortunate that the relentless genius of Ferguson did not bring more opportunities for economic growth in the land of his birth. One of his greatest disappointments was the refusal of the Northern Ireland Government, on two occasions, to support his tractor project. Ferguson claimed that his love for Ulster was greater than his love for any other country on earth. He was proud to be an Ulsterman and it is most fitting that there are several plaques and monuments to him in his native land. There is a plaque on the farm house of his birth, in Growell, and another on the site of his original showroom which is now the Ulster Bank building, Lower Donegall Street, Belfast. The Ulster Folk and Transport Museum at Cultra has an early tractor and plough and a full-scale replica of his aeroplane. There is also a granite memorial to his pioneering flight on the North Promenade in Newcastle, County Down. Ferguson received an honorary degree of Doctor of Science from Queen's University, Belfast, in 1948, and an honorary degree of Master of Engineering from Trinity College, Dublin, in 1949. He was offered a knighthood on two occasions, by the Labor and Conservative Governments (Wymer 1961). The British Prime Minister, Sir Winston Churchill, proposed to Ferguson that he should be offered a knighthood and in November 1953 he received a formal letter from 10 Downing Street, London (the home of the Prime Minister). The letter asked if this mark of Her Majesty's favor would be agreeable with Ferguson. However, Ferguson declined the offer on the grounds that this honor should be reserved for people such as servicemen and statesmen whose financial reward for their labor is comparatively small. He believed they should not be given to businessmen or industrialists who have the opportunity to become famous or amass wealth and all that wealth can bring them. In his letter of reply to Churchill he wrote, "I fear I have seen, so often, the harmful effects of an Honors List for industrialists, that I believe I have come to the right conclusion when I ask that the Prime Minister would not submit my name to the Queen in this connection." He, among many others, greatly underestimated his accomplishments and contributions to Britain and the world. A knighthood would have been no less than this man deserved.

It is also unfortunate that the history books will tend to remember Henry George (Harry) Ferguson as a businessman who fought and won a David and Goliath legal action against the Ford Motor Company. This is a grave injustice, for Ferguson was a superb innovator and engineer who built up his business on the basis of very small capitol resources. Harry Ferguson revolutionized mechanized farming in the 1940s. His invention of the three-point linkage system meant that one tractor could be used to pull a variety of implements. Before this invention, farmers had to have a different tractor for different jobs. His system also brought greater safety and stability to tractors. He was the cofounder of the Coventry tractor manufacturing company of Massey-Ferguson. The TE20 tractor was built in Coventry, England, and reached production of more than half a million, with hundreds of thousands of successor models built at the plant for almost 50 years. It was fitting that in 2008, Coventry considered Ferguson for one of the first 10 names for the city's Walk of Fame. In 2006, the Northern Bank Limited, Northern Ireland, issued a 20 pounds sterling banknote with a portrait of Ferguson and the Belfast plough. On August 16, 2008, Growell opened a memorial garden, near the home of his birth, to honor his contributions to society. At the time of writing this article, plans are underway to commemorate the 100th anniversary of his first powered flight in Ireland in that small monoplane on December 31, 1909, at Hillsborough. Ferguson may not have soared very high that particular day, but his mechanical genius was to lift mankind to new heights.

Acknowledgements The author wishes to thank the Belfast Telegraph for providing the newspaper articles concerning the death of Harry Ferguson and the subsequent inquest. Articles were found in the 25th, 26th and 28th of October, 1960, and the 8th and 9th of November, 1960, issues of the newspaper. Thanks are also due to the Belfast City Council, the Public Record Office of Northern Ireland, and the Ferguson Family Museum, Isle of Wight for the information they provided. The author would also like to thank Mr. Michael Kean for the schematic drawings for the kinematic analysis and dynamic force analysis of the three point hitch. Finally, the author would like to acknowledge Mr. Jack Woods for the detailed information he so willing provided in numerous emails on background and historical aspects of the Ferguson family.

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Patents filed by Ferguson can be located at: http://www.google.com/patents

Patents filed by Ferguson can also be located at the European Patent Office: http://ep.espacenet.com

Juanelo (1501–1585)

Emilio Bautista, José Luis Muñoz, and Javier Echávarri

Abstract Juanelo Turriano was a clockmaker, astronomer, mathematician, and a mechanical and hydraulic engineer. He worked for kings Charles I and Philip II during the Iberian Empire. His most important device was called the "Dancing Machine" and was built in the sixteenth century in Toledo, the capital city of Spain at that time, to raise water from the River Tagus to the city, 90 m above the river, with only the power of the water flow. He is also famous because he is supposed to be co-author of the "The Twenty-One Books of Devices and Machines of Juanelo Turriano" written in the second half of the sixteenth century.

Biographical Notes

Giovanni Torriani, known as Gianello Turriano or Juanelo Turriano, was born in 1501 in Cremona (Italy) to a humble family. During the long nights as a shepherd, he became very interested in astronomy and others sciences (Del Campo y Francés 1997).

When Charles I of Spain became Charles V of Germany, Juanelo's life changed. The governor of Milan, Ferrante Gonzaga, wanted to give Charles V an astronomical clock made in the fourteenth century by Giovanni Dondi, which was one of the most important medieval technological works. Charles V's interest in mechanical engineering, art and especially clocks was common knowledge. Dondi's clock did not work and Juanelo was the only one able to repair it. This made him a really famous clockmaker. And he received orders from all the courts in Europe for his timepieces.

Around 1530 he came to Spain and became clockmaker to Charles V (Valverde Sepúlveda 2001); he even accompanied Charles V when he retired to the Monastery of Yuste in 1557. One year later, Charles V died and his son Philip II became King

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of Spain. Philip II was not as interested in clocks as his father, thus Juanelo worked for him in other fields such as mathematics. For this, Philip II called him "The Wise Mathematician". At the king's court, he became friends with several important Spanish architects and engineers (Del Campo y Francés 1997).

A few years later, thanks to his remarkable water machine in Toledo, Juanelo became known as a magician by the Toledo inhabitants. Even though he was very wellknown at that time, he was very poor because no one paid him for his work; what is more, he had to pay for some of his hydraulic works with his own money.

Juanelo died on 13 June 1585 in Toledo and was buried in the church of the Monastery of El Carmen in Toledo. Up until the last moment, he demanded payment from the city of Toledo but he was never paid, and his family continued with the complaints to the city and even to the king.

Legend says that Juanelo was very old in his last years of life, so he used one of his automatons called "The Stick Man" that begged in the streets, and when someone gave him a coin, he bowed (Cervera Vera 1996). This legend provided the name for a street in Toledo: "Calle del Hombre de Palo" ("The street of The Stick Man").

Figure 1 shows a plaque in the street in Toledo dedicated to "The Stick Man", the text reads "Along this street passed the wooden automaton built by Juanelo Turriano, clockmaker for Charles V, to the amazement and perplexity of the crowd". There is another street named after Juanelo in the centre of Madrid.

Although scarcely any of his works have survived, Juanelo was wellknown during the Renaissance. There are a great number of references to him and especially to his works in many books of engineering of the sixteenth and following centuries,

Fig. 1 A plaque in the Street dedicated to "The Stick Man" of Toledo

as well as in the Spanish literature of Góngora, Lope de Vega and Quevedo. As for portraits, we know that Charles V ordered one, but that portrait was lost as well as the one that Juan de Herrera had in his house. The only surviving objects that bear his likeness are a marble bust and a coin.

The bust, shown in Fig. 2a, was made by Leon de Leoni and is kept in the Santa Cruz Museum in Toledo; it represents Juanelo when he was approximately 45 years old. There is a copy, three times larger, of the bust in the Royal Palace of Madrid, shown in Fig. 2b.

The coin, shown in Fig. 3, is kept in the Archaeological Museum of Madrid. It is thought to have served Titian and El Greco and other anonymous artists of the seventeenth century as inspiration to paint some portraits which look like Juanelo, shown in Fig. 3 (Del Campo y Francés 1997).

As the Iberian Empire grew, Spain became the number one world political and economic power, enabling its empire to reach out to the five continents. It was said that, over the dominions of King Philip II, “the Sun never sets”.

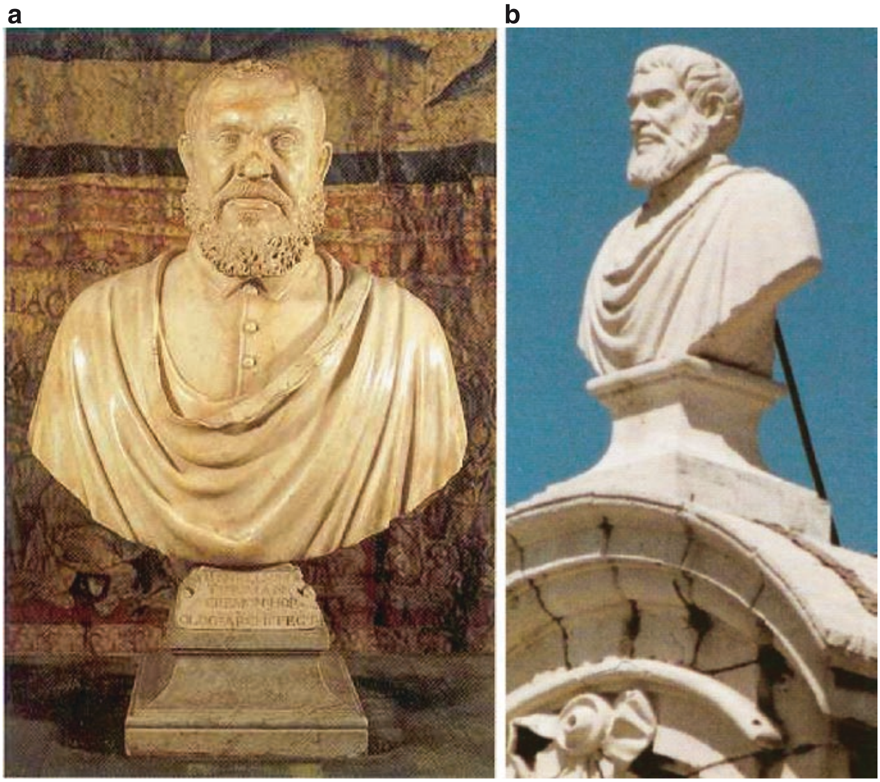

Fig. 2 (**a**) A marble bust of Juanelo Turriano by Leon de Leoni; (**b**) copy of the bust in the Royal Palace of Madrid

Fig. 3 Portrait of Juanelo Turriano on a coin, and a later Portrait of Juanelo (XVII anonym)

Nevertheless, there was a lack of qualified technicians and scientists in Spain at that time (Lusa Monforte 2004), which is quite evident in a letter of Francés de Álava (Bautista et al. 2007), written in the second half of the sixteenth century: "The persons I know in Spain engaged in the service of His Majesty as engineers, except for Fratin (Fratino) and Antonelli, are Jorge Setara, who lives in Perpignan and Baptista Antonelli, brother of the cited Antonelli, who lives in Peñíscola and Cristóbal Antonelli, his nephew, who nowadays is living in Barcelona, and Tiburcio (Spanocci), the one who His Majesty sent to Fuenterrabía, and Felipe Tercio (Terci) who lives in Lisboa. All of them are foreigners, and I do not know a single Spaniard who knows the half of what they do, although I have racked my brains…". In order to avoid such a negative position, a discussion arose about the convenience of establishing a scientific-technical centre in the court.

Juan de Herrera, Juanelo Turriano, Jerónimo de Ayanz and other outstanding engineers and architects in the court, were supposedly decisive in King Philip II deciding the foundation of a popular "Technical Academy" in Madrid (Esteban Piñeiro 2002–2003). The Academy was founded in 1583 and intended for everyone interested in jobs related to the different arts of all the technical activities practised at that time.

List of Main Works

Juanelo's main activities regarding engineering can be divided into two different groups: on the one hand, the design and construction of mechanical devices and, on the other hand, the elaboration of manuscripts.

Mechanical devices:

- Clocks: the “Astrarium” clock and the tower clocks of the monastery of El Escorial near Madrid.
- Two hydraulic devices for raising water from the river Tagus to the city of Toledo.

Manuscripts:

- Breve discorso alla Majestad de Re Catolico interno la reduttione dell anno et restitutione del Calendario con la dichiaratione deglo instrumenti da eso per mostrarla in atto prattico (Brief speech for His Catholic Majesty about the Calendar...).
- “Trattato dell’acque” (Water Treatise).
- Los Veintiún Libros de los Ingenios y las Máquinas de Juanelo Turriano (The Twenty-One Books of the Devices and Machines of Juanelo Turriano).

Review of the Main Works on Mechanism Design

Although he did not usually write about his works, they are cited in many books of other authors at that time. This is our main source of information because none of his clocks, machines or automatons have been found.

In 1530, Ferrante Gonzaga gave Charles V a medieval astronomical clock called the “Astrarium”, which was repaired by Juanelo, shown in Fig. 4a. Not only he did repair it, but he also made another one which also showed the planetary

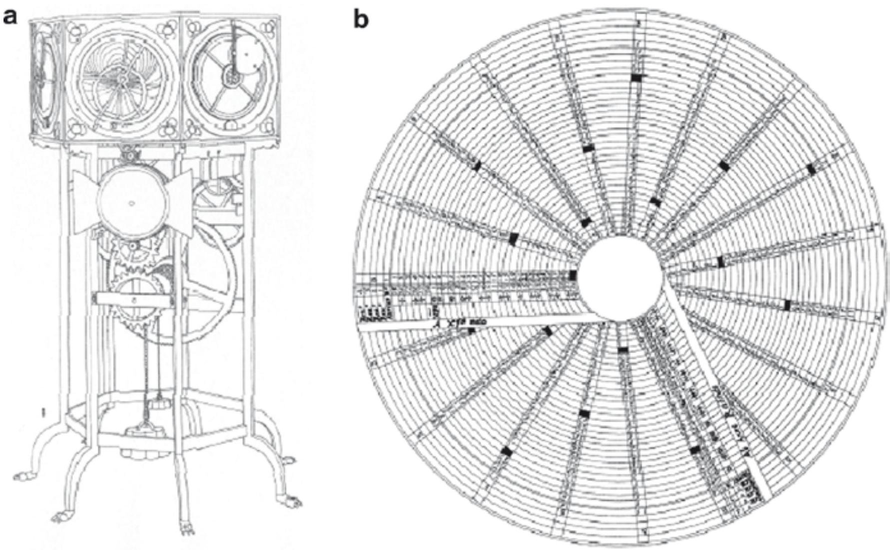

Fig. 4 (**a**) Astronomical clock; (**b**) table obtained from the “Breve discorso alla Majestad de Re Catolico…”

movements. This was called “Crystalline” and it showed the hours, minutes, solar and moon hours, as described planetary movement and it showed the signs of the Zodiac. It was built with more than 1,500 parts, three springs which produced the movement and eight planetary spheres.

When Charles V died and Philip II became king of Spain, Juanelo met Juan de Herrera, one of the most important Spanish architects of the Renaissance and who built the monastery of El Escorial near Madrid (1563–1584). Juanelo took part in the project by helping to build the tower clocks (Del Campo y Francés 1997).

His last job as a clockmaker and astronomer was the solution to the problem of the Catholic calendar. Pope Gregory XIII asked all the kings of Europe to ask the most intelligent people in their courts to give their opinion on this topic. Juanelo not only gave his remarks but also he wrote “Breve discorso alla Majestad de Re Catolico interno la reduttione dell anno et restitutione del Calendario con la dichiaratione deglo instrumenti da eso per mostrarla in atto prattico”, where he detailed two solutions for Easter to be always on the same date (Fig. 4b).

Juanelo also invented automatons with human aspects. Apart from the cited “The Stick Man”, another famous automaton attributed to Juanelo is “The lady from Vienna”, shown in Fig. 5.

His main work is considered to be the hydraulic device built in Toledo between 1565 and 1569, which was ordered by the Marquis of Vasto.

In those days, Toledo suffered from a shortage of water in its reservoir, so they needed a machine which was able to raise water from the River Tagus up to the

Fig. 5 The automaton called “The Lady of Vienna” (García-Diego 1982)

Alcázar, the highest part of Toledo; this meant that the water had to be raised 90 m and it could not be done with a pump because the pipes would not withstand the pressure, as happened with the previous device built by German mining engineers (Bautista et al. 2000).

It had to raise 12,400 L round-the-clock, which meant that the machine had to work non-stop. The current of the Tagus itself served as the driving force as well as supplying the water needed for the city. It was the machine's size that made it very significant as a work of mechanical engineering (Porres Martín-Cleto 1987).

We have no complete drawing of Juanelo's device but there is a manuscript description with a rough diagram, shown in Fig. 6, made by the Precentor of Évora (Portugal) in 1604.

His machine was undoubtedly a great feat of engineering for the time, both in size and complexity. The sizes of its parts and the high forces received were a considerable challenge to the technical know-how of that period. In addition, being a machine with so many moving parts meant the dynamic effects would be significant and its joints subjected to considerable tribological actions (Bautista et al. 2007).

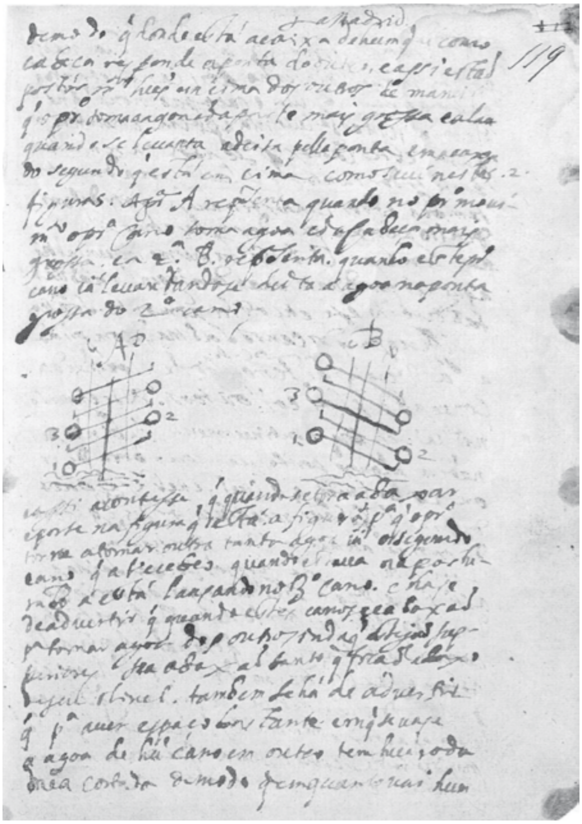

Fig. 6 Manuscript description of the hydraulic device, by the Precentor of Évora (Portugal)

An attempt to explain how this machine worked was published by Luis de Escosura in 1888, though the author himself recognised his doubts about the reconstruction proposed, shown in Fig. 7a. It was based on Valturio's adjustable ladder (1534) shown in Fig. 7b, obtained from the book "De Re Militari" (On the Military Arts).

The different documents of the period and later studies enabled Ladislao Reti to make a fairly close reconstruction of the mechanical device, in 1967, which is shown in Fig. 8.

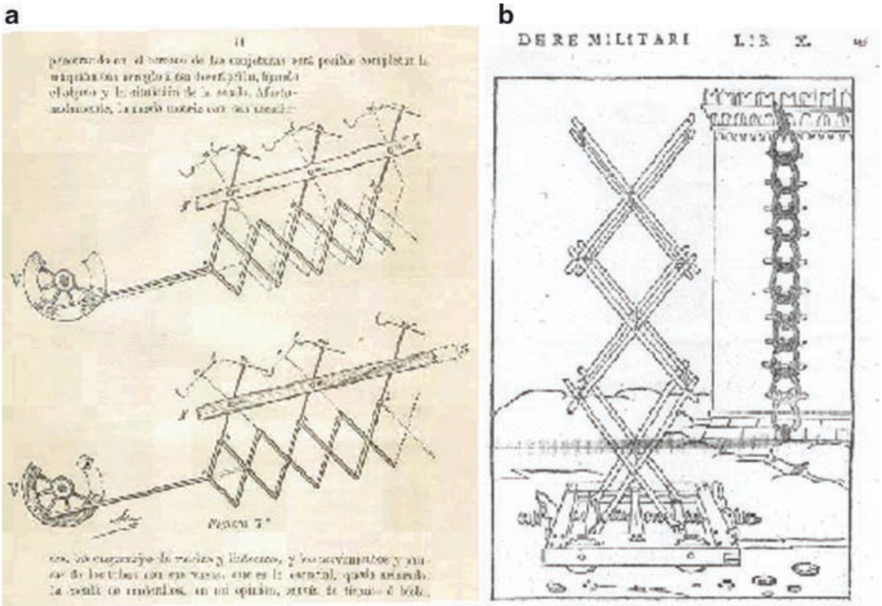

Fig. 7 (**a**) Explanatory sketch of Juanelo's machine, by Luis de Escosura (1888); (**b**) Valturio's adjustable ladder (1534)

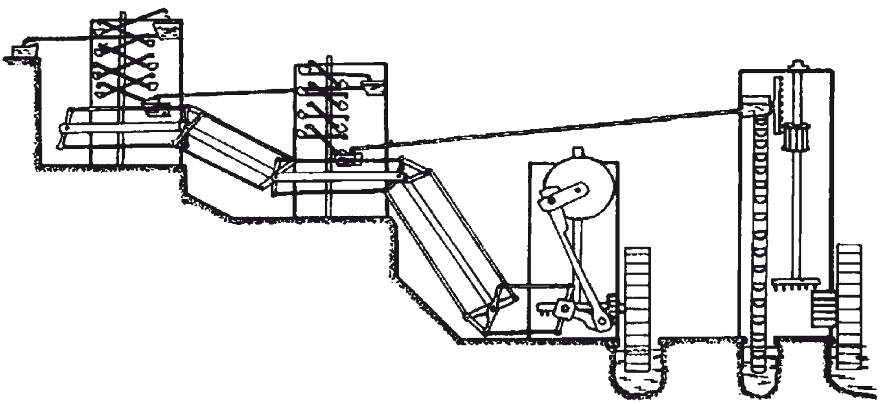

Fig. 8 Diagram of Juanelo's device in Toledo, according to Ladislao Reti's reconstruction

This illustration shows how the river flow operated two water wheels with paddles. The first moved a mechanism with a water wheel that raised the water several metres to a reservoir. The second wheel used another connecting rod-crank-based mechanism to start up the rocking movement of the vertical systems called towers, which enabled the water to be raised from the reservoir under atmospheric pressure.

It was designed to overcome any difference in level, since, as the water ran in contact with the air, no excesses of pressure occurred due to the pumping height, as would happen in a usual pipe system. A greater difference in level only required an increase in the number of sequentially connected towers.

The tower diagram in Fig. 9a shows two working positions for the device, based on a set of pivoted buckets and cups that raised the water in stages, due to the backward and forward motion of the cups. When the water reached the top, it was fed through some pipes to the next tower, and so on until it reached its destination.

Both the device and the way it worked were very curious at the time. These facts contributed to its inventor's fame and the name by which it became popularly known, "The Dancing Machine". A contemporary traveller named Kenelm Digby wrote in respect of the device "…and so the two sides of the machine were like two legs that trod the water in turn".

This gives strength to Nicolás García Tapia's reconstruction (2002) concerning the existence of arches for collecting water from both sides of a tower.

Indeed, Nicolás García Tapia's reconstruction in Fig. 9b of Juan Ramos' diagram shows there were two input and two output arches, situated either side of the tower. When the first cup was introduced into the arch to take water, the opposite one was raised, passing the water on to the next, and each container was full when its

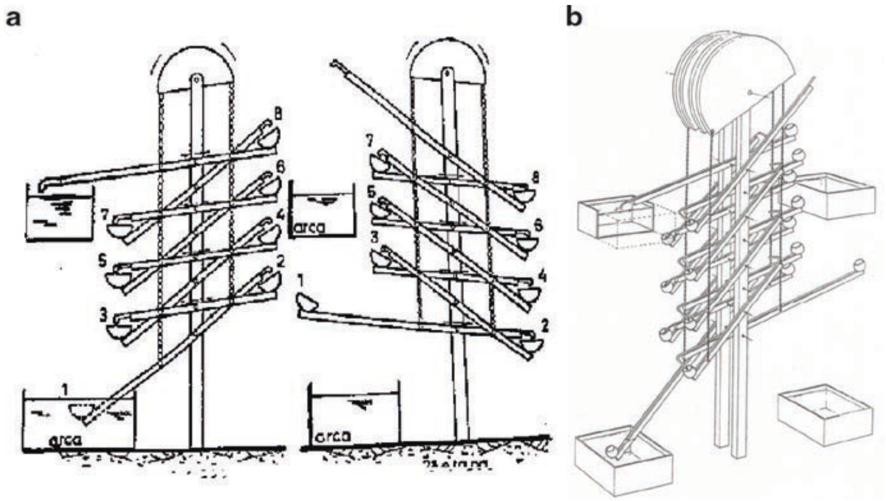

Fig. 9 (**a**) Details of Juanelo's hydraulic device; (**b**) a recent three-dimensional reconstruction of the tower by Nicolás García Tapia

opposite one was empty. The water was thus made to flow continuously with a co-ordinated and precise movement.

Once the device was finished they measured the water volume and it was 50% per cent greater than expected, which meant 17,000 L of water per day.

The first device was a great success, so there was a proposal to build three more devices. However, only the first project came to fruition.

The second device was started in 1575 and finished in 1581 and the water that it supplied was for the town.

When Juanelo died, the only one who knew how to use the device was his grandson who died in 1597.

In 1617, the machine finally stopped working due to lack of maintenance and knowledge of how to use it. The last official document where it is mentioned was an inventory written in 1639.

A machine with a tower quite similar to Juanelo's device can be found in the famous book called "Le diverse et artificiose machine del Capitano Agostino Ramelli" ("The various and ingenious machines of Captain Agostino Ramelli"), a large catalogue of machines finished in 1588, a few years after the death of Juanelo.

Ramelli's book contains 195 superb figures of various kind of machines along with detailed descriptions of each one, including comments on how it was built and how it worked. He endowed his drawings with such clarity that he could be later studied in a large number of fields.

One of the more than 100 water-raising machines described is shown in Fig. 10 (Ceccarelli 2006). It was driven by a water-wheel which moved two gears, the movement being transmitted to a tower with a water-raising system in stages, using a method similar to Juanelo's hydraulic device.

Juanelo shared his knowledge with some of the most important engineers in Spain, during important irrigation works carried out while Philip II was king. The last time that Juanelo was asked for his opinion about a large project was in 1580. The best engineers of that time, Giorgio Fratin, Juan Baptista and Cristobal Antonelli worked on the project of the biggest dam in the world.

One engineering treatise which was supposedly due to Juanelo is the "Trattato dell'acque" (Water Treatise) which is kept in the National Library of Florence. It is considered as a previous work of one of the few written works attributed to Juanelo: "Los Veintiún Libros de los Ingenios y las Máquinas de Juanelo Turriano" (The Twenty-One Books of Devices and Machines of Juanelo Turriano). These books were written in Spanish at the end of the sixteenth century.

Though this work is signed by Juanelo, some experts say that it was not written by him but dedicated to him because of his fame at that time all around the world. Others consider that the reference to Juanelo is used to remark the quality of the manuscript.

Some experts consider the possibility of this manuscript having been written by various different co-authors. In the opinion of Nicolás García Tapia (1987, 1990a, b), one of them could be Pedro Juan de Lastanosa, because the manuscript contains words taken from a Spanish dialect spoken in the area where Lastanosa lived.

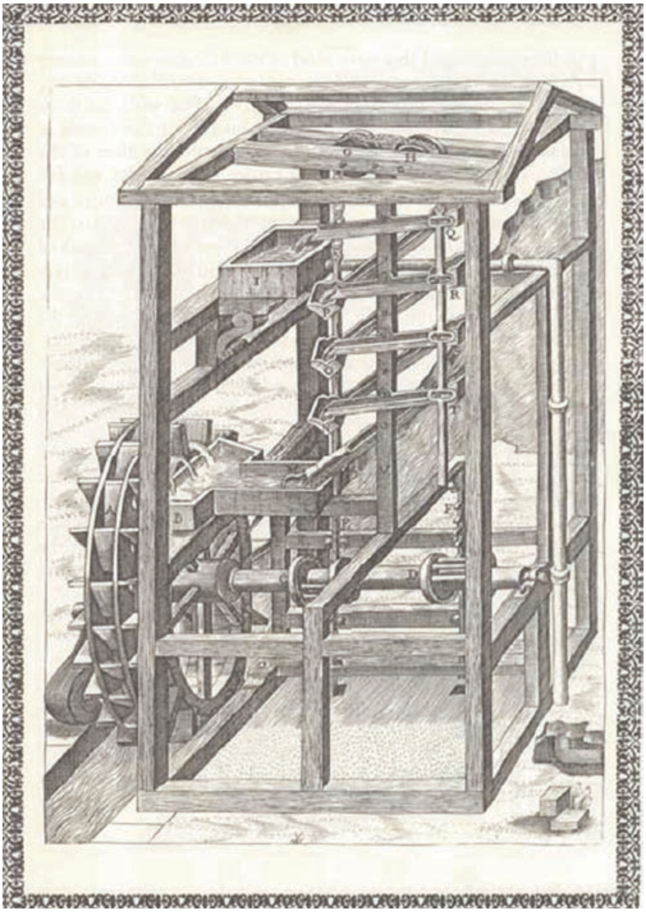

Fig. 10 A water-raising machine included in Ramelli's book

The search for the authors of the Twenty-One Books has promoted the in-depth study of this work.

This collection of books, ordered to be written by "the Catholic King Philip II, King of Spain and the New World", represents an impressive written source for the knowledge of the mechanical arts known and practised in the sixteenth century. Some historians and engineers define it as a Machine Encyclopaedia (Goicolea 2000).

These books, finished in approximately1570, include descriptions of a high number of machines of the time, classified by their function (Instituto Cervantes 1998). They are remarkable in their references to practical devices, such as pumps, mills, elevators, presses and others machines, mainly powered by water, wind, gravity or animal traction.

The front page and some illustrations of machines are shown in Fig. 11. All these machines, and their components, are widely explained and commented on in the text. In detail, this work includes the following contents:

- The first chapter talk about water: its quality, properties, source and effects.
- The second chapter examines the signs that we can follow to find water.
- Chapter 3 teaches how to distinguish between drinkable and non-drinkable water.
- The fourth chapter talks about water levels.
- The fifth chapter teaches how to make water pipes and water conduits.
- In Chapters 6–10 we can read about the different ways of moving water, and storing it.
- Chapter 11 talks about different kinds of mills.
- Chapter 12 teaches how to separate flour from straw.
- Chapter 13 explains the different uses of mills
- Chapter 14 talks about boats that were used to cross rivers when there was no bridge.
- Chapter 15 talks about wooden bridges.
- Chapter 16 talks about materials like wood and stone.
- Chapter 17 includes more precise information on stone: how to treat it and its quality.
- Chapter 18 sets out different ways of building stone bridges.
- Chapter 19 talks about how building in ports should be done.
- Chapter 20 explains how to protect ports from the open sea.
- The last chapter talks about tides, water clocks and the different effects of water.

On the Circulation of Works

Thanks to official letters, literature and some engineering books of that age, we have been able to earn something about Juanelo's devices, mainly regarding the hydraulic devices built in Toledo.

During the Iberian Empire, the interest in mechanical engineering remained patent with the manuscript "Trattato dell'acque" (Water Treatise). The treatise is written in Spanish and was discovered recently in Florence by the researcher María Teresa Cacho. It has 84 pages and approximately 350 images and is supposedly a preliminary work of the most important manuscript attributed to Juanelo: "Los veintiún libros de ingenios y máquinas" (The Twenty-One Books of Devices and Machines), completed in 1570.

The Twenty-One Books kept in the National Library of Madrid (www.bne.es) have 949 pages and 509 images, including most of the illustrations of the previous Water Treatise. In addition, in these Twenty-One Books, the author improves the clarity of the comments and the quality and details of the figures.

The original manuscript was not published at that time due to the information about materials and works that required the Royal Permission of Philip II. Its publication would have allowed a dissemination comparable to the most

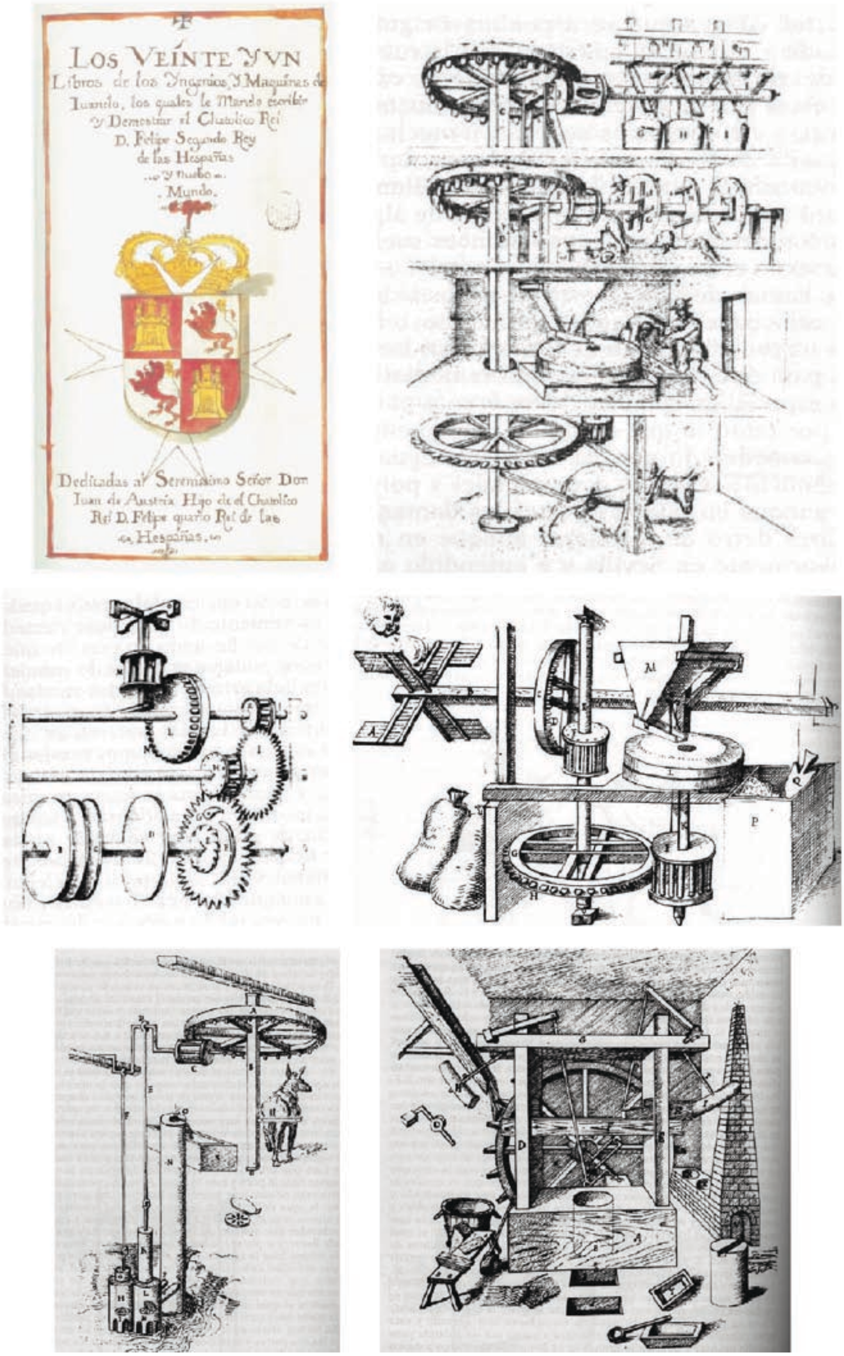

Fig. 11 Front page and some machines in the Twenty-One Books

remarkable European treatises of the Renaissance. It was known and probably used by important engineers and architects during the seventeenth and eighteenth centuries, such as Gómez de Mora, Teodoro Ardemans and Benito Bails.

These Twenty-One Books remained in hiding until the 1960s of the past century when some historians interested in technology rediscovered them, publishing diverse works. Professor Alexander Keller, researcher in the field of History of Science, contributed to the spread of Juanelo's work by translating the Twenty-One Books into English. The Civil Engineers Association published an edition in 1983 and the Juanelo Turriano Foundation (www.juaneloturriano.com), created in 1987 by the Engineer José Antonio García-Diego, prepared a facsimile edition in 1997.

There is another copy of this work, also entitled The Twenty-One Books, kept in Barcelona. This issue is quite similar to the one in Madrid, with 609 pages and 404 figures. It belongs to a private collection and this is why it is not yet well known.

Modern Interpretation of the Main Contributions

Although we do not know exactly what they were like, Fig. 12 shows some modern reduced-scale models of the hydraulic devices originally designed and built by Juanelo (www.juaneloturriano.com) (Jufre 2007).

In addition, Fig. 13 shows some recent virtual reconstructions of the hydraulic devices and the spheres of the astronomical clock made by Juanelo (Bermejo 2005, Jufre 2007).

It is remarkable that the Proto-industry in the sixteenth century, regarding early industries involved in manufacturing goods for trade, has been recently studied by Keller and Silva Suárez (2004), following the contents of The Twenty-One Books of

Fig. 12 Reduced-scale models of the hydraulic devices

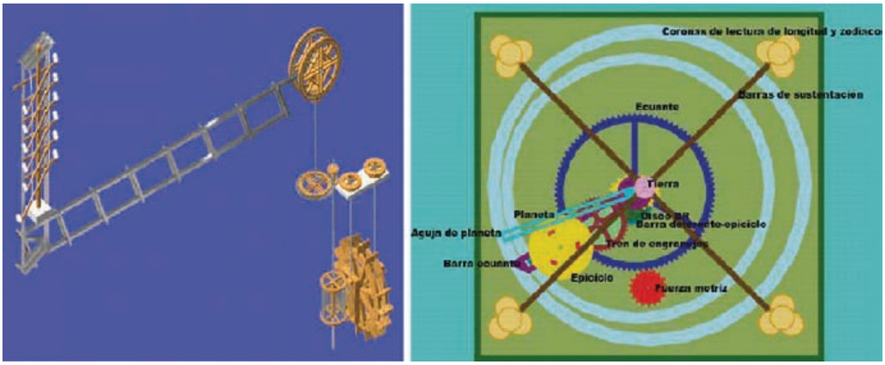

Fig. 13 Virtual models of some famous devices: the hydraulic devices and the spheres of the astronomical clock

Devices and Machines. The detailed analysis of the treatise from this point of view enhances the knowledge on the state of technology at that time concerning different kinds of grinding mills and other devices moved hydraulically, such as oil-presses or fulling hammers. Other Proto-industrial processes are also described, such as the washing of wool, and the production of starch, alum, vitriol and saltpetre.

The discovery of the Twenty-One Books of Devices and Machines, was added to the recent studies developed by García Tapia (1990a, b, 2001) concerning "Royal Privileges for Inventions" (or Spanish Patents) mainly at the end of the sixteenth and the beginning of the seventeenth centuries.

The quantity and quality of the registered inventions, with or without Royal Patent, lets us suppose a rapid increase in the number of scientists and technicians, coming mainly from Italy and other European countries, to serve the Spanish Crown, constituting a genuine community, essential for the technical and scientific growth of the Iberian Empire during its Golden Age.

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José María Lanz y Zaldívar (1764–1839)

Carlos S. López Cajún

Abstract The Mexican José María Lanz y Zaldívar was one of the authors, together with the Spaniard Agustín de Betancourt, of the first book about industrial kinematics, dealing with mechanisms classification in a systematic fashion. The book, written in French, was published first in Paris in 1908 and later was translated to English and German. Furthermore, at the end of the eighteenth and the first part of the nineteenth centuries, apparently Lanz y Zaldívar played an important role in developing modern engineering in Europe.

Biographical Notes

The mathematician, mechanical and hydraulic engineer Lanz y (and) Zaldívar was born in Campeche, México in 1764. He pursued studies at the *Instituto Campechano* and sometime after he was instructor at the same institution. Successively, he moved to Spain where he studied naval engineering, and obtained the position of Cadiz' Alférez (similar to Lieutenant) of the Marine Guards. He was at the service of the Royal Fleet of Spain with the above-mentioned official rank. From 1782, Lanz, with the degree of ship's lieutenant was in service in the military *fragata* San Fernando at La Habana's offshore. By the end of 1782 he was moved to the fragata Santa Lucía. The latter used to make trips from la Habana (Cuba) to Veracruz (Mexico) as was registered in the so-called *hoja de servicios* (sheet of services) shown in Fig. 1. Then, he was sent to Yucatán by Colonel Borja to work on the *henequen* (hemp) and the *jarcia* (ropes) being fabricated with this fiber. Indeed, in 1783 Lanz was living in Yucatán, where he studied the possibility of using *henequen* to fabricate naval *aparejos* and wrote

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DOI 10.1007/978-90-481-2346-9_6,

N 12
D. Joseph Maria Lanz
natural de Campeche,
de Estado Soltero

Fechas en que empezó á servir los Empleos.	Dia	Mes	Año	Años	Meses	Dias	Tiempo que sirvió cada uno de los Empleos.
Guardia-Marina	13	Oct.e	1781	1.	2.	7.	De Guardia Mar.na
Alferez de Fragata	21	Dic.e	1782	3.	3.	3.	De Alf.z de Fragata
Alferez de Navio	25	Nov.e	1785	1.	1.	2.	De Alferez de Nav.o
Ten.te de Fragata	28	Ab.l	1787	3.	10.	2.	De Ten.te de Frag.ta
Teniente de Navio	1.o	Nov.e	1791	2.	11.	10	De Ten.te de Nav.o
Total del tiempo que sirvió hasta 11. de Feb.o de 1794, q. por R.l orden de la misma fha. se le dió de baja				12	3	24	

Extracto de sus Servicios.

Estuvo embarcado quatro años, dos meses, y doce dias, y navegó en America, y Europa. Sobre el Navio S.n Fernando se halló en el Combate de la Esquadra combinada contra la Inglesa, en Octubre de 82. A principios del año de 83 fué destinado á la fragata Santa Lucia, comisionada á llevar la noticia de la paz á la Havana, y Vera Cruz: Fué comisionado por el Brigadier, y Comandante General D. Francisco de Borxa á ir á Yucatan á tomar conocimiento del cultivo, abono y método conque en aquella Provincia tra...

Fig. 1 Lanz's sheet of services (Archivo de la Marina de Guerra de Viso del Marqués) a report on this task. (This report was published in the *Registro Yucateco*, although, according to Justo Sierra O'Reilly, it was thought that the real author was Policarpo Antonio Echánove y Arzubia. However, Joaquín Lanz Trueba in the brochure *Estudios sobre el henequén*, published in Campeche in 1926, showed that Lanz y Zaldívar was the first to write about this plant.) On the 1st of January of 1784, Lanz returned to La Habana, where for some time he was in service on the *fragata* Santa Dorotea.

Lanz returned to Madrid in 1789 to participate, under Mendoza's (Lanz' advisor) direction, in a trip through France, England, Germany, Sweden, Poland and Russia to collect data, designs and documentation. After the trip through Europe, and back in Spain, he became director of a clock factory.

Because of his outstanding scientific activity, he obtained a scholarship for studying in Paris where he had met Monge and Betancourt by the end of 1789. Lanz y Zaldívar got married in Paris where he decided to stay with his wife. However, from 1802 to 1805 he lived in Madrid and taught at the *Escuela de Caminos y Canales* (School of Roads and Channels). Actually, Lanz lived in Spain in an intensive epoch of intellectual renovation fostered by the egregious figure of Carlos III and his successor Carlos IV.

In 1808, together with Agustín Betancourt, he published the book *Essai sur la composition des machines* in Paris (Lanz and Betancourt, 1808). This is a basic book about industrial kinematics. By the end of the eighteenth and the first part of the nineteenth centuries, Lanz played an important role in developing modern engineering in Europe.

He was expelled from Paris because of his ideological links with the French revolution. Nevertheless, it seems inaccurate that he was receiving Napoleon I's orders, as pointed out by Antonio Rumeu de Armas (1983) in his book, but was actually working on the orders of Napoleon's brother Jose I Bonaparte, King of Spain. Because of that, he went back to Spain and took second-level political positions in the administration. (Rumeu's book has seven chapters, three appendices, and reproduces among other illustrations, the first page of Lanz's service sheet, the cover of the first edition of *Essai sur la composition des machines*, and two of Lanz's letters. One letter is addressed to the Conde Fernán de Núñez and the other one is addressed to the Principe de la Paz, dated 1793 and 1796, respectively.) In 1832, the Board of the *Real Conservatorio de Artes* proposed to the Treasury Minister that Lanz y Zaldívar be appointed (the equivalent of) Full Professor. Lanz y Zaldívar died in Paris in 1839.

According to Rumeu's book, Antonio Gutiérrez, a student of Lanz y Zaldívar, described him, at the age of 67, as kind and good with a reddish face, gross, and short. As a recognition of him after his death, in 1848 a portrait was ordered for Antonio García (Vicuña 1888), and supposedly was exhibited at the *Real Conservatorio de Artes*. So far, unfortunately, the author did not found the portrait.

Essai sur la Composition des Machines

Introduction

Modern activity relating to mechanism design can be considered as starting with the foundation of the *École Polytechnique* in Paris in 1784. This can be also considered the beginning of the Theory of Machines and Mechanisms (TMM), that greatly evolved from the nineteenth century to a topic of modern engineering that today we call Machine and Mechanism Science (MMS). The founding fathers of TMM can be considered to be those who established the *École Polytechnique* and particularly the first teachers of the disciplines that have contributed to the formation of modern industrial engineering. Among those first teachers, also investigators, one can recognize Gaspard Monge, Lazare Carnot, Luis Lagrange, Jean Pierre Nicolas Hachette, Louis Poinsot, Paul Réné Binet, Claude Louis Marie Henri Navier, Dominique François Jean Arago, Jacques Philippe Marie Binet, Jean Victor Poncelet, Jean Marie Constant Duhamel, Félix Savary, Alexix Thérèse Petit, Gaspard Gustave Coriolis, Michel Chasles. Some of them were also *École* students, and later they became professors of mechanics and/or machines at the *École*.

In particular, however, one can recognize in Gaspard Monge (1746–1818) the first teacher of TMM, since he first planned specific classes on mechanism analysis and design at the beginning of the *École Polytechnique*. Monge proposed these classes as the final application of his program on Descriptive Geometry. But only in 1806 the Council of the *École* did approve the teaching for 10 h of mechanism analysis. Meanwhile, Monge had investigated mechanisms by informing other teachers on this topic. His successor was Jean Pierre Nicolas Hachette (1769–1834), who was in fact the teacher who gave the first classes on mechanisms (Hachette 1811) and continued his teaching activities for a long time.

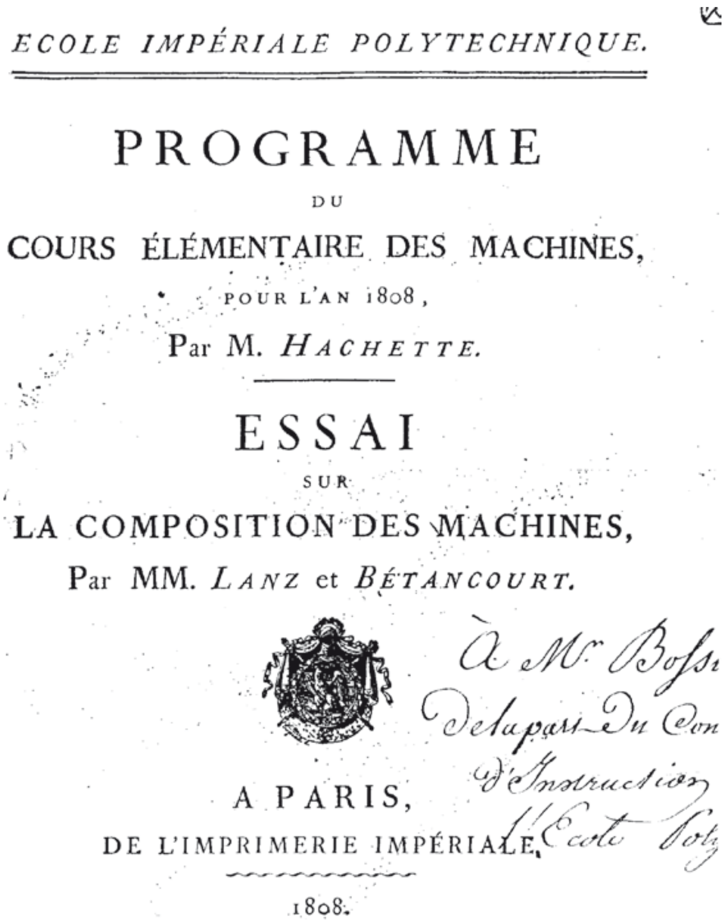
Among those students who attended the first classes on mechanisms which were conducted under the supervision of Monge, one can recognize José María Lanz y Zaldívar and Agustín de Betancourt. Their personalities and activities can be considered very significant and illustrative of early modern industrial engineers, not only for the brilliant academic and technical contributions, but even for the intense engineering activity, and with a wide radius of action. However, Lanz and Betancourt are yet not fully considered in the history of modern TMM, since they are not cited or at the most, mentioned with little information (García-Diego 1985; Rubio and Cuadrado 2000; López-Cajún and Ceccarelli 2005; Ceccarelli et al. 2006).

In this section, details of contributions and activities by Lanz are reported and discussed with the aim of stressing not only the historical significance, but also the pioneering activities in modern engineering. Particular attention has been addressed to the revision of the *Essai sur la composition des machines* that was first published at Paris in 1808, as the text of the early teachings on mechanisms, and in the form that was inspired by Monge, but given by Hachette (1811).

The *Essai sur la composition des machines* was written as related to an Elementary Course on Machines as an application of classes of Descriptive

Geometry given at the *École Polytechnique*. The course was planned in 1795, but only Hachette started it in 1806.

The first draft of the *Essai* was reorganized by Lanz in the years 1805–1807. Lanz and Betancourt reviewed the *Essai* together during the 4 months of coincidence in Paris and submitted it to the *École Polytechnique* in the second semester of 1808. At the same time, Hachette began a course on the Elements of Machines, and he prepared a program of lessons and tables to classify elementary machines. Thus, since Monge and Hachette had knowledge of the book prepared by Lanz and Betancourt, they proposed its publication within the framework of the *École Polytechnique*. Hachette reviewed the manuscript with the idea of adapting it for the above-mentioned program and the *Essai* was published in 1808, and included Hachette's program as shown in Fig. 2. In this first edition, the table of classification


ECOLE IMPÉRIALE POLYTECHNIQUE.

PROGRAMME

DU

COURS ÉLÉMENTAIRE DES MACHINES,

POUR L'AN 1808,

Par M. HACHETTE.

ESSAI

SUR

LA COMPOSITION DES MACHINES,

Par MM. LANZ et BÉTANCOURT.

A PARIS,

DE L'IMPRIMERIE IMPÉRIALE.

1808.

Fig. 2 Title page of the Essai sur la composition des machines

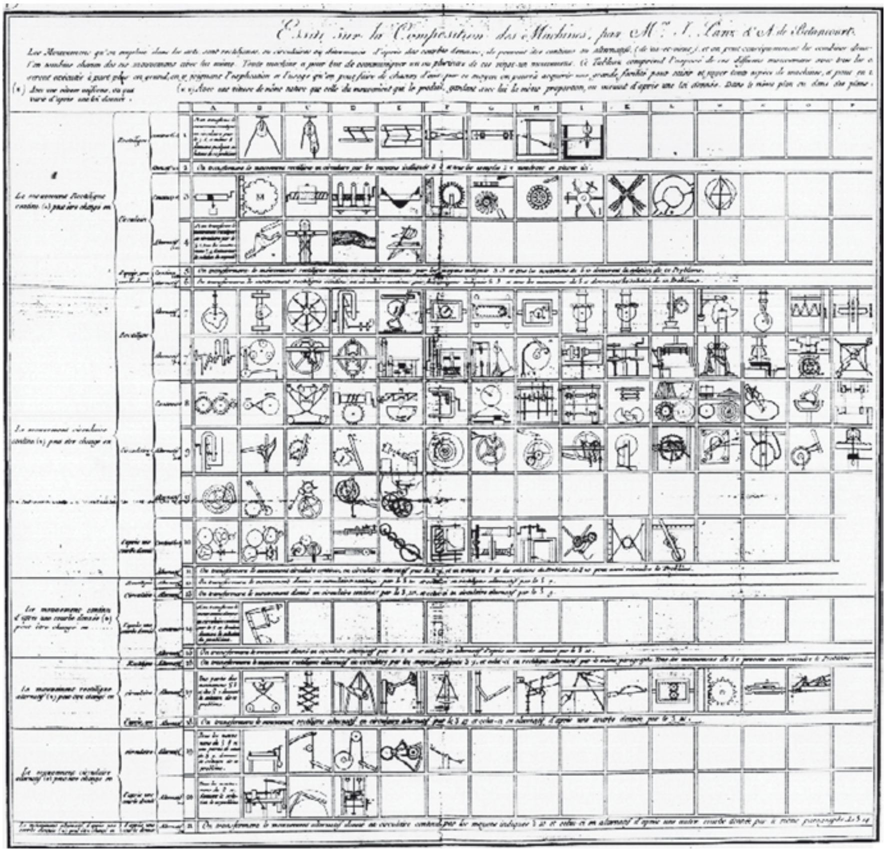


Fig. 3 The table for mechanism classification by Lanz and Betancourt

of Hachette appears at the beginning together with one more complete table by Lanz and Betancourt (Fig. 3).

The content of the book is based on a comprehensive classification of mechanisms that were obtained from considering circular and straight-line motions both for input and output links in continued or alternative modes. Thus, ten classes of mechanisms were identified, as shown in the Table of Fig. 4 and in Fig. 5 by using basically existing well-known mechanism designs and referencing to several technical sources of that time.

The classes of mechanisms are combinations of circular and straight-line input-output motions taking into consideration continuous or alternating motions that could have had practical applications at that time, but still of current interest. Indeed, the treatment of the mechanism that is identified in the table of the classification is described and discussed in detail both for general and for specific purposes. This was done by means of a modern kinematic approach and addressing attention to motion properties and mechanism behavior.

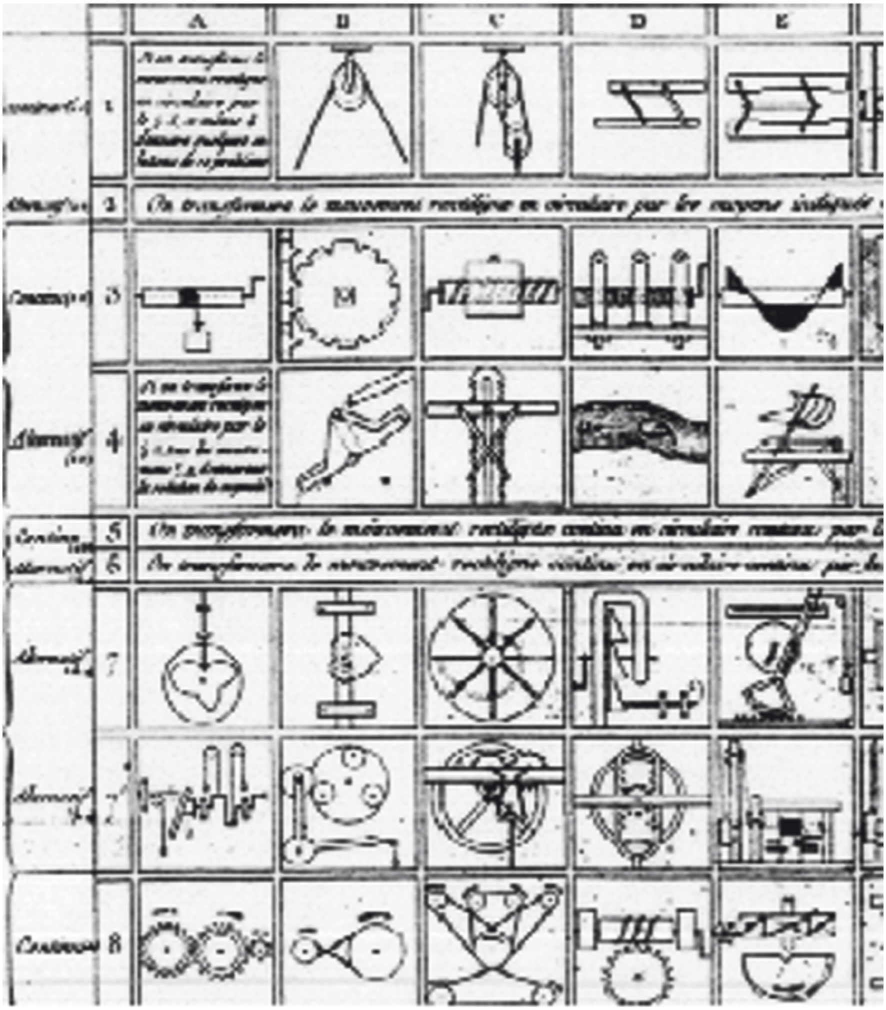


Fig. 4 A section of the table of mechanism classifications

Considerations are also deduced for design purposes. Examples from the *Essai*, which are explained on pages 114–115 and 109–110, respectively, are illustrated in Figs. 5 and 6. In particular, an analysis of the Watt linkage for straight-line guidance is shown in Fig. 5. This was done by using several configurations of the mechanism to emphasize the efficiency of it. The mechanisms shown in Figs. 5 and 6 were analyzed from a practical viewpoint, also showing alternative solutions.

The work in the *Essai* can be considered as a synthesis of the personal experiences of Lanz and Betancourt after maturation within the framework of the rigorous formation at the *École Polytechnique* under the supervision of Monge and Hachette.

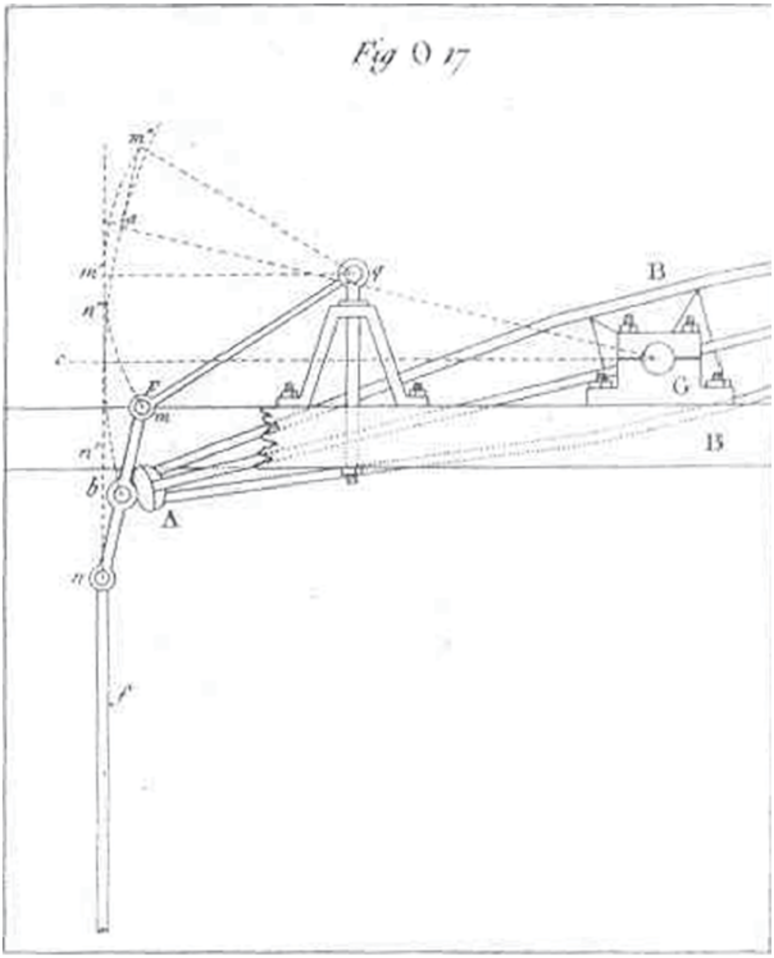


Fig. 5 Example of the Essai: the Watt four-bar linkage

The systematic approach was a successful attempt to treat, with a unique framework the great variety of mechanisms that were designed and used at that time, including an effort for the conception of additional mechanisms. The early kinematic analysis is used in the *Essai* to study and identify basic properties of mechanisms, from a general abstract viewpoint, in order to free the mechanism designs for specific purposes, as used in the previous *Theatrum Machinarum*.

In the *Essai*, in addition to the machine collections, are included the then-existing bibliography, inventors and scope of use of the machines. Indeed, at the end of the eighteenth century, there was already a need for a modern collection of used mechanisms with detailed technical analysis. These were produced much more in depth than in the past handbooks like the *Theatrum Machinarum*, mainly in France, as illustrated by first patents or by new collections like, for example, in the *Enciclopedie*.

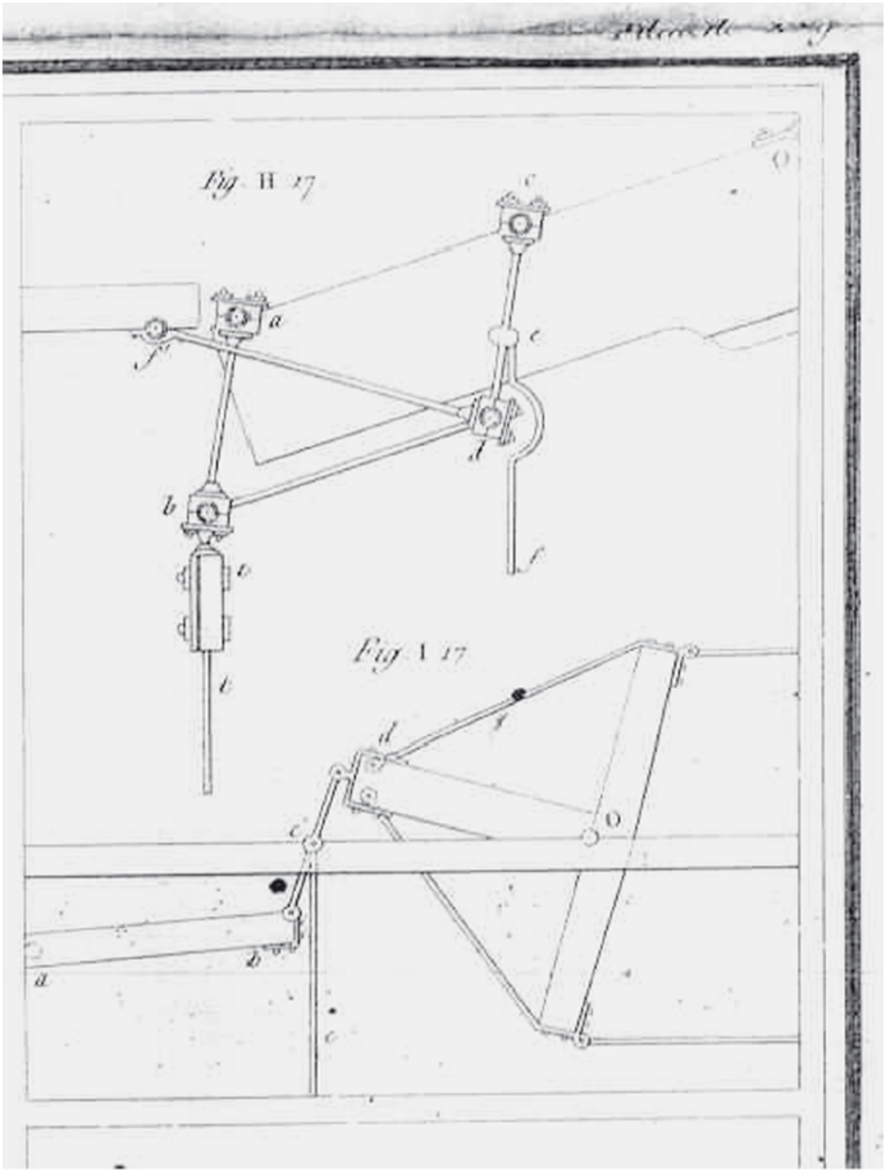


Fig. 6 Example of analysis of linkage mechanisms in the Essai: a study of different practical solutions

On the Circulation of the *ESSAI*

There are three editions in French from the *Essai*. The first one was published in 1808, and it includes the *Programme du cours Élémentaire des Machines pour l'an 1808* by Hachette. The second one was published in 1819 without the text of Hachette, and the third one was published in 1840. There are also two editions in English with the title "Analytical essay on the construction of machines". The first edition was published by R. Ackerman in 1820 and the second one was published in 1822 as included in the "Essays on practical mechanics" by Thomas Fenwick. There is also a German edition, published in 1829, and titled "Versuch über Zusammensetzung der Maschinen" von Lanz und Betancourt.

Modern Interpretation of Main Contributions

The *Essai* was used throughout the whole nineteenth century as a fundamental technical treatise for both research and professional activity and it inspired the work and research of many kinematicians in the nineteenth century, mainly with the aim of improving and/or completing the mechanism classification with the evolution and enlargement of Mechanism Design and Technology.

The modern content of the text can be recognized in an exhaustive classification of the existing mechanisms and in a synthetic description of each mechanism, even with formulation whose purpose was the design. This approach has been very successful for a long time. In fact, the *Essai* has been republished and translated in several languages. It has also inspired other milestone works in TMM, which have been used by practicing engineers throughout the whole nineteenth century.

Acknowledgements The author wishes to thank to Elga Egorova for providing some of the information written in the Introduction of this work. Also the *Consejo Nacional de Ciencia y Tecnología of Mexico* under grant 51410-Y.

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Nicolae Manolescu (1907–1993)

Theodor Ionescu

Abstract Nicolae Manolescu is the founder of the Romanian school of Mechanism and Machine Science (MMS) and one of the IFToMM founders.Through his extensive scientific activity, he approached numerous MMS topics but, above all, he carried out studies on the numerical, structural and kinematic analysis and synthesis of the plane kinematic chains and of various degrees of mobility mechanisms, as well as on the kinetostatic and dynamic analysis of mechanisms. Throughout his entire activity he promoted MMS at national level and essentially contributed to the worldwide recognition of the Romanian school of MMS.

Biographical Notes

Nicolae Manolescu was born on 11 April 1907 in Adjudul Vechi, a small town in the eastern part of Romania as the second son of Ion Manolescu, a railway employee, and Ecaterina, housewife.

He began primary school in 1913 in his home town and continued his education in Focsani, a town with a rich cultural tradition. After leaving the secondary school in 1926, he entered the Polytechnic School in Timisoara at which, in 1931, he took a graduate degree in electromechanical engineering.

Completing military service in 1932, he began his engineering career at the Braila town Municipal Works and, after a time, he moved to the CFR (Romanian State Railways) where he held several technical and managerial positions between 1932 and 1956.

Although he had worked as an assistant lecturer during his last year at Timisoara Polytechnic School and delivered lectures at the Military College, the year 1949 marked the beginning of his long-standing, complex university career.

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Between 1949 and 1959, he was an academic at the Railways Technical Institute of Bucharest and at the Oil and Gas Institute of Bucharest (1950–1958). Combining research with teaching, Nicolae Manolescu climbed the academic ladder through hard work, professional competence and complete dedication.

In 1956, he joined the Polytechnic Institute of Bucharest. His rich technical and scientific culture enabled him to also offer courses in the domains of Strength of Materials, Machine Parts, Dynamics of Railway Vehicles, Thermotechnics, Mechanics, Mathematics.

Professor Manolescu got his Ph.D. degree in MMS in 1969 with a comprehensive work “Contributions to the Numerical, Structural and Kinematic Synthesis of Assur Groups, of Kinematic Chains, of Mechanisms and of Articulated Plane Motor-Mechanisms”. In recognition of his overwhelming activity, he was conferred in 1971, with the scientific title of “Doctor Docent” in the field of Mechanism and Machine Science.

Endowed with a prodigious memory and a remarkable working power, he fully engaged himself in guiding younger colleagues and subordinates, conducting research and doctoral theses, contributing to national and international technical journals, lecturing at world famous technical universities, organizing and taking part in symposia, conferences and congresses. He also held the Chair of Mechanism and Machine Theory between 1962 and 1972 and was the Dean of the Transportation Faculty of the Bucharest Polytechnics between 1958 and 1972. He also acted as a technical adviser to the Ministry of Transportation.

As a consulting professor, he continued to carry out academic teaching, doing research and managing the Romanian branch of IFToMM from 1972 until his death in 1993.

Figure 1 presents Professor Nicolae Manolescu addressing the audience at his 80 years anniversary in 1987.

Nicolae Manolescu crowned his lifetime’s scientific and technical activity by his election in 1991 as a corresponding member of the Romanian Academy.

A great promoter of MMS in Romania and in the world, he was one of the IFToMM founders and an active member of the IFToMM Technical Committee for Linkages and Cams and of the IFToMM Permanent Commission for Standardization of Terminology. He was the founder of the Romanian branch of IFToMM, e.g. the Romanian Association for the Theory of Mechanisms and Machines (ARoTMM) and held its chair for a long period. It was he who initiated the “SYROM” International Symposium on Theory and Practice of Mechanisms, within IFToMM, which has taken place in Romania every 4 years since 1973, bringing together world MMS personalities and promoting their activities and works.

The results of his studies and research can be found in many courses, academic books and treatises on MMS, in more than 150 articles in technical journals, and more than 120 papers at national and international conferences and congresses.

In his private life, Professor Manolescu had a great tragedy, loosing his first wife and his two children, in the Second World War bombardments in 1944.

He died on 10 October 1993 as a tragic consequence of a car accident.

Fig. 1 Nicolae Manolescu in 1987, addressing the audience at his 80 years anniversary (Author's photo archive)

List of Main Works

Here are some of his main works:

- Books/Courses/Treatises (in Romanian): "Theory of Mechanisms and Machines", 1955; "Theory of Mechanisms and Machines. Kinetostatics and Dynamics", 1958; "Collection of Problems in Mechanism and Machine Theory ", 1963; "Collection of Problems in Mechanism and Machine Theory", 1968; "Theory of Mechanisms and Machines", 1972.
- Doctoral thesis (in Romanian): "Contributions to the numerical, structural and kinematic synthesis of Assur Groups, of kinematic chains, of mechanisms and of articulated plane motor-mechanisms", 1969.
- Papers/articles (in Romanian) : "On the mechanisms made up of different family kinematic chains", 1961 ; "Structural synthesis of plane articulated kinematic chains with 10 elements, 13 kinematic pairs, and degree of freedom L = 4", 1969.
- Papers/articles (in English or French): "Sur la détermination du degree de mobilité des mecanismes", 1963; "Une methode unitaire pour la formation des chaines cinematiques et des mecanismes plans articules avec differents degrés de liberté et mobilité", 1964; "Systematisation et classification des mécanismes – moteurs plans articules, a deux degrés de mobilite '*total*', (M = 2) et '*partial*', (M = 2)", 1965; "The methods of formation of Assur groups function of the number of loops (Zg) and of the rank of links (J)", 1966; "Structural

synthesis of plane kinematic chains with multiple joints and five degrees of freedom $L_3 = 5$ '*total*', $L_3 = 5$ '*partial*' and $L_3 = 5$ '*fractional*'", 1967; "Structural and kinematic synthesis of plane driving-mechanisms with multiple joints and two degrees of mobility: '*Total*' $M_3 = 2$ and '*Partial*' $M_3 = 2$", 1968; "For a united point of view in the study of the structural analysis of kinematic chains and mechanisms", 1968; "Criteria of forming the plane jointed mechanisms with multiple joints and simple links with e = 11 links and $M_3 = 2$ degrees of mobility '*partial*', '*partial-total*' and '*fractional*'", 1971; "La détermination des variants indépendante des fermes Baranov avec e = 9 élements en utilisant la méthode de graphisation inverse", 1971; "The method of determination of the number of structural kinematic variants of KCsj by joints simplifying", 1971; "A method based on Baranov trusses and using graph theory to find all the planar jointed kinematic chains and mechanisms", 1973; "La comparaison des chaines cinématiques et des mécanismes au point de vue structural a l'aide de la théorie des graphes", 1975; "The unitary method of structural synthesis of all the planar jointed Kinematic chains (KCmjsl)", 1979; "A unified method for the formation of all planar jointed kinematic chains and Baranov trusses", 1979; "La formation des fermes Baranov avec $L_3 = 0$ et 1 a l'aide de la méthode unitaire elaboree pour les chaines cinématiques plans articulees", 1981; "The history of the original methods used in the synthesis of the planar kinematic chains with different degrees of freedom (liberty)", 1988; "L'état actuel du nombre des variants nonisomorphes des chaines cinematiques plans avec articulations multiples et éléments simples (CCpames) et e = 12, $C_5 = 16$ et $L_3 = 4$ degres de liberte", 1989; "Sur la synthese structurale des chaines cinématiques plans avec articulations multiples, $L_3 = 6$ degrés de liberte et e = 8 et 10 elements simples (CCpames)", 1989; "The planar initial jointed kinematic chain", 1993; "L'histoire de l'optimisation de la synthèse des chaines cinématiques plans articulés avec differentes degrés de liberté", 1993.

Review of Main Works

Looking back at the life and work of Manolescu, we have to notice his vast scientific and pedagogical activity concerning mechanisms and machines and, at the same time, his total commitment to engineering. His studies and research were essential for understanding and solving many difficult problems related to the practice of mechanisms and machines in industry and transportation.

As it would be unrealistic and practically impossible to present his lifetime activity within these few pages, we are going to give a concise selection of his most interesting scientific topics.

Concerning the mobility degree of mechanisms, Manolescu extended the original Ozol formula to

$$M_f = \sum_{m=f+1}^{5} (6-m)\,c_m - (6-f)Z, \tag{1}$$

where Z is the number of independent cycles of the mechanism, c_m the number of kinematic pairs of class m, $f = (6 - b)$ – family of the space in which a free element has b degrees of freedom, M the degree of mobility of the mechanism of family f.

Manolescu also established methods for determining the family f of a mechanism by exploring the joining conditions of the kinematic elements and/or by identifying the Assur groups making up the mechanism, thus facilitating the Dobrovolski formula application:

$$M_f = (6-f)n - \sum_{m=f+1}^{5} (m-f)\,c_m \tag{2}$$

where n is the number of kinematic elements.

Figure 2, from Manolescu et al. (1972), presents, for exemplification, the structural scheme of a steam locomotive's distribution mechanism with 14 links and 20 kinematic pairs and, in conformity with relation 2, a degree of mobility $M = 2$. This is also obvious when considering the Assur groups composing this mechanism: dyads (2, 3), (4, 5), (12, 13) and a double triad (6, 7, 8, 9, 10, 11) and the remaining two driving elements : links 1 and 14.

Manolescu considered the problem of structural and numerical synthesis of the plane kinematic chains with simple elements and simple and multiple joints and of the derived mechanisms, as well, which are fundamental for the study of mechanisms structure, kinematics and kinetostatics. Consequently, his studies and research in this domain were developed throughout his entire life, the prominent results and gains being discussed in many papers and communications.

The purpose was to elaborate an optimized methodology for the structural synthesis of planar-jointed kinematic chains (PJKC), capable of delivering all kinematic chains which were able, in their turn, to generate all existing plane mechanisms. A lot of scientists strived to achieve this objective, among whom were Crossley, Kurt Hain, Woo, Kiper, Schian, Mruthyuniaya, Hwang, Rao, but Manolescu played the major role in elaborating it.

These configurations, being of greatest interest from the theoretical point of view, unfortunately may not be found, in their integrality, to be viable and applicable in the real practice of machines and mechanisms.

In his research, Manolescu introduced new concepts and definitions, such as motor mechanism (MM) – a mechanism with a driving element; initial mechanism (IM) – a mechanism made up of fixed and driving elements; Assur group (AG) – a subsystem in the componence of a mechanism, characterized by a degree of mobility $M = 0$; degree of mobility "*total*" – when the movements of all driven elements depend simultaneously on the movements of all driving elements; degree of mobility "*partial*" – when the movements of the driven elements do not depend simultaneously on the movements of the driving elements; degree of mobility "*fractional*" – when

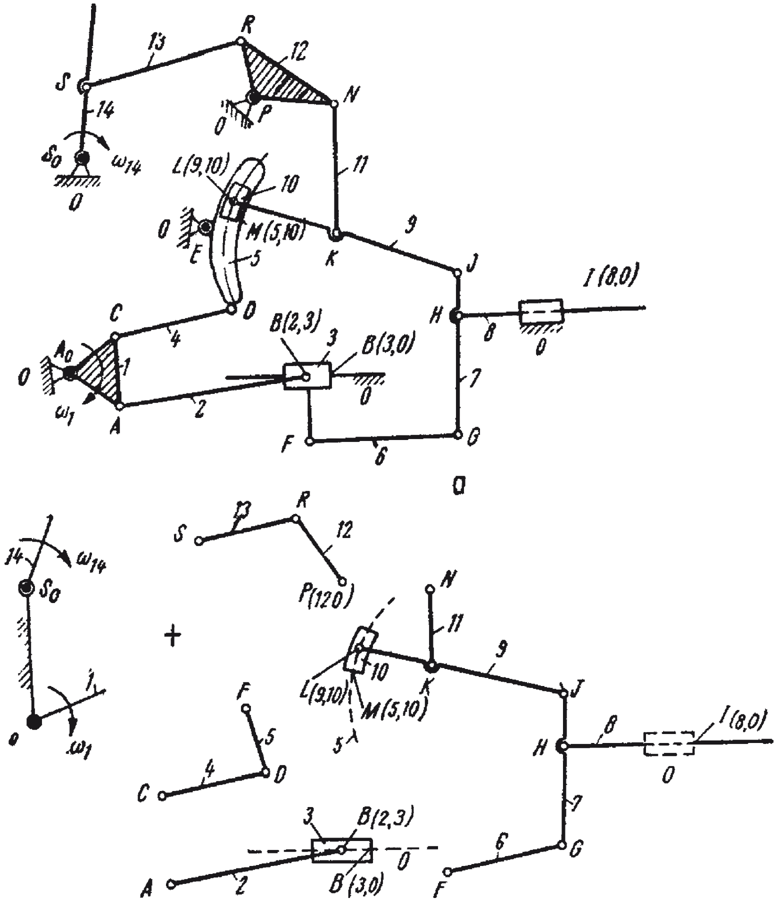


Fig. 2 The steam locomotive distribution mechanism (Manolescu et al. 1972)

there are some driven elements whose movements do not depend on the movements of all driving elements; Baranov truss (BT) – a closed (overconstrained) kinematic chain, which by loosing an element give birth to a corresponding Assur group; graphisizing operation(G) – transforming a structural scheme of a kinematic chain into a graph; inverse graphisizing operation (G) – transforming a graph into a structural scheme of a kinematic chain; joints simplification (JS)- transforming a multiple kinematic pair into several simple kinematic pairs; amplification with *dyads* (AD) – connecting Assur groups of the "*dyad*" type to a kinematic chain.

Figure 3, Manolescu (1964), shows the generation of planar-jointed kinematic chains, using Assur groups and leading to mechanisms with a degree of mobility *"total"* (a), *"partial"* (b) and *"fractional"* (c). These aspects were taken into consideration by many researchers such as Cebisev, Gruebler, Kraus, Crossley and Kurt Hain, who initially proposed the terms *" total"* and *"partial"*.

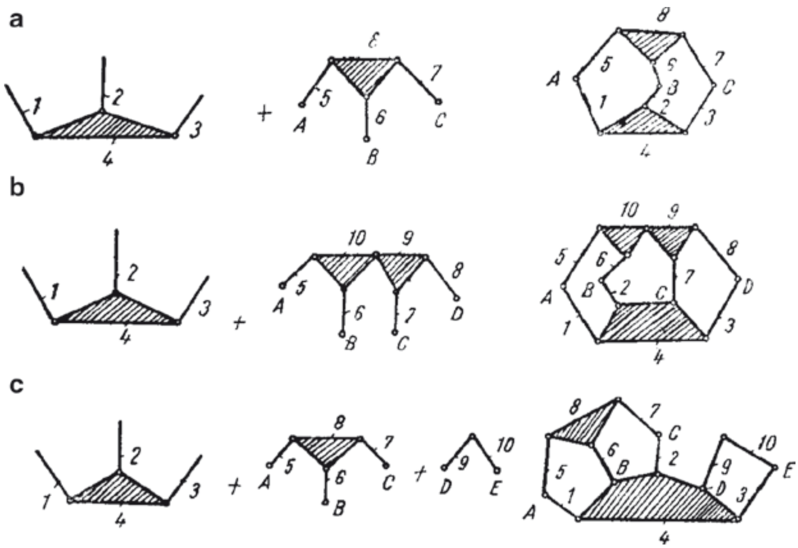


Fig. 3 Generation of planar jointed kinematic chains with a degree of freedom “total”, “partial” and “fractional” (Manolescu 1964)

All these concepts of Manolescu are widely used now by the MMS Romanian school and also by many other scientists and researchers in the MMS field.

Over time, Prof. Manolescu developed and experimented several methodologies for the structural and numerical synthesis of kinematic chains and mechanisms. He used them comparatively on sample cases, even combining them and, eventually, arriving at his own conclusions upon their particularities and advantages/disadvantages. He was permanently struggling to improve them, with the declared intention of discovering all the (possible) existing configurations of planar jointed kinematic chains.

A first methodology is based on Assur groups. The plane kinematic chains of a given degree of freedom are obtained by successively amplifying an initial chain (of the same degree of freedom) with Assur groups, until the achievement of the considered number of kinematic elements and kinematic pairs. Finally, the solutions are selected from pre-established criteria and only the distinctly nonisomorphic configurations are retained.

With regard to mechanisms, Fig. 4. in Manolescu, Environment and Planning (1979), presents Manolescu’s vision of the two methodologies used for the formation of planar driving mechanisms (PDM) : the methodology based on Assur groups – dyad, triad, tetrad (columns 1–3) and the classical methodology (Reuleax 1876), by defining the fixed link of a planar-jointed kinematic chain and then the driving link (columns 5, 4, 3).

A second methodology developed by Prof. Manolescu is derived from Baranov trusses amplified by nonassuric groups. This was used mostly as a comparative and verifying methodology and gave way to a third and more elaborated methodology,

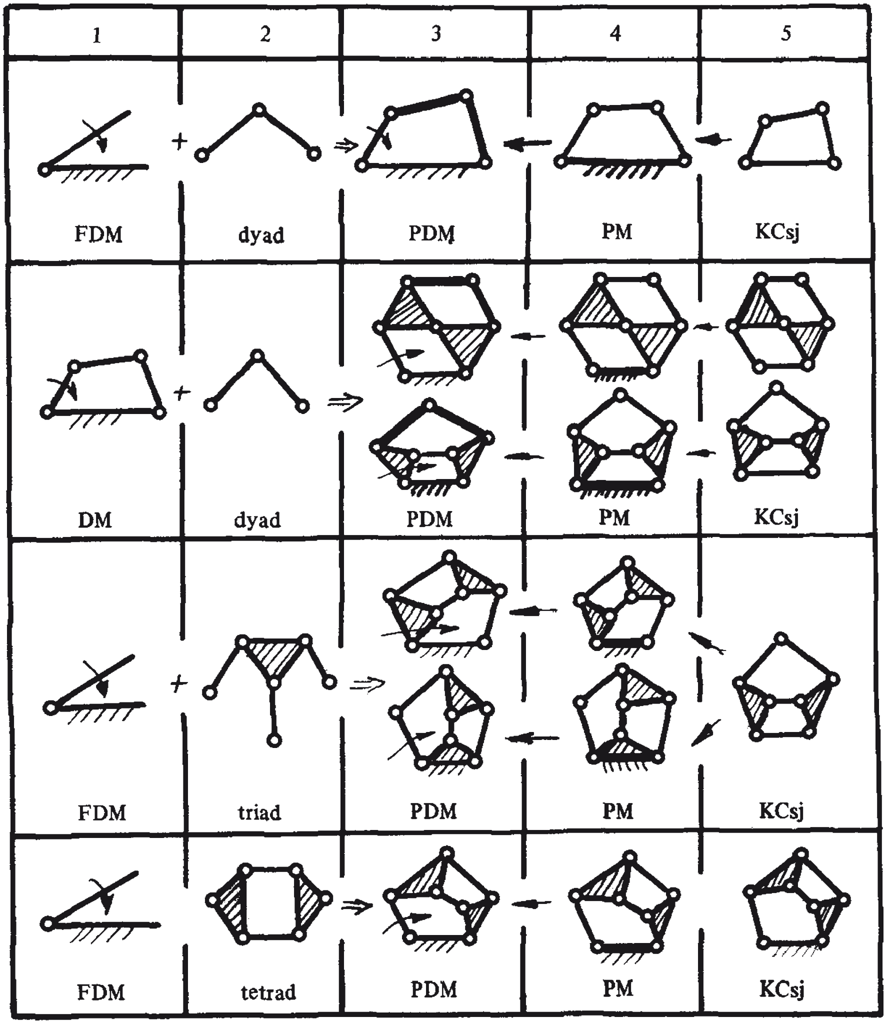


Fig. 4 Two methods of formation of planar-driving mechanisms (Manolescu, Environment and Planning B 1979)

based on graph theory. The graph theory takes into consideration the associated graph of a planar jointed kinematic chain (PJKC). This associated graph has knots corresponding to the kinematic chain elements and, simultaneously, the lines corresponding to the kinematic pairs.

An example for obtaining "Stephenson" and "Watt" planar-jointed kinematic chains from a Baranov truss with five elements by the successive operations of graphisizing (G) and joints simplification (JS), is shown in Fig. 5, by Grecu (2007).

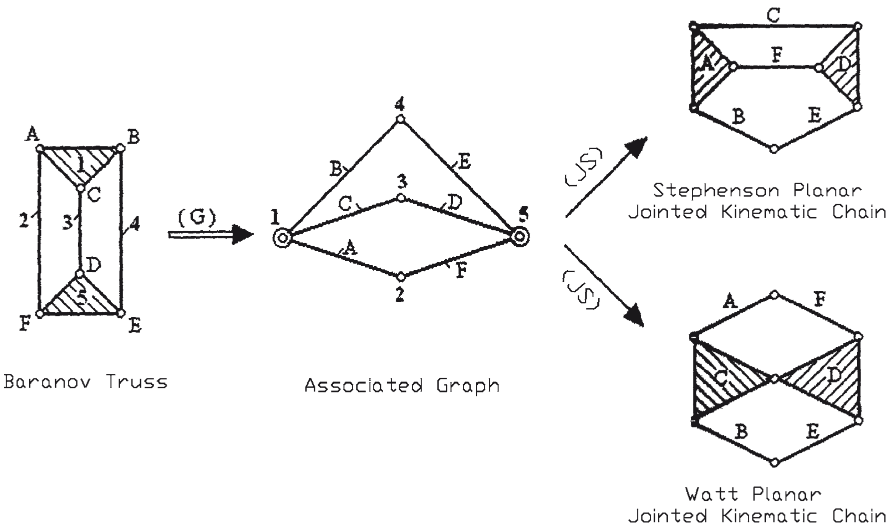


Fig. 5 Generation of "Stephenson" and "Watt" planar jointed kinematic chains from the Baranov truss by (G) + (JS) operations (Grecu 2007)

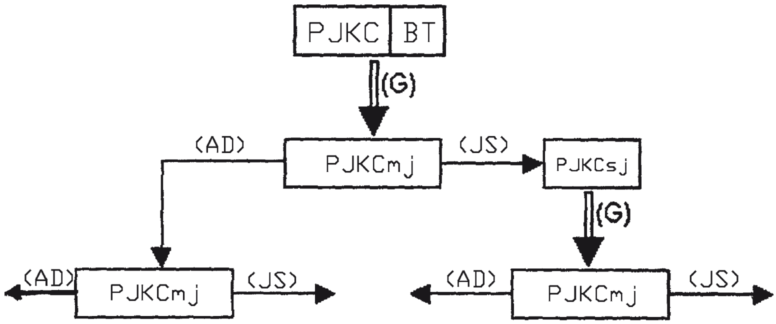


Fig. 6 The basic algorithm of Manolescu's structural synthesis Methodology (**a**) Manolescu et al. (1972); (**b**) Grecu (2007)

By noticing that the associated graph of a planar-jointed kinematic chain (or Baranov truss) can itself be considered a planar-jointed kinematic chain with multiple joints (PJKCmj) (see Fig. 5.), Manolescu delivered his ultimate structural synthesis methodology based on the combination and multiple use of operations of graphisizing (G), joint simplification (JS) and amplification with *dyads* (AD). The basic algorithm of this methodology is presented in Fig. 6. by Manolescu et al. (1972) and by Grecu (2007).

Starting from a planar-jointed kinematic chain (PJKC) or Baranov truss (BT), by the graphisizing operation one comes to its associated graph, which in its turn can be considered a planar jointed kinematic chain with multiple joints (PJKCmj). By applying the operation of joints simplification (JS), we come to another planar-jointed kinematic chain with simple joints (PJKCsj), of the same degree of freedom; or, by applying the operation of amplification with *dyads* (AD), we come to another different planar-jointed kinematic chain with multiple joints (PJKCmj) with more elements but with the same degree of freedom.

The process can be continued by repeatedly applying, in an arborescent manner, these operations of graphisizing (G), joints simplification (JS), amplification with *dyads* (AD), thus getting several new solutions of planar-jointed kinematic chains with even more elements.

By this methodology, Manolescu was able to verify the computer-aided solutions obtained by researchers in India and Taiwan and to achieve his goal of discovering all the existing configurations. The methodology can be also extended to the study of kinematic chains with superior kinematic pairs, cams, cylindrical gears, etc.

In his last studies, Manolescu introduced the concepts of “planar initial jointed kinematic chain” (PIJKC) and “planar initial jointed kinematic chain with simple links” (PIJKCsl).

The following tables are relevant for these concepts and express some of Manolescu’s last published achievements.

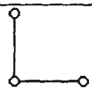
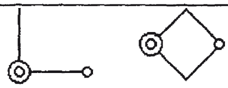
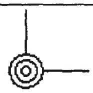
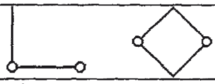
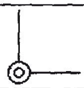
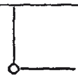
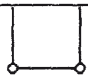
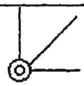
Figure 7, from Manolescu (1993) and also Grecu (2007) presents the nonisomorph variants of planar initial jointed kinematic chain with simple links-PIJKCsl.

In Figure 8, of Manolescu (1993), are shown the generation of planar-jointed kinematic chains with simple links, multiple joints and degree of freedom $L = 4$.

In Figure 9, of Manolescu (1993), the generation of planar-jointed kinematic chains with simple links, multiple joints and degree of freedom $L = 5$ is explained.

Figure 10, of Manolescu (1993), shows the generation of planar-jointed kinematic chains with simple links, multiple joints and degree of freedom $L = 6$.

Professor Nicolae Manolescu definitely left his mark upon the Romanian school of mechanisms and machines. His studies and findings are fundamental to the further development of MMS in Romania and abroad. For hundreds of polytechnics graduates, he will be remembered as a great teacher, an innovative, sympathetic and creative one. His life and dedicated work are, above all, an inspiration for all of us who knew him and have read his works. Figure 11 shows Professor Nicolae Manolescu with some of his pupils and collaborators at his 1992 anniversary at Bucharest Polytechnic Instuitute.

Degree of Freedom	Structural Characteristics: Number of links	Structural Characteristics: Number of Multiple Joints	Structural schema of the PIJKC sl
$L_3 = -1$	$e = 1$	$C_5^1 = 2$	
$L_3 = 0$	$e = 2$	$C_5^1 = 3$	
		$C_5^1 = 1; C_5^2 = 1$	
		$C_5^3 = 1$	
$L_3 = 1$	$e = 1$	$C_5^1 = 1$	
$L_3 = 2$	$e = 2$	$C_5^1 = 2$	
		$C_5^2 = 1$	
$L_3 = 3$	$e = 1$	$C_5^1 = 0$	
$L_3 = 4$	$e = 2$	$C_5^1 = 1$	
$L_3 = 5$	$e = 3$	$C_5^1 = 2$	
		$C_5^2 = 1$	

C_5^1 = Simple joint; C_5^2 = Double joint; C_5^3 = Triple joint

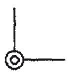
  

Fig. 7 The nonisomorph variants of planar initial jointed kinematic chain with simple links (**a**) Manolescu (1993); (**b**) Grecu (2007)

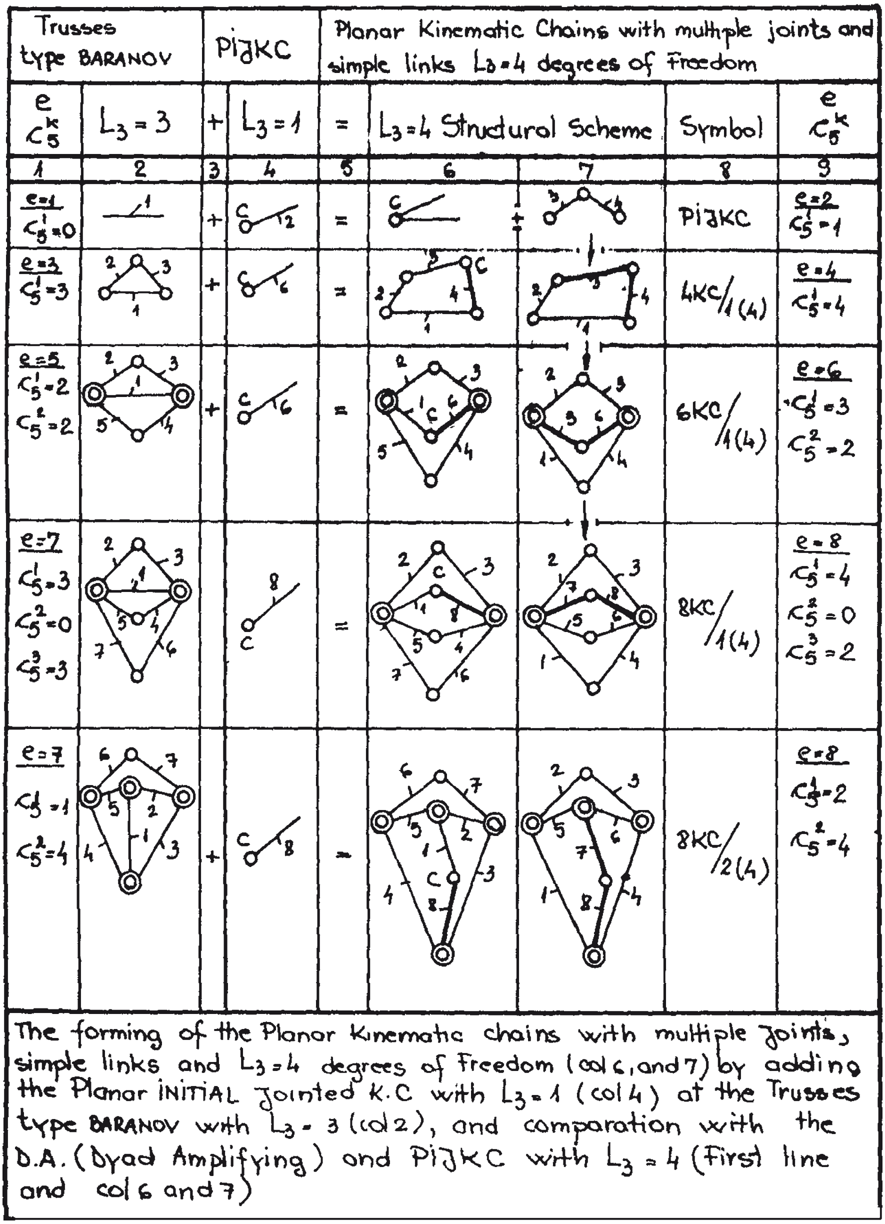


Fig. 8 The generation of planar jointed kinematic chains with simple links, multiple joints and degree of freedom L = 4 (Manolescu 1993)

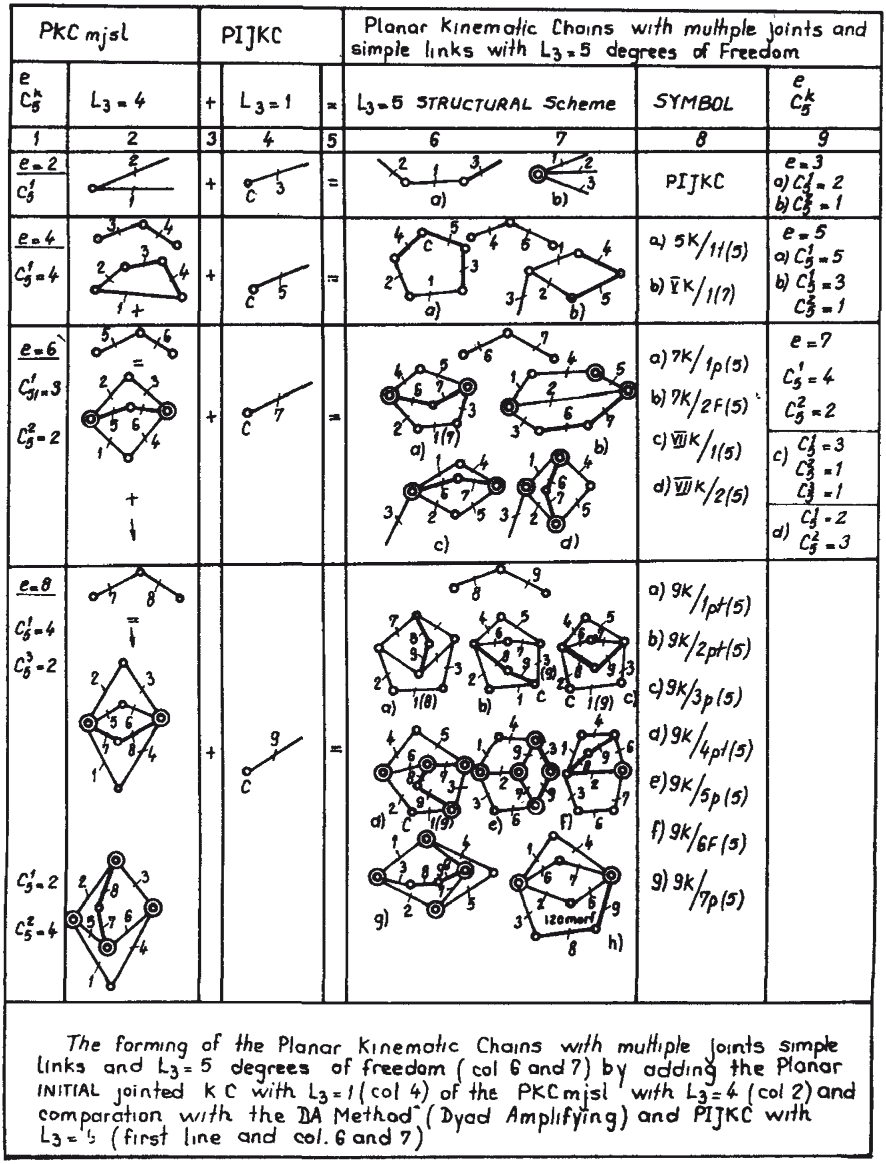


Fig. 9 The generation of planar jointed kinematic chains with simple links, multiple joints and degree of freedom L = 5 (Manolescu 1993)

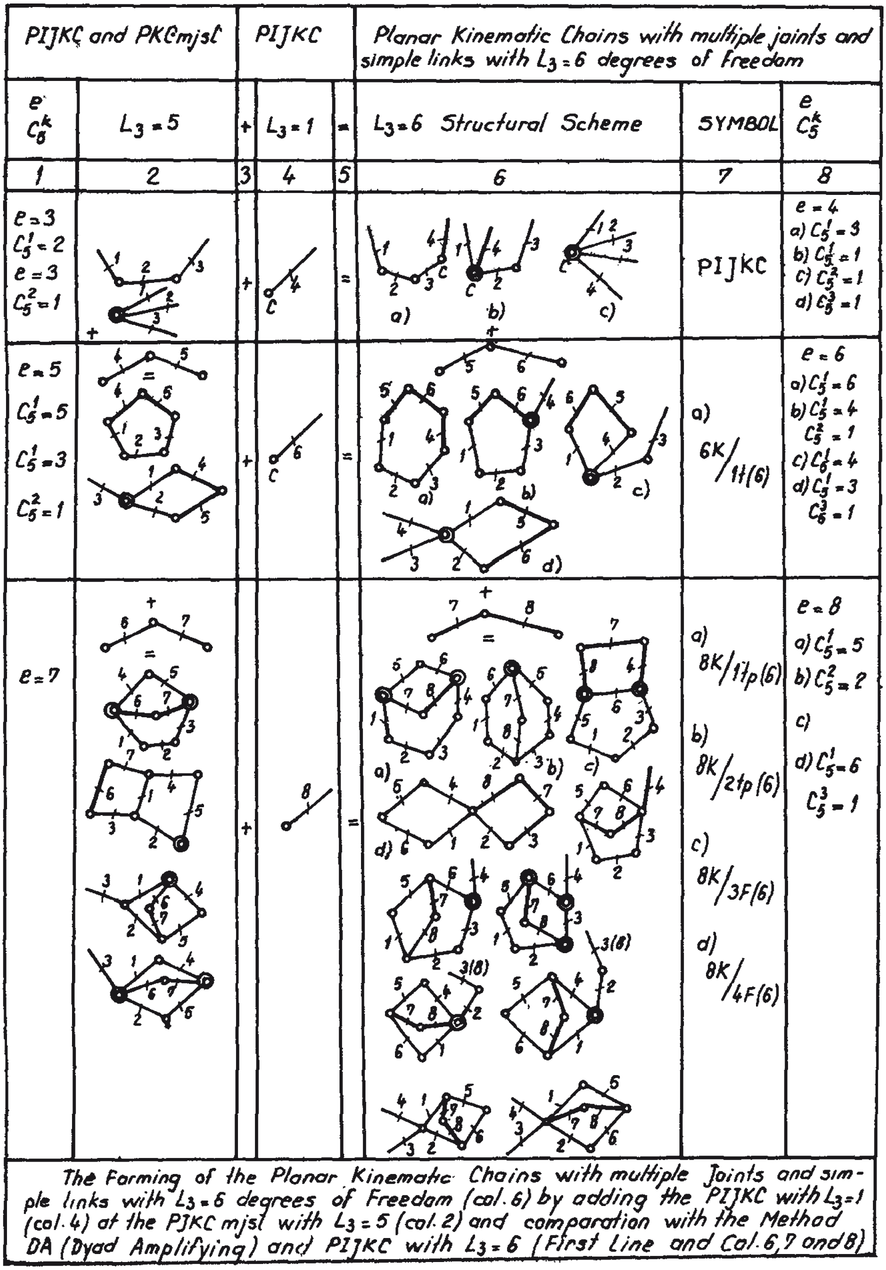


Fig. 10 The generation of planar jointed kinematic chains with simple links, multiple joints and degree of freedom L = 6 (Manolescu 1993)

Fig. 11 Nicolae Manolescu at his 1992 anniversary at Bucharest Polytechnic Institute, chair of Mechanisms and Machines (flanked, from left to right, by S. Cononovici, A. Lascu, F. Duditza and R. Bogdan, T. Ionescu, P. Alexandru, B. Grecu, F. Nitzu, I. Tempea) (Author's photo archive)

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Francesco Masi (1852–1944)

Marco Ceccarelli

Abstract In this paper, the figure and work of Francesco Masi is presented as an influent professor in the field of TMM in Italy. His main contribution, still of present-day significance, can be recognized in the rigorous systematization of Reuleaux's classification of mechanisms together with an analytical approach for analysis and synthesis of mechanisms. He was also a scientist and engineer in approaching design problems and teaching developments in mechanical engineering at large, and particularly in TMM, lubrication and machine drawing.

Introduction

The second half of the nineteenth century can be considered as the Golden Age for TMM (Theory of Machines and Mechanisms) since it has been developed to high levels of knowledge and practical applications. This happened mainly all around Europe during the Industrial Revolution. But in a very rich literature, some relevant works and personalities are forgotten in today's memory and consideration for the History of TMM. This is the case of most of the Italian literature on kinematics, and the Italian personalities are rediscovered only now, together with their contributions regarding TMM success, both in formation of engineers and research developments with practical applications in new machinery, as pointed out in Ceccarelli (2000).

The Italian tradition in the field of mechanics goes back to the first studies in the twelfth century and continues over the centuries with considerable contributions.

In particular, mechanics received a great boost by the work of Galileo Galilei (Galilei 1600) and Guidobaldo Del Monte (Del Monte 1577) in the sixteenth century and their influence was considerable throughout the eighteenth century too, as

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pointed out in Ceccarelli (1998, 2000). With this cultural background, new achievements were obtained in mechanics so that in the eighteenth century mechanics and mechanical engineering were addressed as separate mature disciplines apart from mathematics. Thus, specific books were written and academic courses were established in several Italian Universities.

These former developments produced a very promising environment for modern enhancements. Italian personalities are recognised and well known from the seventeenth and eighteenth centuries as, for example, Paolo Branca (Branca 1629), Evangelista Torricelli (Torricelli 1919), Guido Grandi (Grandi 1739), Paolo Frisi (Frisi 1765, 1777), Ruggero Boscovich (Boscovich 1763), only to cite some. But the cultural influence of Italian universities was reduced so that in the nineteenth century they were not considered centres of excellence as they had been in the previous century. Nevertheless, exiting activity was carried out in the field of mechanical engineering mainly with the aim of establishing a modern view of the field. Moreover, specific developments were obtained and original contributions were proposed. However, these works circulated with difficulty, even in Italy, probably since at the beginning of the century, there was a considerable number of small kingdoms and later, the main aim was the attempt to obtain a unified culture and organization when the Italian nation was achieved. Another reason for forgetting about Italian works can be the fact that the nineteenth century can be considered as a recent past in Italian culture and because of this, it is not yet considered worthy of attention. In fact, in the Italian libraries, the books of the past century are not classified in ancient funds but neither are they catalogued in modern databases. Most the time they are just stored somewhere. In addition, although memory of the personalities still exists, their works are sometimes considered as out-of-date, without taking into account that they have been useful as an important basis for modern developments.

In the second half of the nineteenth century, schools of engineering were established in most of the Italian universities, but it was only after the Decree of 3 July 1879 that the course "Kinematics Applied to Machinery" was introduced on a regular basis in the curricula of industrial engineers (Pugno 1959).

Nevertheless, only in the oldest Italian universities there was a well-established tradition and in-depth works were carried out in TMM. In fact, we have found textbooks (sometimes handwritten) for regular academic courses on TMM or kinematics given in Turin, Milan, Padua, Pisa, Bologna, Rome, and Naples.

In Turin, following the work by Lagrange and Papacino, courses on TMM were given by Carlo Ignazio Giulio (Giulio 1846), Galileo Ferraris, Domenico Tessari (Tessari 1890), Scipione Cappa (Cappa 1890). Other contributions were given by Elia Ovazza (who seems to be the first female engineer in Italy) (1890), and M. Panetti (1913).

In Milan, after Ruggero Boscovich, relevant Academic personalities can be recognised in Ernesto Cavalli (Cavalli 1882, 1889, 1908), and Gian Antonio Maggi, (Maggi 1896, 1914). Secondary works were developed by Ugo Ancona (Ancona 1896), Giusto Bellavitis (1852), and Ernesto Padova (Padova 1884).

In Bologna, after Gaetano Giorgini (1836), Domenico Chelini (Chelini 1862), and Francesco Masi (Masi 1883, 1897a) made significant contributions to TMM.

In Rome, works on TMM were written by Ugo Cerruti (Cerruti 1898) and Carlo Saviotti (Saviotti 1890). A temporally presence was Lorenzo Allievi, who published a masterpiece (Allievi 1895) on planar kinematics after giving lectures for only 1 year (Ceccarelli and Koetsier 2008). A late successor of Saviotti was Anastasio Anastasi (1908).

In Naples, an important personality on mechanics at large was Giovanni Battaglini (Battaglini 1870, 1873), and in the field of TMM Dino Padelletti (1884), had a good reputation.

In addition, professors were involved in promoting the academy and specifically TMM in more than one university. An emblematic example is Ernesto Cavalli who taught in Milan, Livorno, Pisa and Naples, as reported in his textbooks (Cavalli 1882, 1889, 1908).

The figure and work of Francesco Masi in Bologna University can be considered representative of the Italian fecundity in the field of kinematics of mechanisms, beside the relevance of his work and activity in mechanical engineering generally.

This paper is an attempt to pay due tribute to the personality of Francesco Masi (1852–1944) by surveying his teaching activities and his works that were published and circulated, unfortunately, only in the newly established Italian nation.

Biographical Notes

Francesco Masi (Fig. 1) was born on 28 February 1852 in Guastalla (Reggio Emilia). He obtained his engineer's degree in 1875 at the Royal School of Engineering in Turin. His first employment in 1875 was as professor of Physics and Mechanics at

Fig. 1 A portrait of Francesco Masi (1852–1944)

the Technical College in Cagliari. In 1877, he returned to Bologna to the Royal School of Engineering as assistant professor in the field of Mechanics of Machinery. In 1891, he was appointed full professor at Bologna University where he remained until his death on 30 November 1944 in Bologna. He married Teresa, the daughter of the famous Italian poet Giosuè Carducci, but they never had children.

Unfortunately, no detailed biographical information can be found to better characterize the wide interests that Francesco Masi had during his long life. Masi focused his attention on TMM but also on the fields of hydraulics, technical drawing, mechanics of agricultural machines by developing teaching activities in Technical Colleges and at Bologna University.

List of Main Works

The following publications can be considered as the main works os Francesco Masi. (All are written in Italian and were published in Italy only) (Masi 1927):

1. The bridge on Panaro river in Vignola, 1875.
2. The Rectory Factory for baskets in Bologna, 1880.
3. On the couplings for spherical four-bar linkages, 1880.
4. The irrigation in Modena lands, 1882.
5. Handbook for Applied Kinematics – New classification of mechanisms, 1883 (Masi 1883).
6. Determination of clear spans of bridges, 1885.
7. Methods for corrosion defense, 1885.
8. Properties of Watt curve, 1890.
9. Lectures on Hydraulics at Royal School of Engineering in Bologna, 1893.
10. Experimental methods in the teaching at Technical Professional Colleges, 1890.
11. Treatise on Civil and Industrial Constructions as co-author, published by F. Vallardi, 1890 and successive editions.
12. Drawing of mechanical parts for Technical Colleges, 1891 (Masi 1891).
13. Study of vein obtained by means of shining projections, 1895.
14. Theory of Mechanisms, 1897 (Masi 1897a).
15. New views on theoretical and experimental investigations on friction, 1897 (Masi 1897b).
16. Experiences on friction, 1897 (Masi 1897c).
17. Kinematics of mechanisms and Kinetics of machines, 1920.
18. Plough for hills, Patent, 1920.
19. Lecture Notes of Mechanics for Agriculture at the Royal Agriculture Institute in Bologna, 1926.

The variety of subjects in the above-mentioned publications shows a large variety of interests on which Francesco Masi continuously worked throughout his long academic career. In fact, he was well reputed and his memory is still persistent in the Italian Academy, not only in the field of TMM but even for his contributions in machine drawing and tribology.

Teaching Activity

Francesco Masi paid much attention to his teaching activity in the framework of both University formation of engineers and Technical Colleges for technicians. He started his career just after he obtained his engineer's degree by giving classes at a technical college in Cagliari. This experience was so fruitful for him that he continued to teach at technical colleges, even when he held the position of full professor at the University of Bologna. In particular, he devoted his efforts mainly to the subjects of technical drawing and machine design in the technical college Aldini-Valeriani in Bologna until 1906. During this period, he prepared and published the textbooks (10 and 12 on the list) (Masi 1927). In particular, the textbook on technical drawing (Masi 1891) (Fig. 2) was particularly appreciated and indeed was well used even at the level of University teaching for a long period as a significant development of the Italian tradition following the results of Quintino Sella, as pointed out in Ceccarelli and Cigola (2007).

In this textbook, Masi collected 60 drawings of the main, basic components of machines that are represented in great details for their construction, by using projections and many sections with further developments for technical views and drawing. As a conclusive example, he reported the technical drawing of a locomotive. He also included discussions and expressions both with theoretical and practical formulation for the design of mechanical parts within each drawing table. In addition, for each drawing, he explained the generalities of the technical drawing and specific particularities for the representation of details as a further development of the work by Quintino Sella, who got inspiration from Monge's Descriptive Geometry. Masi emphasized the need of writing the sizes within the figures of the drawings by quoting all the dimensions, although he recommended the use of a proper scale to indicate the real proportions. He developed technical drawing with more technical emphasis by strongly reducing the artistic features of shadows and chiaro-scuro according to Sella's approach too. Nevertheless, he recommended and used to represent through limited signs, the objects as lightened by rays at 45° from the left. He used broken-line segments as a conventional indication for different materials. Today, this textbook on Technical Drawing receives much interest from the historical viewpoint, since its completeness and clarity make it a fundamental source for understanding the historical development of technical drawing and its standardization mainly but not only in an Italian framework.

The textbook No.19 in the list (Masi 1927) on agriculture mechanics was written by Francesco Masi as a result of his teaching at the Royal Agriculture Institute in Bologna that he started in 1903.

Masi collected most of his research experiences and novel contributions in the textbooks for TMM (Masi 1883, 1897a), that are Nos. 5 and 14 in the list

Fig. 2 Cover page of the textbook on mechanical drawing by Francesco Masi, published in 1891

(Masi 1927), Fig. 3. They can be considered his main works. Both books on TMM were a great success, since they were used for a long time, even in other universities in Italy. In fact, they can still be found in the libraries of many Italian schools of engineering. Successively, he revised and completed the content for more wider TMM teaching in the textbook No.17 in (Masi 1927) that was published in 1920 but it was not successful as the other two.

Fig. 3 Cover pages of works by Francesco Masi on TMM and mechanism design: (**a**) Handbook of applied kinematics in 1883. (**b**) Theory of mechanisms in 1897

The book Masi (1897a) has a clear teaching purpose while the book Masi (1883) is much more a treatise for a new classification of mechanisms. Indeed, the book Masi (1897a) includes the content of the book Masi (1883) in a specific chapter on mechanism classification and together with Masi (1920), they complete a set that Masi prepared for the Course of Mechanics of Machinery that he taught continuously throughout his long career.

In Masi (1897a), the Theory of Mechanisms is treated both in theoretical aspects and practical applications. The first three chapters deal with the fundamentals of theoretical kinematics by explaining the kinematics of relative motion, determination of centrodes, curvature analysis of trajectory, determination of inflection circle and cycloid curves by using a graphical approach and an analytical formulation.

Chapter 4 is devoted to the study of the motion of a body on a plane by looking at the number of contact points from a kinematic viewpoint. Chapter 5 attaches the problem of instantaneous motion for the determination of the centrodes and axoides of the motion. Chapter 6 is a detailed analysis of gears with theoretical formulation and practical design rules. Chapter 7 summarizes the classification procedure that Masi elaborated in Masi (1883) as an improvement of Reuleaux's work (Reuleaux 1875).

The symbolic notation is introduced together with the notion of kinematic inversion. Successively, the general synthesis problem is discussed. A general classification of mechanisms is introduced as a function of the kinematic composition of the kinematic chain of mechanisms. This is proposed as the unifying aspect that permits us to treat all the mechanisms within a unique frame for kinematic analysis. In fact, the remaining Chapters from 8 to 15 describe all the classes of mechanisms that are included in the classification, namely linkages, gearing systems, wedges and cams, spur gears, epicyclic trains, ratchet gears, and belt transmissions.

The successful teaching approach in Masi (1897a) can be understood by looking at the clarity of the explanations that are completed by means of essential formulation and exhaustive schemes. In the discussion of each mechanism, theory is properly combined with a discussion for practical applications. In the following, examples are discussed to show Masi's approach.

In Fig. 4, kinematic schemes that are presented are useful for analyzing a Watt parallelogram. In particular, in Masi's Figure 257, a graphical procedure is outlined to draw a Watt curve of a point O of the coupler with the following procedure: by using the circles with centers A and D whose radius are AB and DC, respectively, a general point P of the curve can be determined from points M and N on the circles through the segment MP that is long like OB on the straight-line MN. N is determined by using the CB length as the radius of a circle with its center in M to intersect the circle with its center in D.

Thus, once the procedure for analysis formulation is outlined, Masi stresses the main kinematic characteristics of the Watt curve such as a sixth-order curve and the consequent order of contact of the curve with straight-line yy. A practical study of the curve is further suggested by using the variable mechanism design of Figure 258 to investigate differences in the curve as a function of the position of the tracing point O on the coupler. Results are shown in the drawn Figures from 259 to 264 that have been obtained experimentally, as reported in Fig. 5. Then, Figure 265 is proposed to outline a synthesis procedure and evaluation of the maximum deviation of the curve from the straight-line yy, through graphical determination. The sequence of the graphical construction for the synthesis is represented as a function of the data CD and angle 2α. By using angles β and λ (which are between OO_1 and yy), the maximum deviation ε can be computed as $OO_1 \sin \lambda$, whose simplification is obtained from geometric reasoning on Figure 266 to obtain $\varepsilon < AB / 2{,}592$ as a practical expression.

In Fig. 6, the study for constraining the planar motion of a body is discussed to explain the thesis that four contact points are necessary and sufficient to avoid relative translation of the body but they are only necessary to avoid relative rotation. The discussion is illustrated by looking at the intersection points of the normal lines at the contacts to determine the triangles abc and cde in Figure 55: if abc is inside cde, the relative rotation is impossible.

The extension to a general case with any number of contacts is discussed by referring No. 56 in Fig. 6 in which the basic polygon is determined by the normal lines from the contacts. Then, the conditions for possible relative rotation depend on the topology of the polygon considering the orientation of the sides: when the polygon is convex with the inside not overlapping circuits, the relative rotation is not possible.

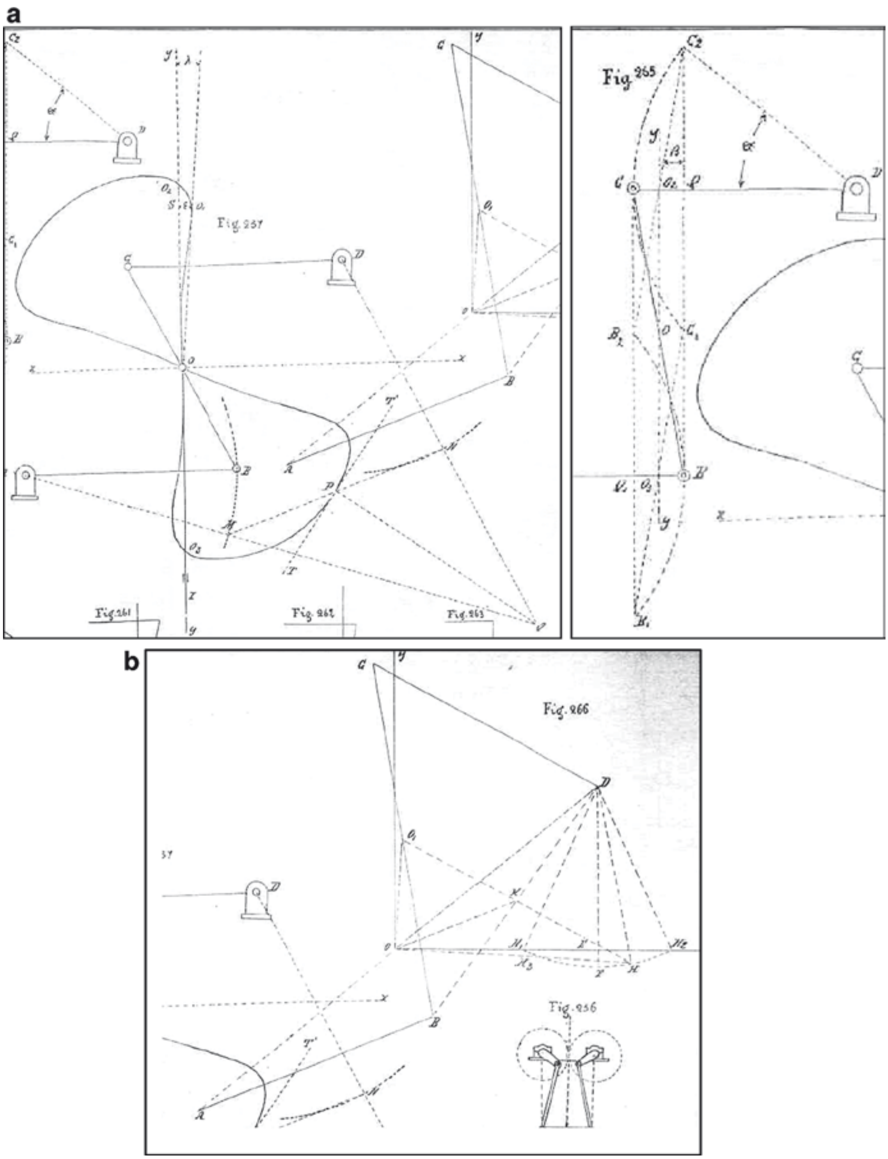

Fig. 4 Kinematic schemes for Watt parallelogram in Masi (1897a): (**a**) Figs. 257 and 265; (**b**) Fig. 266

In Fig. 7a, the case of hypoid gears is discussed by using the scheme of Figure 148 to give practical indications for a successful manufacturing and efficient use (equal normal pitches, small transmission forces, limited skew distance) and to compute the angular velocity ratio as ω_2/ω_1 after some algebraic manipulations of

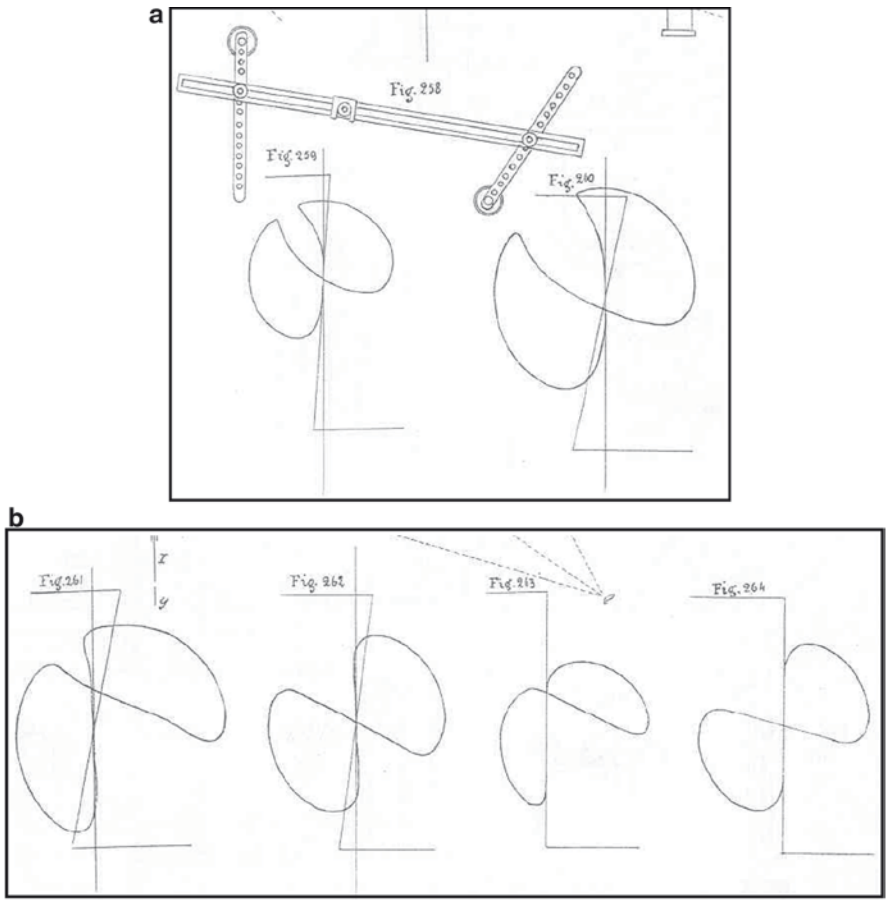

Fig. 5 A parametric study on coupler curves of the Watt parallelogram in Masi (1897a): (**a**) Figs. 258–260; (**b**) Figs. 261–264

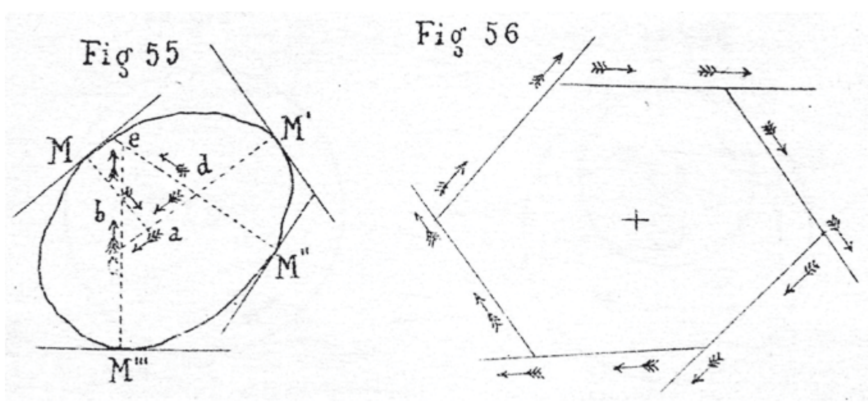

Fig. 6 Models for static analysis of multiple contacts in Masi (1897)

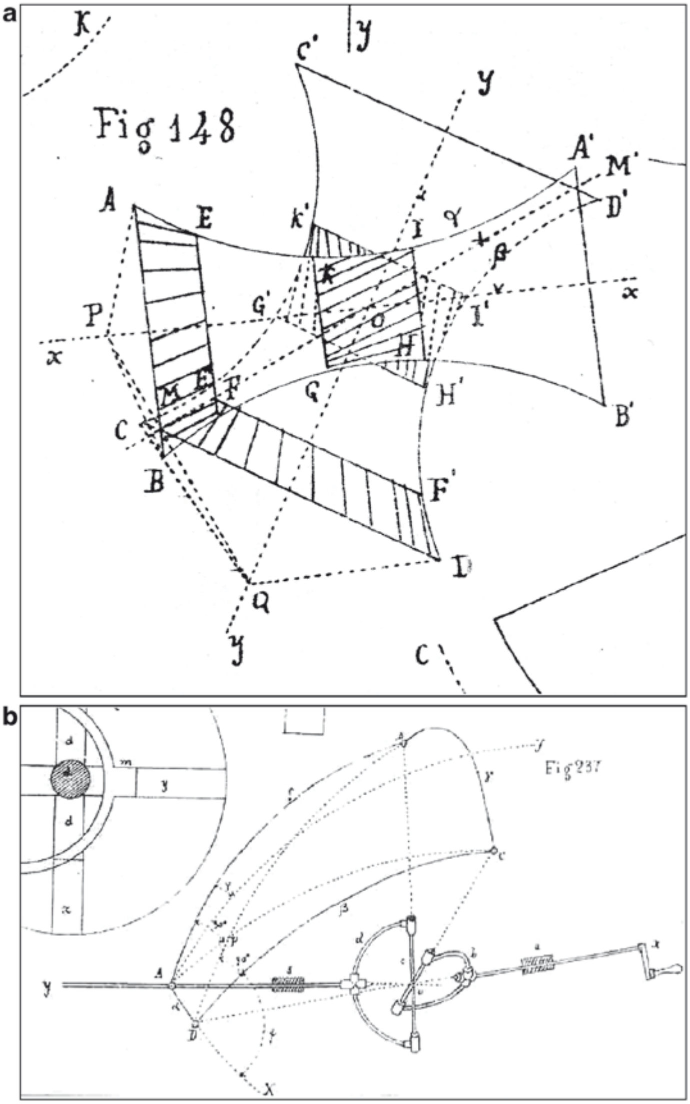

Fig. 7 Kinematic schemes in Masi (1897a) for: (**a**) hypoid gears; (**b**) Hooke's joint

the fundamental design parameters as n_1/n_2, with n_1 and n_2 as the number of teeth in gears 1 and 2, respectively.

In Fig. 7b, similarly, the Hooke joint (mainly known in Italy as the Cardan joint) is studied to characterize its kinematic operation as a function of its design parameters with formulation derivation and information for successful uses like in tower clocks, windmills, and land agriculture machinery. In particular, by referring to the scheme No. 237 in Fig. 7b, Masi deduced the well-known ration input-output in

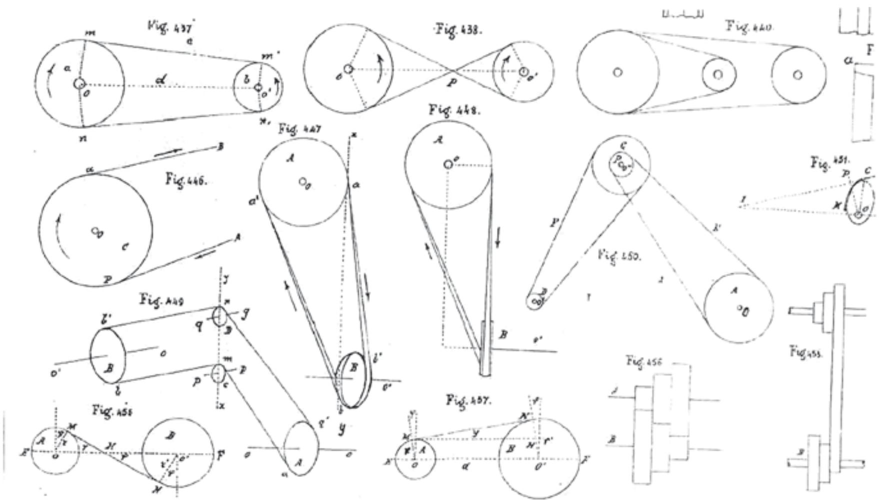

Fig. 8 Schemes and design solutions for belt transmissions in Masi (1897a)

term of cos α/(1−sin²α sin²φ) in a straightforward way by using the time derivative of geometrical expressions for the angle α among points A, O, and D and angle φ among points B, A, and Y in the structure and operation of the mechanism.

In Fig. 8, there are schemes that Masi used to describe the functionality and variety of belt systems for power transmissions. Figure 8 is an example summarizing the approach that Masi used to treat mechanisms giving theory (even trough drawings), computations, design details, and information of applications for each case. The large variety of studied mechanisms can be appreciated by the 515 schemes that he drew in his book (Masi 1897a).

It is worth noting that most of the treatments of reported mechanisms can be still considered today to be of both of theoretical/computational validity and practical interest.

Modern Interpretation of the Main Contributions

In the field of TMM, Francesco Masi made relevant contributions in a systematic approach for teaching TMM, as an historical evolution of the work by C. Giulio (Giulio 1846) in Italy and as a modern organization by following the works of R. Willis (Willis 1841) and F. Reuleaux (Reuleaux 1875). In addition, he has contributed to the scientific developments of topics regarding mechanism classification and mechanism design. The brilliant organization of the teaching on mechanisms and related theories can be appreciated in the organization of his textbooks, as outlined in previous section.

Relevant is the enhancement that Masi elaborated in Masi (1883) for the mechanism classification by using Reuleaux's approach and formalism in Reuleaux

(1875). Masi revised and completed the mechanism notation by expressing the following formalism: type symbols for general design characteristics of bodies, like for example, C is for cylinder, P is for prismatic box, R_d is for geared wheel; shape symbols for the specific geometry of the body, like for example, C^+ is for bulk cylinder (pivot), C^- is for hole cylinder (bearing), P^+ is for bulk prismatic box (slider), P^- is for prismatic guide; relationship symbols for describing the relations between two elements of a kinematic chain, like for example, || is for parallel axes, x is for crossing lines, < is for inclined lines. Therefore, any mechanism can be represented by a formula, when additional signs are used for fixed bodies (segment with dashed lines), elastic bodies (wave segment), and moving bodies (straight segment) like, for example, the cases shown in Fig. 9.

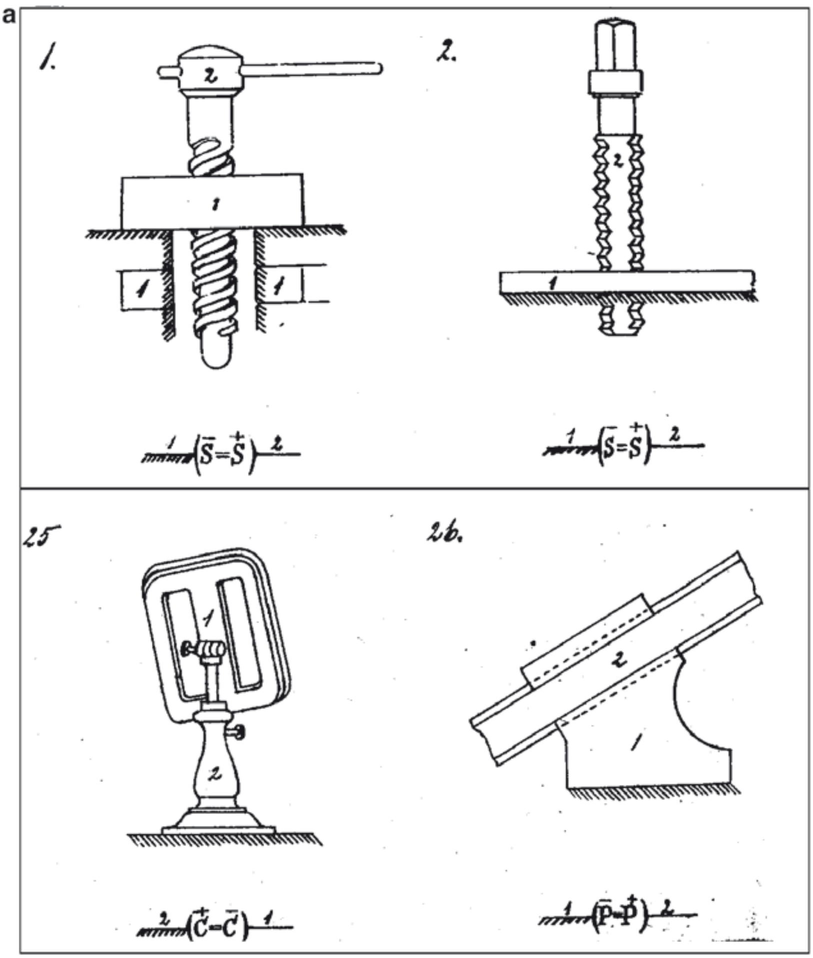

Fig. 9 Examples of notation and formalism for analytical representation of mechanisms in Masi (1883): (**a**) basic pairs; (**b**) cam mechanisms

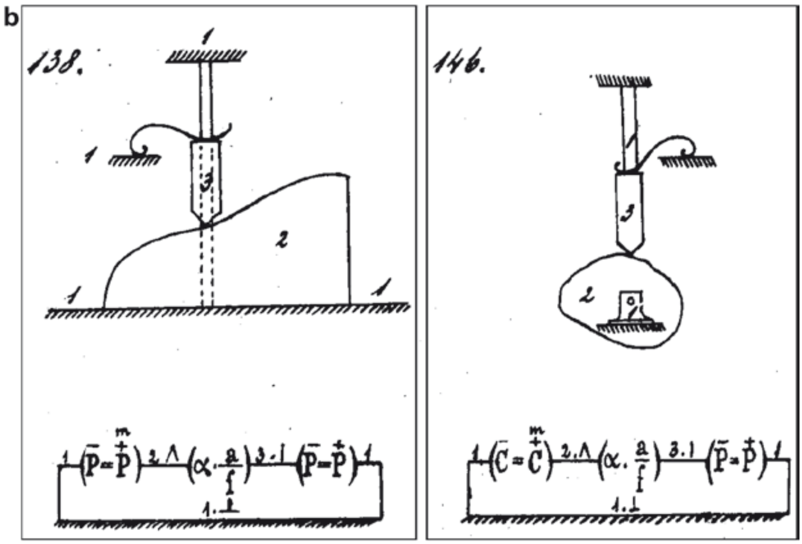

Fig. 9 (continued)

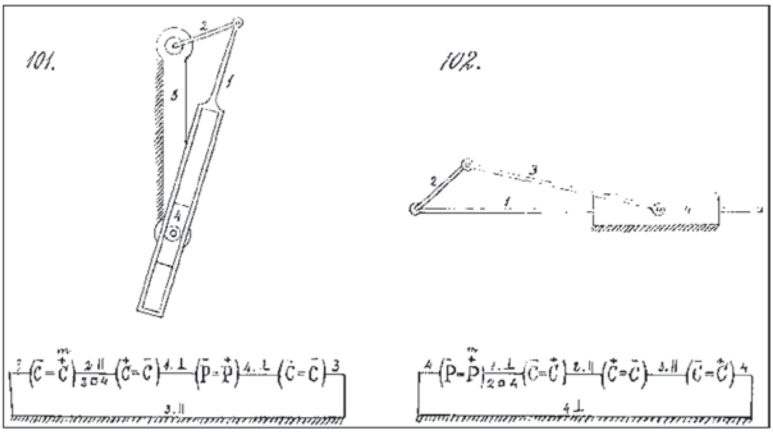

Fig. 10 Notations and schemes of mechanisms from the slider-crank chain in Masi (1883)

The notation was an attempt to develop a more analytical representation of mechanisms, avoiding encumbering mechanism drawings, even with the aim of using it for analytical treatment of the basic kinematic properties. But, as we know, it was unsuccessful because of the complexity both in writing and understanding, as the examples in Fig. 10 illustrate for the case of slider-clank mechanisms and inversions.

Some practical interest of this notation can be recognized in the definition of mechanisms by means of kinematic inversion, like the example in Fig. 10 illustrates when one considers permutation of the order of the mechanism components in choosing the frame link for the mechanism. The notation is attractive because it also can be very synthetic in showing the variety of possibilities of a kinematic chain like in the example of Fig. 11.

In addition, the formalism of the proposed notation can be considered as part of the classification rules, when one considers that the characters/rules of the classification can be expressed as functions of the introduced symbols for the fundamental kinematic properties of kinematic design of mechanisms.

Following Reuleaux's work, Masi proposed his view and formulation of mechanism classification. His view also takes into account the previous attempts of an exhaustive classification of existing mechanisms that were elaborated during the nineteenth century (Ceccarelli 2004). The basic rules of Masi's classification of mechanisms can be recognized in the concepts of simple and compound mechanisms, the kinematic chain and its inversion, categories and classes of mechanisms (Masi 1883).

Simple mechanisms are considered to be composed of one circuit of linked bodies only; compound mechanisms are those with more circuits of links with a different nature. The concept of a kinematic chain, which is the kinematic structure of mechanisms when any link is considered as a fixed frame, is useful to consider the kinematic architecture of mechanisms as mechanism topology. The kinematic inversion consists in considering any link of the mechanism as a fixed frame for different specific mechanisms as introduced by Reuleaux (1875).

A category of simple mechanisms is identified by the number of pairs of different types that are in the kinematic chain. Thus, the first category for so-called homogenous mechanisms is made of all the pairs with components of the same nature, even repeated in the chain like, for example, revolute joints or prismatic

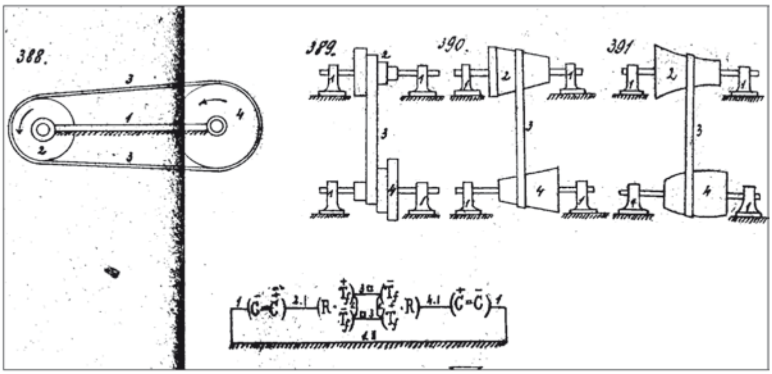

Fig. 11 Notation and schemes for a variety of belt transmissions as represented by one formula in Masi (1883)

joints, and so on. The second category for binary mechanisms is composed of two pairs of different natures, even repeated in the chain like, for example, revolute joint with prismatic guide or revolute joint with screw, and so on. Although there were a wide range of theoretical possibilities, Masi identified eight categories only, those of practical engineering interest that are made of articulation joint ($C^+ = C^-$ or $P^+ = P^-$), point with a line ($\alpha.\alpha$), two lines ($a.\alpha$), two screws ($S^+ = S^-$), two wheels (R.R), two gears ($R_d.R_d$), one gear with a pawl ($R_d.a$); compression and traction elements (with a complex notation!).

In each category, there are several possible mechanisms that can be grouped in classes with the same kinematic design. Thus, for the first category, the first class can be identified as grouping all the linkages that are composed of revolute joints (that Masi advised as the only practical ones in the category). The second class is composed of cams and wedges; the third class includes sockets; screws are in the fourth class; wheel connections are the fifth class; gears are the sixth class; the seventh class is composed of ratchets; and the eighth class is given by elements working by compression or traction.

Compound mechanisms can be classified similarly to simple mechanisms by categories and classes depending on the number of kinematic chains and their nature, respectively.

By using the above-mentioned concepts and rules, Masi classified the mechanisms according to Tables 1 and 2, by starting from the eight practical simple classes only. He advised that many of the counted mechanisms in the classes can

Table 1 Classification of simple mechanisms in (Masi 1883)

Category	Number of classes	Description of classes
Homogeneous	8	Linkages
Binary	28	Wedges and cams, sockets, screws, wheels, gears, ratchets, mechanism by traction and compression
Ternary	56	Gears with sockets, ratchets with gears
Quaternary	70	
5th	56	
6th	28	
7th	8	
8th	1	

Table 2 Classification of compound mechanisms in Masi (1883)

Category	Number of classes	Description of classes
Homogeneous	225	Compound linkages, screws, wheels, gears, ratchets, mechanisms by traction and compression
Binary	25,200	Gears and linkages, sockets and traction elements, ratchets and gears, ratchets and linkages, linkages and compression systems
Ternary	1,873,200	Same as binary
Quaternary	10,362,600	Same as binary
205th	… 1	Same as binary

be determined only theoretically (with the help of the notation!) and therefore they should be invented. Likewise, extending the consideration to more simple categories with other basic rules/structures, any other mechanisms can be invented but practical applications should be thought to be specifically part of the invention.

Thus, he applied his theory for mechanism classification by giving a unifying view of mechanisms that are also the basis of the systematic organization for teaching mechanism design. He also gave a computation of the design possibility, as reported in Table 2, in which he calculated up to 25,200 binary mechanisms and 10,362,600 quaternary mechanisms.

Regarding mechanism design, Masi clearly expressed the basic characteristics through kinematic schemes throughout his textbooks (Masi 1883, 1897a), with the aim of facilitating understanding the kinematics and the potentiality of mechanisms in practical applications.

Those comprehensive views, whose examples are illustrated in Figs. 4–8, were achieved by Masi through his encyclopedic knowledge of mechanisms that he elaborated, thanks also to his classification procedure.

Circulation of Masi's Work

Although Masi's works were very relevant and successful during his time, they were rarely considered after the Second World War. This is due mainly to two facts, namely the graphical approach and orientation of Italian users, by whom the works were written. The graphical approach was developed and greatly developed in the second half of the nineteenth century and Masi strongly used it when completed, together with some analytical formulation. But the real limitation for the circulation of Masi's work can be considered in Italian writings and orientation to the teaching in the Italian schools of engineering. This feature rapidly circulated Masi's work in Italy, mainly at the time of his career in the nineteenth century. The main orientation to Italian users can be understood when one considers that the Italian nation was only unified in 1860 and, since then, great efforts have been made to produce a common national frame for university formation.

We can consider three main topics in which Masi made relevant contributions that circulated successfully the memory of which is persistent in Italian schools of engineering, namely technical drawing for machinery, friction and early tribology, TMM and mechanism design.

Technical drawing for machinery was of great interest for technical colleges and professional activity for many years. Masi's work was considered relevant for University formation. Today, this work is addresse mainly for historical investigations on the developments of drawing technique and representations of machine elements, as indicated in Ceccarelli and Cigola (2007).

Masi's works on friction can be considered to be a significant early development of modern tribology and because of that character, they were much considered at the beginning of the Italian community on tribology. Masi's works on tribology

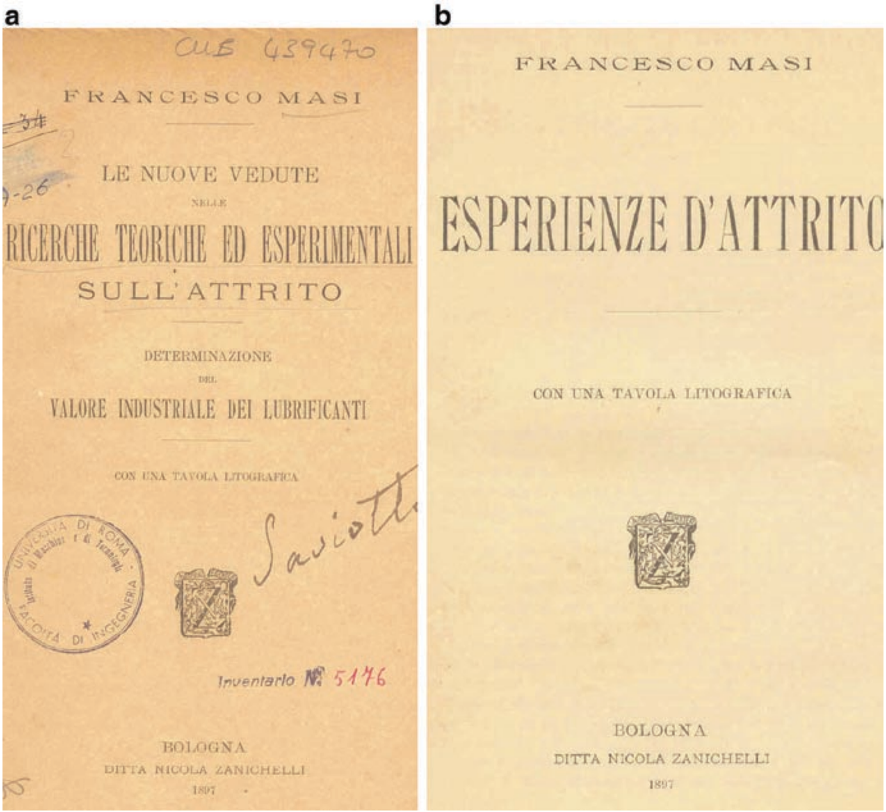

Fig. 12 Cover pages of works by Francesco Masi: (**a**) new perspectives on theoretical and experimental researches on friction in 1897b; (**b**) experiences on friction in 1897c

(Masi 1897b, c) are No.15 and 16 in the list (Masi 1927), Fig. 12, can be remembered mainly as reports of investigations.

His treatise (Masi 1897b), Fig. 12a, is a clear discussion of the state-of-arts in the field of friction evaluation that is oriented to machinery applications referring to lubrication properties. The most important theories of the time (by Petroff, Hirn, Thurstin, Kirchweger, Poiseuille) are also overviewed by referring to Italian experiences in order to propose further developments that Masi applied to practical cases for evaluation and choice of lubricant oils. An example of those results is shown in Fig. 13 also indicating the details and modernity of Masis' studies.

The experimental approach of the investigation led Masi to conceive a suitable new procedure and equipment, like the test-bed in Fig. 14 that he used to develop further knowledge of the topic of friction and lubrication, and to obtain useful results for practical engineering with determination of friction and lubrication properties as a function of environment and operation variables. Both works (Masi 1897b, c) were used even as practical handbooks on industrial engineering.

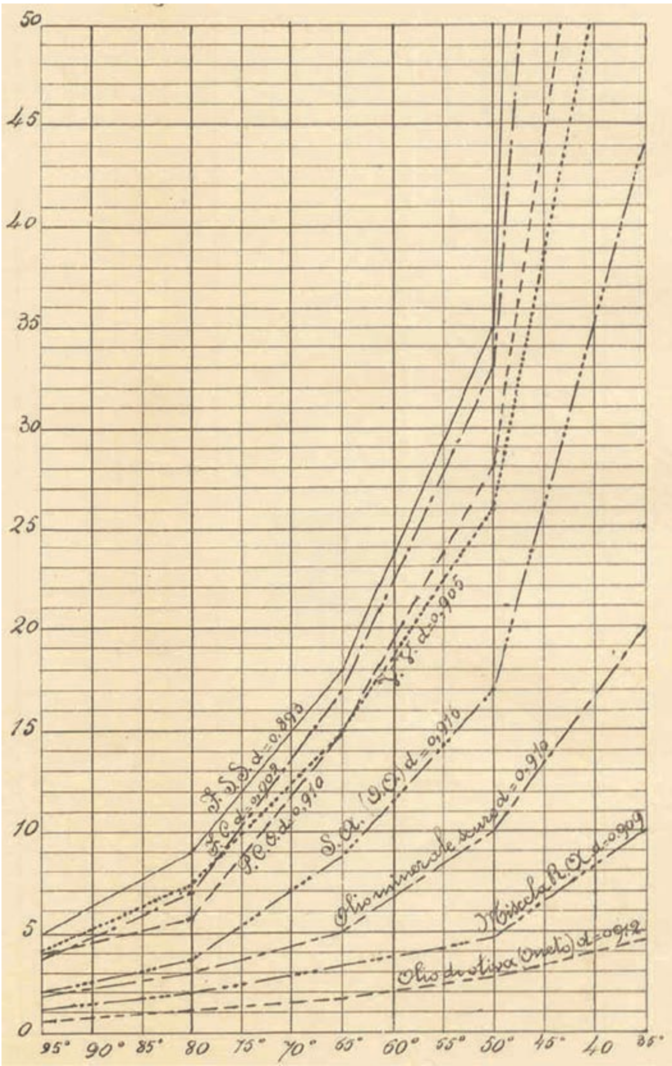

Fig. 13 Experimental results for viscosity characteristics of several lubricant oils in Masi (1897b)

However, the most successful works by Masi, also in terms of circulation, can be considered to be the books Masi (1883, 1897a) on TMM and Mechanism Design. They were used for long periods and even when they were successed by new textbooks, they were always considered as a sources of inspiration both for technical contents and conceptual explanations of mechanisms and their kinematic proprieties.

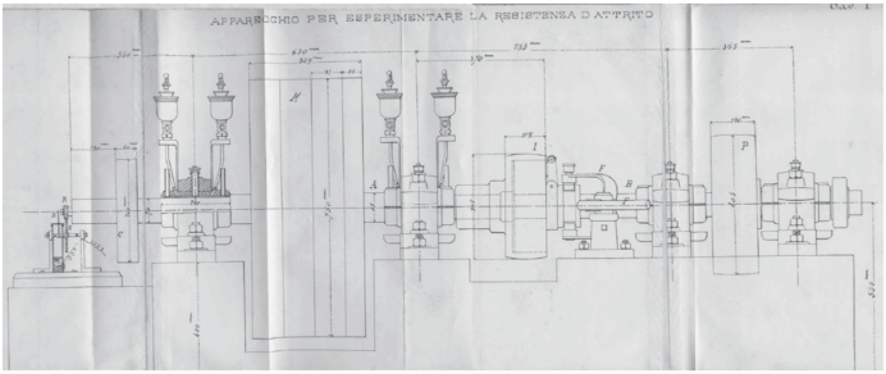

Fig. 14 Mechanical design of a new machine for friction experiments as reported in Masi (1897c)

The significance of the scientific figure of Francesco Masi is nowadays well recognized in the Italian Community for TMM but still his contributions are not know abroad, mainly because of language constraints.

The memory of Francesco Masi in Bologna is still present, even at level of current University professors. Emblematic is the story of Masi's house that he left to the School of Engineering in Bologna after his death, since he had no children to leave his proprieties to. The house, located near the School of Engineering with a nice garden, was not used for a long time and therefore it was sold in the 1950s. Today, there is great interest in having it back within the University's fold, also to recognize the personality of Francesco Masi.

Conclusions

The personality of Francesco Masi has been illustrated by emphasizing his relevant contributions in TMM that were and still are influent in the Italian Academy. Masi always developed his research activity with a vision to teaching activity and by looking at practical engineering applications, even when he encountered problems with very theoretical formulations. His work has been an inspiration for many generations in Italy and is still considered as an interesting source. Unfortunately, Masi's work is not known abroad and this paper is an attempt to refresh the memory and to point out modernity of his publications in TMM.

Acknowledgements The author wishes to thank the library of the Department of Mechanics and Aeronautics of "La Sapienza" University of Rome (Italy), the library of the Department of Mathematics of Politecnico di Milano (Italy), the library of Politecnico di Torino (Italy), the University library of Bologna (Italy), the University library of Padua (Italy), the University library of Pisa (Italy), the University library "Boaga" of Roma (Italy), the University library of Torino (Italy), the Apostolic Library in Vatican, and Library of Montecassino Abbey for help in the search for original material.

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Adam Morecki (1929–2001)

Teresa Zielinska and Krzysztof Kedzior

Abstract Adam Morecki contributed significantly to the advancements in several fields of mechanical science. He worked on the classification of mechanisms, developed the model of skeletal muscles co-operation, stimulated great progress in modeling and design of elastic manipulators and walking machines. The paper presents Morecki's life, the history of his fundamental works, and the facts proving his contribution towards the development of mechanics.

Biographical Notes

Professor Adam Morecki was born on 5 September 1929 in Kraków (Cracow), Poland. His youth was associated with the terrifying period of World War II. The experience of that time affected the whole of his life. He lived very intensely, exploiting every minute, as if he was living not only for himself but also for those who were not so lucky and did not manage to survive (Fig. 1).

He obtained an M.Sc. degree in 1951 from the Faculty of Electronics at the Academy of Mining and Metallurgy (now: AGH University of Science and Technology) in Cracow. In 1949, he started to work as an assistant in the Chair of Mechanics and Strength of Materials at the Academy. In 1952, he was selected from many candidates for studying at the Institute of Mining in Moscow, where in 1955 he received his Ph.D. degree for the dissertation on "*Investigation into safe braking process and rational selection of the brake type*".

After returning to Poland, he was appointed by the Polish Ministry of Higher Education to work at Warsaw University of Technology (WUT). Together with Professor Jan Oderfeld, he was assigned the important task of founding the chair of the theory of machines and mechanisms.

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M. Ceccarelli (ed.), *Distinguished Figures in Mechanism and Machine Science: Their Contributions and Legacies, Part 2*, History of Mechanism and Machine Science 7,
DOI 10.1007/978-90-481-2346-9_9,

Fig. 1 Portrait of Adam Morecki

He was motivated all his life by a sense of that task, and his academic career developed as follows:

1955–1958	— Assistant professor
1958–1968	— Associate professor
1968–1974	— Professor and
1974–2001	— Full professor at the Faculty of Power and Aeronautical Engineering, WUT

In September 1969, Adam Morecki organized the second World Congress on the Theory of Machines and Mechanisms. During that event, held in Zakopane, Poland, the International Federation for the Theory of Machines and Mechanisms (IFToMM) was founded. Professor Morecki, together with other members of the founding committee, signed the IFToMM foundation act.

He served as the head of the Dynamic Measurements Chair (1961–1970), head of the of Theory of Machines and Mechanisms Chair (1978–1984), vice-dean of the faculty (1961–1964), head of the Research Team of Robotics and Biomechanical Engineering (1964–2000). Being a very active person, he also worked as a part-time professor at the Institute of Fundamental Research Problems of the Polish Academy of Sciences in Warsaw (1955–1965) and at the Institute of Mechanics and Vibroacoustics at the Academy of Mining and Metallurgy in Cracow (1986–1997).

For many years, he was a general secretary of the IFToMM. Then, he was the chairman of IFToMM Robotics Technical Committee between 1982 and

1989. In the years 1992–1995, Professor Morecki held the position of IFToMM president. He was a member of the Executive Council of the International Federation of Robotics (1989–1991, 1996–1997) and a member of the Executive Council of the International Centre for Mechanical Sciences (CISM) from 1986.

He remained extremely active, also running domestic affairs; for example, he was the president of the Polish Society of Biomechanics (1988–1992), vice-president of the Committee for Automatic Control and Robotics of the Polish Academy of Sciences, a member of the executive board of the Committee for Machine Building (PAS), president of the Polish Committee of TMM affiliated to the Committee for Machine Building PAS, a member of the Committee for Biocybernetics at the Institute of Biocybernetics and Biomedical Engineering PAS, a member of the Academy of Engineering in Poland and a member of the Warsaw Scientific Society.

In the years 1991–1995, serving as the general secretary of IFToMM, he organized over 70 congresses and meetings of technical committees and other boards in Europe, the USA and Canada. When he was a co-chairman of the Program Committee of CISM-IFToMM, he organized 12 symposia on Robots and Manipulator Systems (the symposia were referred to as "RoManSy") in the years 1976–1998. With this initiative, Morecki contributed significantly to the promotion of biomechanics. The first RoManSy meetings were marked by verification of some novel results obtained in the study of walking robots. Active orthoses to replace the human amputated limbs were also the subject of research and investigations. During those times, it was a very novel and revoluntary research area. In 1994, he said that "RoManSy 10 opens the 3rd period of activity. Of course it is not easy to predict the future, but in my opinion the theory and practice of robots and manipulators will continue to be of great importance for future development of science and technology". He edited or co-edited the symposia proceedings issued in the years 1973–2000 (Fig. 2). From the formal point of view, those events have demonstrated a long-lasting partnership between the two international institutions; that is CISM and IFToMM. Moreover, he contributed towards the organization of six schools of biomechanics at the International Centre for Biocybernetics of the Polish Academy of Sciences.

His remarkable achievements in science, education and organization were awarded by the Academy of Mining and Metallurgy in Cracow with an Honorary Doctorate. He was also received many awards from various Polish and international organizations; for example, he received the prestigious Engelberger Award for Education in Robotics in Singapore (1995).

Morecki was one of the architects of the Polish School of Theory of Machines and Mechanisms and the founder of the Polish Research School in Biomechanics and Robotics. He supervised 24 doctoral students.

He pursued intense scientific and organizational activities until the last moments of his life. He died on 20 May 2001.

Fig. 2 Volumes of the proceedings of robots and manipulator systems symposia

Course of the Research and Fundamental Monographs

In 1962, together with his colleague Kazimierz Fidelus, Morecki created the research team and launched the investigations into measurements in mechanics, biomechanics and bio-cybernetics, taking into account both the theory and practice. The group was involved in theoretical research as well as in the development of the devices helping them in experiments (Fig. 3).

The first studies were focused on the application of electromyography (EMG) to control a human arm-like manipulator with seven degrees of freedom driven by artificial pneumatic muscles. The first papers on the subject were published as early as in 1964. Also in 1964, the regular “Friday Seminars” were launched. Those meetings soon became well known and attracted many scientists and students from other centers.

In 1971, a monograph presenting the mechanical principles of the biological system’s locomotion was published (Morecki et al. 1971). The scope of the monograph covered a variety of biomechanical problems, such as structure of bio-mechanisms, analysis of bio-kinematical chain driven by muscles, problem of muscle force distribution, models of human extremity control, synthesis of bio-manipulators and

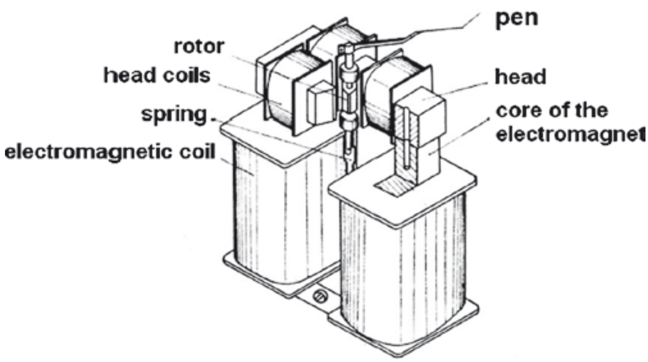

Fig. 3 Scheme of the electromagnetic registrator

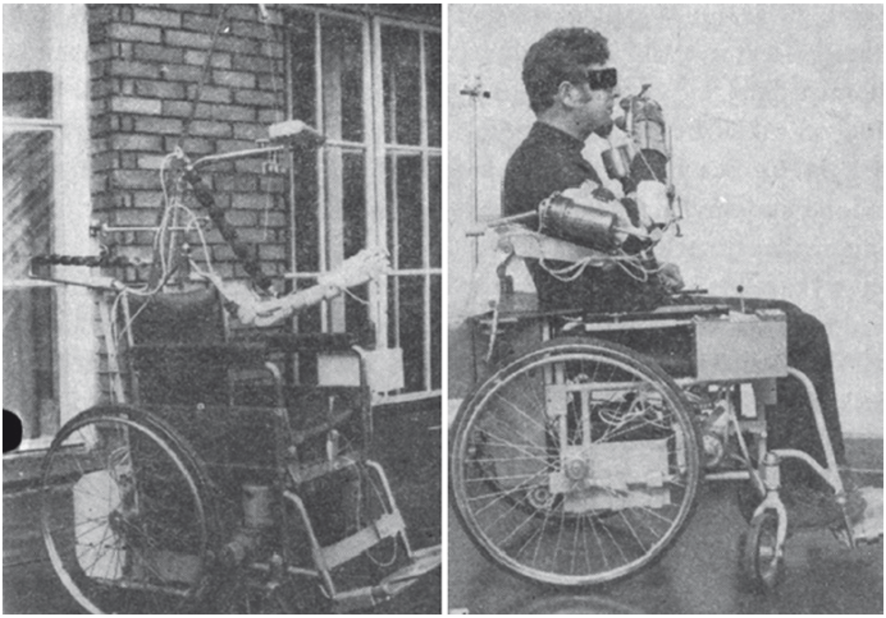

Fig. 4 Orthoses mounted on a wheelchair – 1974

bio-prostheses. The authors presented the state of the art, the results they obtained and guidelines for future research. This fundamental book attracted great interest and encouraged researchers to undertake the study in biomechanics using the interdisciplinary approach.

In the following years, the research conducted by the team tended towards applications. The implanted stimulators of human limb muscles, two types of EMG controlled orthoses (Fig. 4) and EMG controlled prosthesis with pneumatic drives were developed and clinically tested.

This experimental work resulted in the second monograph by the same authors on cybernetic models of animal and robot motion systems (Morecki et al. 1979). The book, first published in Polish, was very soon translated into English.

Since the late 1970s, Prof. Morecki focused his attention on robotics. However, the research he conducted always revealed some sort of "biomechanical flavour".

The spine-type and elephant trunk-type manipulators were designed and built by the research team he supervised. The results created a basis for the monograph published in Polish (Morecki and Knapczyk 1993) and in English (Morecki and Knapczyk 1999).

Contribution Towards the Development of Mechanics

The scientific activity of Adam Morecki covered a wide range of issues concerning applied mechanics and biomechanics. He contributed to the study of mechanism kinematics and dynamics, theory of gears, application of electrical methods to measurements of mechanical parameters, bionics of motion, biomechanical engineering and rehabilitation. He initiated the research and formulated basic concepts of the theory of anthropomorphic robots and manipulators. In view of the research subject his scientific activity can be divided into four periods.

The first period, leading to his Ph.D. degree, was devoted to classical mechanisms and the research into the methods for their improvement.

The second period started when he took the job at Warsaw University of Technology and devoted his attention to the measurements of mechanical quantities in view of both the theory and practice. For the first time in Poland, he used strain gauges in solving both the industrial and research problems. He also initiated the production of tensometric amplifiers and mercury commutators. Among his other significant achievements, one should mention here the fact that he inspired the design and supervised the team working on the construction and implementation of a special machine for dynamometer calibration. The main designer of those machines was W.Narkiewicz. The design was patented. The machines were used in Poland and Germany. They are still in use in Poland (Fig. 5). The bigger machine allows the calibration of dynamometers within the range from 0 to 60,000 N under automatic control with an accuracy of 0.01%. The smaller machine has the range up to 5,000 N. The automatic control system ensures a fast and stable change of the loading mass. For example, the change by 100 kg takes only 2 s. Over 40 years experience of the machine exploitation has proved their good quality and reliability. The first prototype was ready in 1961 and during the next 10 years, the design was gradually improved. As compared to other similar devices, the machines offer much faster and more stable changes of the load and higher accuracy. The Polish machine works in the Central Office of Measures and is used as a calibration tool for the force templates in all Polish laboratories.

The third period of Professor Morecki's scientific life began around 1962 with his fascination for biomechanics and bio-cybernetics (Fig. 6). It brought about his most significant achievements, including the pneumatics muscles (Fig. 7) and the

Fig. 5 Machines used for calibration of force patterns, on the left – a machine with the range 0–60,000 N, on the right – a machine with the range 0–5,000 N, the picture was taken in 2008

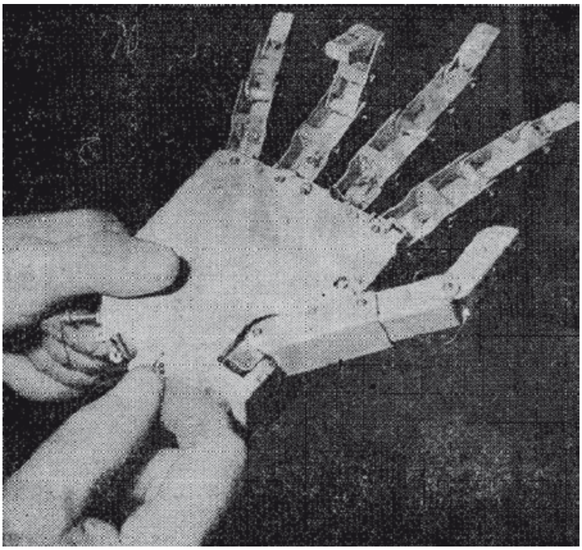

Fig. 6 Artificial hand – 1970

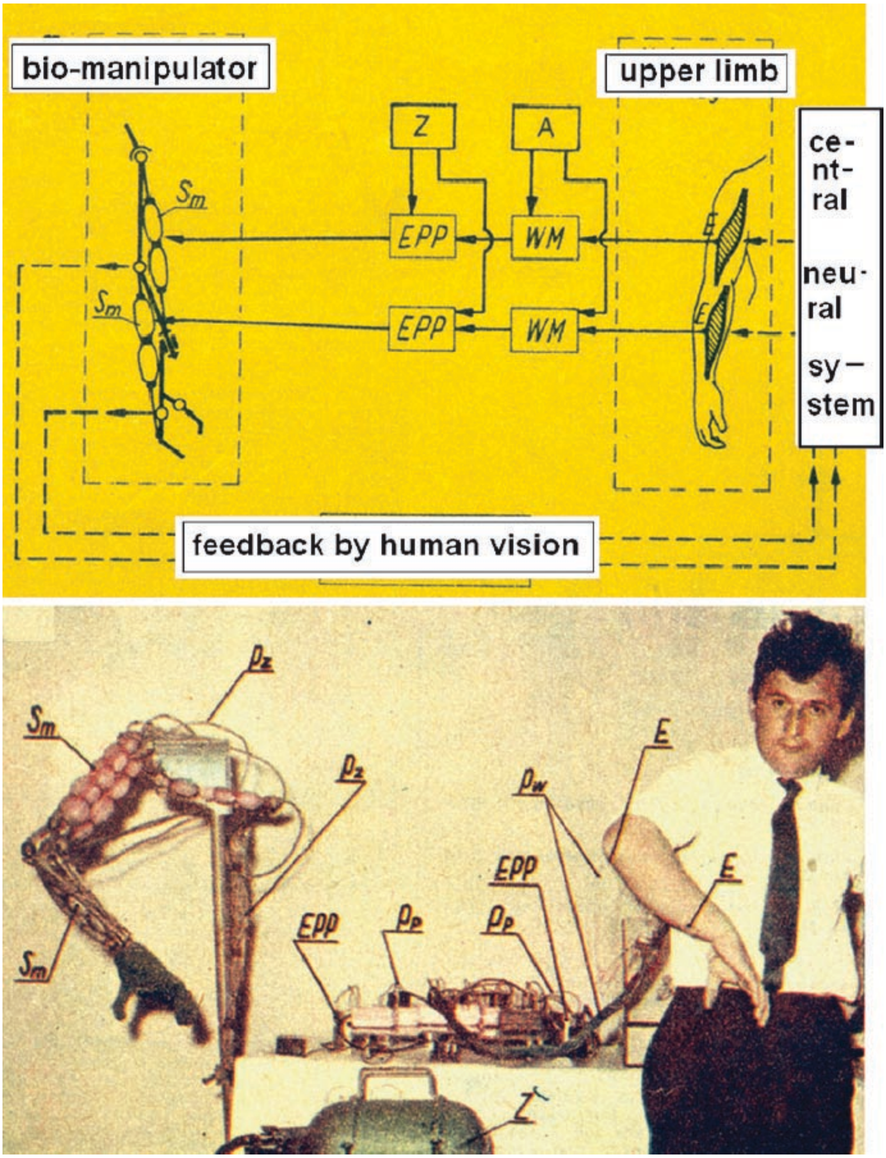

Fig. 7 The concept of pneumatic prothesis control introduced by Morecki, in which EMG signals were employed, and the experimental rig

prosthesis activated by EMG signals (Fig. 8). Roughly speaking, the period lasted until his death. It should be noted that during those years, Professor Morecki not only launched the pioneering research aimed at solving new problems but also stimulated the improvement of the devices already available and necessary for

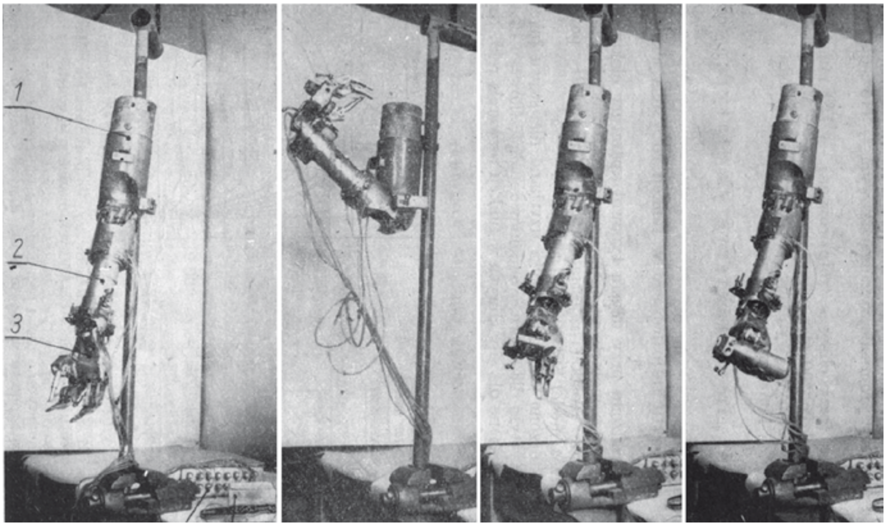

Fig. 8 Orthoses controlled by EMG signals with pneaumatic actuators – 1975

experimental purposes. One can mention here the eight-channel recorded for registering the electric signals monitored by sensors. The measurements were recorded on a paper tape as functions of time, the monitored signal range was 0–4 V with frequency up to 100 Hz, the measurement accuracy was 5%. The recorder was used by the research team supervised by Professor Morecki in the investigations into electro-stimulation.

Professor Morecki co-operated with the Academy of Physical Education (now the Józef Piłsudski University of Physical Education) in Warsaw. Within the framework of this collaboration, a variety of devices for monitoring the efforts of sportsmen were created by the team supervised by him; for example, dynamometric platforms measuring the ground reaction forces during walking, strain gauge insoles and devices measuring the linear and angular moments of a ball.

During the fourth part of his scientific activity, he concentrated his research on nature-inspired robots; that is, elastic manipulators and walking machines (Morecki et al. 2002). Many ideas of Adam Morecki were embodied in working prototypes. For example, it is worthwhile to mention here the elastic manipulator, the design properties of which were inspired by the elephant trunk, and the other one which referred to the structure of the spinal cord (Fig. 9). To develop a manipulator of the elephant trunk type, the animal trunk was studied beforehand together with its muscles. The ranges and positions during a particular manipulation were recorded and analyzed. The real muscle structure of the elephant trunk was studied to design manipulator driving systems.

Professor Morecki had a great gift for creative transformation of biological patterns into advanced mechanical devices. Before starting the design, an in-depth

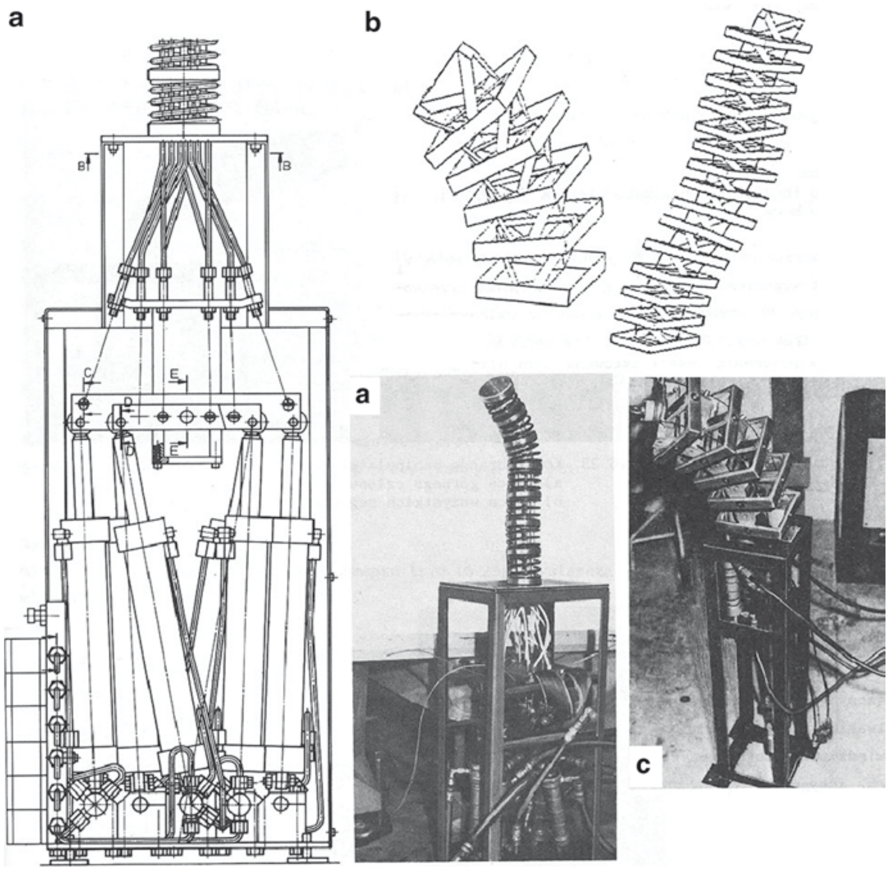

Fig. 9 Elastic manipulators, their structures and prototypes (**a**) elephant trunk type, (**b**) spinal cord type

study and brainstorming were conducted, having in mind the performances of biological systems (Fig. 10). That profited in the development of several unique prototypes.

Throughout the whole of his scientific activity, he was convinced that scientists dealing with mechanics should look for inspiration in nature (Morecki et al. 1988). That idea, among many other achievements, brought about the design of a four-legged walking machine similar to animal quadrupeds, produced by the research team in the years 1973–1976. The leg structures of a four-legged walking machine were similar to those of horse legs. A. Morecki showed that carefully investigated and suitably generalized properties of different types of motion observed in nature, can be successfully applied to motion synthesis of some mechanical systems; such as, anthropomorphic manipulators and walking machines (Morecki and Zielinska 1992, 1993).

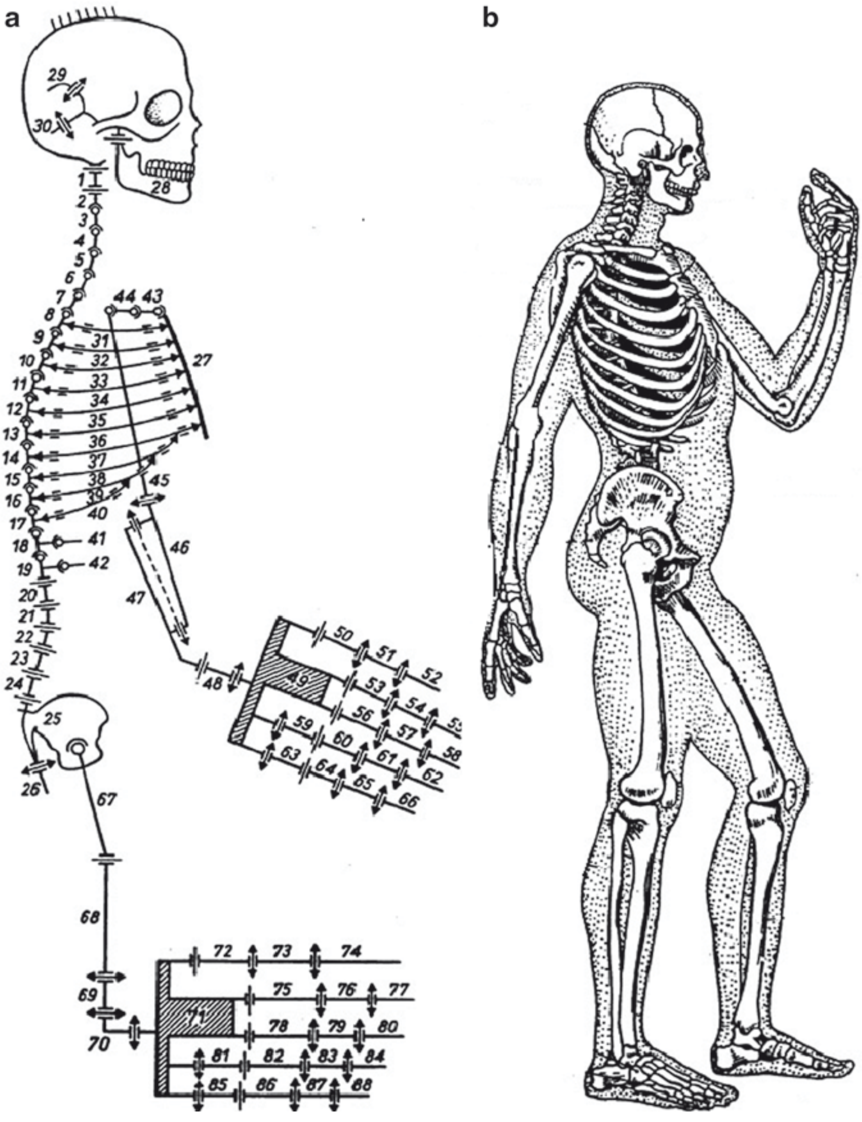

Fig. 10 Human body: (**a**) kinemarical structure proposed by Morecki, (**b**) view of the skeleton

Below is a list of the successfully accomplished tasks that Professor Morecki considered to be his most important scientific achievements:

– Devising a new method for mechanism classification
– Development of a model representing force distributions in skeletal muscles

- Putting forward a concept of stimulator activation schemes for human extremity control
- Putting forward some modeling and design methods for elastic manipulators
- Investigations into human and walking machine locomotion properties that brought about general models of locomotory behavior

The results he obtained were published in 324 papers and 38 monographs. He obtained 17 patents for his designs.

Summary

Adam Morecki was a great scientist in view of both the commitment and novel problem-solving approaches he fostered. He had great intuition besides his deep knowledge which resulted in finding solutions to important scientific problems. He stimulated scientific development in his students and other researchers concentrating their attention on issues crucial for progress in the field. Both of the authors are his followers and highly appreciate his support and humanistic attitude towards the people he co-operated with.

Acknowledgements The authors express their thanks to Dr. Cezary Rzymkowski for his help in collecting the material necessary for the preparation of this manuscript.

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Feodor Orlov 1843–1892

Alexander Golovin, Valentin Tarabarin, and Zinaida Tarabarina

Abstract Professor Feodor Orlov was one of the founders of the Moscow School of Applied Mechanics. His activities from the year 1872 until his death in 1892 were connected with the two biggest academies: the Moscow University and the Imperial Moscow Technical School (IMTS). He had graduated at the Moscow University and then worked there as an invited professor at the chair of applied mechanics. The chair of Applied Mechanics of IMTS (now TMM) has existed as an independent educational department since 1872, in other words, since the time when Orlov began to teach his course. In 1868, the Imperial Moscow Technical Secondary School (IMTS) was by law confirmed as the Supreme Educational School. It had the following divisions: Mechanical, Chemical and Mechanical-Building. The academy status required an important rise in the scientific level of all courses. Orlov's main course was that of applied mechanics, which he, according to the Great Russian mathematician and mechanician Professor N. Zhukovsky, was the best in Russia. Moreover, Orlov prepared and read courses about thermodynamics, hydraulics, steam engines and the resistance of materials. The creating of the mechanic collection in the Moscow University and the IMTS was Orlov's greatest service. In the IMTS (today it is called the Bauman Moscow State Technical University), the main part of this collection, gathered by Orlov, is housed. Orlov dreamt about going in for abstract mathematics. But his financial position made him spend most of his time working with applied disciplines. However, he had written a number of unique mathematical articles. He was one of the founders of the Polytechnic Society and its vice-president.

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Biographical Notes

Feodor Orlov (Fig. 1) was born in 1843 in a village, Velikoe, of the Novgorod province (Yershov 1854; Orlov 1885/86; Zernov 1895/96; Zhoukovsky 1898/99, 1921; Scientific School of Bauman Moscow State Technical University 1995; Volcnkevich 2000). He was the son of the medical officer who graduated at Moscow University. After his father's death in 1851, he left for Moscow. Because of his difficult financial position, Feodor Orlov had been admitted to the Yaroslavl gymnasium at public expense. In Yaroslavl, he lived under the guardianship of his uncle, who was a professor of Yaroslavl's seminary. The deep religious upbringing of Orlov can be explained by the moral influence of his uncle. Orlov graduated from the gymnasium with a gold medal in 1859 and then entered Moscow University, where he graduated in 1863. Because of the poor financial status of his family Orlov, had to give private lessons. In the University, he was one of the elite students who came to the professor of the mechanics. Brashman took their meetings very seriously and he organized them every weekend. After graduating at the University, Orlov did not leave it and continued working at the Chair of Abstract Mathematics to get ready for receiving his master's decree. In 1867, he published his first scientific work "The proof of Euler's theory". In 1869, he supported his dissertation, which was called "About reciprocity of differential equations", for the degree of master. After the death of Professor A. Yershov, the chair of Applied Mathematics in the Moscow University became free. The Council of the University decided that this place must be occupied by a person who had a very good grounding in mathematics, which would guarantee good knowledge of Mechanics, and recommended Orlov for this position. At the same time, the Council interceded with the Ministry for Orlov to be sent abroad in preparation for his future job. Orlov agreed to move abroad not without doubts because he had his own scientific plans in the field of Mathematic. Though he understood that this offer

Fig. 1 Feodor Orlov (1843–1892)

could help him get a well-paid job and become the provider for his family. In September 1869, he left for St. Petersburg where he met two great Russian scientists: P. Chebyshev and J. Vyshnegradsky. They gave Orlov some practical advice about living abroad and handed him letters of recommendation to European scientists. Chebyshev told Orlov about a new leading mechanism which let Chebyshev create a unique construction of a steam engine. During the period between 1869 and 1870, Orlov attended the Abstract and Applied Mathematics lectures in Zurich in Switzerland. He also translated Chebyshev's article about parallelograms for the "Civilingeneur" magazine. In 1870, he was elected to be the head of the Practical Mechanics and Thermodynamics' chair in IMTS. In the summer of that year he also attended the lectures of professors F. Reuleaux and Christoffel at the Gewerbe-Academie and Weierstrass and Kronecker in the Berlin University. Orlov was mostly influenced by the director of Gewerbe-Academie F. Reuleaux. Orlov listened to the course of kinematics, read by F. Reuleaux with great interest. Many of Reuleaux's ideas, which were not very popular in Russia those days, Orlov used in his educational activities later. He wrote: "Reuleaux gives very good experience of setting forth kinematics with another point of view. The formula with which he shows the structure of mechanism and methods, opened by himself, lead him to the most unexpected results". The demonstrations of machine and mechanism models, by Reuleaux had, made an impression on Orlov. It is necessary to say that of the problems delivered by the rector of IMTS, V. Della-Vos, to Orlov was to study the possibility of getting new models for the chair of Mathematics, established by Professor A. Yershov. Then Orlov attended the mathematics lectures of Professor Katalan at Liege University until the end of 1871. Katalan met the young Russian scientist and became interested in his dissertation for the degree of master and then asked Orlov to translate it into French. This translation was presented to the Belgian scientific academy. Katalan offered Orlov the chance to take part in the competition for the Belgium Academy Prize the works in the field of the theory of surfaces. But Orlov refused to do that as he thought that it would be a denial of his main duties. In his diary he wrote: "I am beginning to suffer from remorse because for the last days I have left applied mathematics and become enthusiastic about my past love – abstract mathematics." Later, Orlov removed to France. He lived in Paris until the autumn of 1872, where he attended the lectures in the Ecole Centrale, Ecole Polytechnique, Sorbonne and the College de France. In the autumn of 1872, he returned to Russia and from that year until his death in 1892, Orlov followed practical mechanics courses at the Moscow University and the IMTS. His inaugural speech, which was read in the Moscow University and the IMTS, was the lecture "About machines". There the development of Reuleaux's ideas about kinematics and kinematic pair was stated for the first time. The professors of the IMTS lived in flats, which were allocated to them by the university administration, not far from the University. Orlov settled in one of them with his family, which consisted of his mother and sister. At the same house, where Orlov's flat was, lived Professor Zhukovsky, who became a friend of Orlov. On the basis of his university preparation and the materials which had been collected abroad, Orlov gave several lecture courses. Firstly, we should discuss his main course – "Applied Mechanics". Moreover, he prepared and read thermodynamics, hydraulics, steam engines and resistance of materials lectures. All the courses reflected not only the modern state of science at that time, but were also methodically worked on. The teaching of the applied mechanics at the Moscow University and the IMTS was raised by Orlov to a high level like at no other University in Russia. Professor Zhukovsky stated that those were the best courses in Russia.

Orlov was curator of the applied mechanics room at the Moscow University and the IMTS. The main part of his collection was acquired from Hustav Voight, who had been given the right to make and sell some of the models from the Reuleaux collection in the 1980s. Besides, Voight's models, models of Alexander Clear from Paris, Joseph Shröder and many others were bought.

The models were bought only after thorough selection as the financing had been very limited. Since Orlov's death, many people noticed that the room of mechanisms was set in an ideal situation. Besides that room, Orlov had organized very good sketching and projection classes. He spent much time working individually with his students. He helped them choose a theme for writing their candidate's work, and lent books from his own library. About half of all candidate's works in the Moscow University were written on applied Mechanics.

In 1874, the Scientific Council of the IMTS despatched Orlov, with scientific aims, to Moscow, Nizhegorodsk and Vladimir province. He examined the manufacturing and factory industries there. In 1876, he was assigned to the Philadelphia exhibition to study the state of techniques in the USA. In 1878 he was sent to the World exhibition in Paris. From all these places, Orlov brought a vast amount of stuff which, unfortunately, was not elaborated upon and printed.

In 1875, a group of students made an offer to the rector of the IMTS, V.K. Della-Vos, to organize a society, which would have such a purpose as "intellectual and moral unity and pecuniary mutual aid to the graduated students". The necessity of such a society appeared because most of the graduated students, especially in the first years after graduating at the IMTS, could find a job with merited payment. The offer was supported by the honorary trustee, prince Sergei Alexandrovich Obolonsky. On 14 May 1877, the Emperor enjoined (1) to organize the Polytechnic Society in the IMTS (2) to give 3,000 rubles to the main fund of the Society from the reserve capital of the IMTS.

The first meeting of the Polytechnic Society took place on 4 January 1878. Orlov actively participated, not only in the organization, but also in the work of most of the departments of the Society. He was one of the authors of the charter and in 1886 was elected to be the vice-president. The society consisted of four departments: the Engineer-Mechanical, Engineer-Technological, Editorial and Inquiry. The Editorial department was headed by Orlov and was occupied with edition the works of the Society and scientific-technical magazines such as "Transactions of the Polytechnic Society" (1879), "Proceedings of the Polytechnic Society" (1882), "Bulletin of the Polytechnic Society" (1888), etc. The Inquiry department was occupied with looking at work for different Russian factories and manufactures for the Mechanic Engineers and processing engineers who had graduated at the IMTS. Facts were listed about the quantity of places and quantity of students who had found a work in the reports of the Society. Some graduates were helped materially.

At the suggestion of Orlov in 1887, a new department of the Society was set up – the Department of Technical Education.

Orlov had more than once addressed meetings of the Society. His lectures were accompanied by demonstrations of new models from the mechanics room of the IMTS. Thus on 18 November 1879, Orlov gave a lecture about the leading mechanism of Hart a lecture about the double detector of Sheffer and Budenberg on 15 January 1881. On 21 November 1891, Orlov delivered his last lecture “About the astatic regulators”. On 20 January 1892, Orlov died in the hands of his sister. He is buried in the Alekseevsky cloister next to his mother. In January 1892 after Orlov’s death, members of the Polytechnic Society collected funds and established grant in Orlov’s name for students.

List of Main Works

1. Orlov F.E. The proof of Euler’s theory. Mathematic manual, Volume 2, University Printing Office (Katkov & Co), Moscow, 1867 (in Russian)
2. Orlov F.E. The dissertation about correlation of differential equations. Dissertation was written for receiving the degree of master of abstract mathematics. University Printing Office of A. Mamonov, Bolshaya Dmitrovka, 7, Moscow, 1868 (in Russian)
3. Orlov F.E. Lecture about machines. Inaugural lecture, read at the Moscow University on the 21st of October, 1872, Moscow, Moscow Mathematical Society that belongs to the Moscow University, 1873, reprint from Mathematical Manual published in 1873, Volume 6, 17 pages (in Russian)
4. Lectures about Applied Mathematics that were read by Prof. F.E. Orlov and assembled by students of the 2nd special class, the Practical Academy of Commercial Science, Moscow, 1873, 462 pages, lithographic edition
5. Orlov F.E. Economical significance of machines. The speech of the Imperial Technical School’s professor Orlov F.E. The report of Imperial Moscow Technical School for the year 1878, the second publication, Moscow, University Printing Office, 1879
6. Orlov F.E. The theory of resistance of materials. Notes made from lectures of Prof. Orlov. The first course of special class. 1880, 340 pages
7. Hydraulic engines. Lectures of Prof. F.E. Orlov, 1881. The first special class of IMTS – Moscow; ITMS – 286 pages, illustrations, lithographic edition
8. The theory of steam engines. Lectures of Prof. F.E. Orlov. From the books of Prof. A.P. Gavrilenko. 1881/82, Moscow; IMTS – 246 pages, illustrations (lithographic edition)
9. The theory of steam engines. Lectures of Prof. F.E Orlov, 1882/83, Moscow, IMTS, 286 pages, illustrations, lithographic edition
10. Hydraulics. Lectures of Prof. F.E Orlov. 1882, Moscow, IMTS, 238 pages, illustrations, lithographic edition

11. Orlov F.E. The theory of roulette. Odessa, Printing Office of P.A Zelenskii. Extract from the Notes of mathematical department of Novorossiysk Society of Natural Sciences, 1884, vol. 5
12. Orlov F.E. About the quadrature of roulette. Lecture was read on the 15th of November, 1883, Moscow, Moscow Mathematical Society which belongs to the Moscow university, extract from the Mathematical Manual, 1884, vol. 11, 60 pages
13. Orlov F.E. Applied Mechanics, Moscow, the Printing Office of Zubarev, 1885, 453 pages, lithographic edition
14. Lectures about the theories of steam-engines which were read by Professor F.E. Orlov in 1886/87 academic year and then written down by the student of the third year in the Moscow University A. Sidorov, Moscow, MU, 249 pages, illustrations, lithographic edition
15. General theory of machines. Lectures of Prof. F.E. Orlov, the fourth term, Moscow, of Blagushin, 1887, 148 pages, lithographic edition
16. Steam-engines. Lectures of Prof. F.E. Orlov, the second and third courses of St. Petersburg IMTS,1890, Moscow, IMTS, 276 pages, illustrations, lithographic edition
17. Applied mechanics. The lectures of Prof. F.E. Orlov, 1891/92, Moscow, parts 2 and 3, Moscow, the Printing Office of Bogomolov, 1892, printed with a duplicating machine
18. Thermodynamics. The lectures of Prof. F.E. Orlov, 1891/92, Moscow, IMTS, 246 pages, illustrations, lithographic edition
19. Steam-engines. The lectures of Prof. F.E Orlov, a course of the second special class of engineer-mechanical section, Moscow, IMTS, 1892, 357 pages, printed with a duplication machine
20. Theory of machines. Lectures which were read by Prof. F.E. Orlov in IMTS in 1892, edited in 1893 and allowed by Prof. D.S. Zernovoi, lithographic edition
21. Orlov F.E. Diary of the foreign trip 1869–1872, Moscow, Printing Office of G. Lissner and A. Geshel, 1898, 346 pages

Review of Main Works on Mechanism Design

The main directions of Prof. F. E. Orlov's activity were:

- Establishing the applied mechanics course involving theory of mechanism and machines.
- Creating offices of mechanisms to practically support the applied mechanics course.
- Establishing courses "Theory of Resistance of Materials and Theory of Elasticity", "Theory of Steam Engines", "Steam Engines", "Hydraulics".
- Enthusiasm for problems of abstract mathematics.
- Social and educational activity. Orlov's educational work can be clearly represented by his opinion of establishing the applied mechanics course. Other ones can be described briefly. Five intravital lithographic courses of applied mechanics (1887/88, 1889, 1890/91, 1891, 1892), and one posthumous course of the theory

of machines (1893), are stored in the IMTS library. Orlov gave the applied mechanics course in Moscow University (MU) and Imperial Moscow Technical School (IMTS). The former course was obviously more theoretical while the latter was practical. The persevering educational policy of Orlov was to combine analysis of theoretical problems with a demonstration of their practical solution. Orlov improved his course during the 20 years of his educational activity. One of his last courses is presented below.

Applied Mechanics

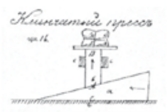
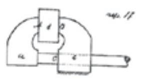
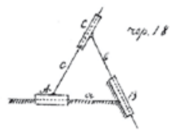
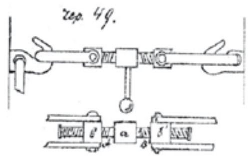
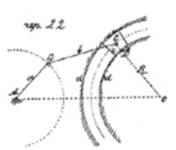
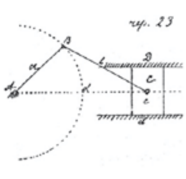
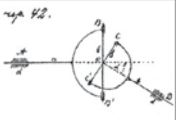
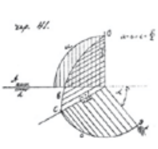
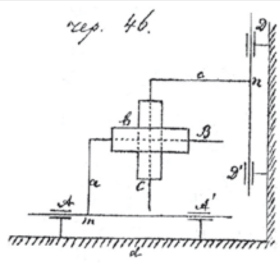
Part 1 – Theory of Mechanisms (224 pages, 232 illustrations); Part 1 consisted of introduction, general theory of mechanisms and analysis of three classes of mechanisms classified according to connection type of their elements. Introduction. Classification of kinematic pairs according to their DOF. Lower and higher pairs. Mechanism is a system with DOF = 1. Like Professor A. Yershov, Orlov used a two-level classification. The first level was classification based on the type of connection of mechanisms elements. The second level was Willis's classification based on a type of moving transformation. Professor Orlov changed the sequence of relation of materials and theoretical level, as opposed to professor A. Yershov (Fig. 2).

Fig. 2 Foedor Orlov's "Applied Mechanics" (part 1)

General theory of mechanisms. Mechanisms with lower kinematic pairs. Mechanisms with prismatic kinematic pairs. Wedge press, grip. Mechanisms with revolute pairs. Four-bar linkage, parallelogram, antiparallelogram. Crank-slider mechanism. Ellipsograph, Oldhem's clutch, sinus-mechanism, etc., Hooke's joint and his analogues, control mechanism for railway semaphore. Mechanisms with screw pairs. Mechanism with three screw pairs. Practical application. Transformation of crank-slider mechanism. Examples of the mechanisms listed here can be seen in Table 1. A further three classes of mechanism classified according to the connection type of mechanisms elements (Willis's classification) are considered.

Class 1. Moving transmission by direct contact. Willis's momentary gear ratio theorem. Teeth-wheels (constant and variable gear ratio with constant indicium). The methods for profile tracing (Poncelet, Camus, Reuleaux). External and internal involute gearing. Cycloidal gearing. Pin gearing. Teeth profiling by two points. Teeth profiling by arcs of a circle (Willis's method). Hooke's wheels. Rotation axes meet, bevel gearing. Skew rotation axes, hyperboloid wheels, screw and worm gearings. Unicycle elliptical wheel. Cam mechanisms (variable gear ratio with variable indicium). Examples of cams with rectilinear and rotary movements. Types of cam mechanisms. Example of practical application.

Table 1 Examples of mechanisms with lower kinematics pairs

Examples of mechanisms with lower kinematics pairs			
1. Mechanisms with prismatic kinematics pairs			3. Mechanisms with screw pairs
 Wedge press	 Grip		 Coupling
2. Mechanisms with revolute pairs			
 		  Hooke's joint	 Control mechanism for railway semaphore

Mechanisms with a constant gear ratio with variable indicium. Examples. Ratchet mechanisms, including clockworks.

Examples of the mechanisms listed here can be seen in Tables 2 and 3. A transmission designed by Orlov and manufactured at the IMTS workrooms is one of them. Unfortunately, it was impossible to find this model. It should be mentioned that Orlov gathered a considerable collection of mechanisms made in Germany and France.

Class 2. Moving transmission by coupler. Mechanisms with parallel axes. Four-bar linkage (instantaneous center of zero-velocity, possible variants of moving transformation, parallelogram, antiparallelogram, Grassgoff's theorem). Crank-slider mechanism, sine-mechanism, ellipsograf. Crank – shaft and eccentric. Hooke's joint.

Class 3. Moving transmission by flexible elements or liquid medium. Belts and ropes.

Part 2. Theory of machines (344 pp., 247 ill.) This part accords to the second stage of "Applied mechanics" course (Golovin and Danilenko 2000), namely, the problems of friction and dynamic theory of machines (Table 4), theory of motors (Tables 5 and 6). Dynamic theory of machines. Machine and mechanism. The foundation of machine dynamics. Kinetic energy and dissipation. Speed control of machine and reason for using fly-wheel: gain in mass of fly-wheel or gain in mass of coupler, for example? About regulation: Watt's inertia governor, parabolic and pseudoparabolic governor, etc. Problems of friction. General problems. Some

Table 2 Examples of moving transmission by direct contact (gearing)

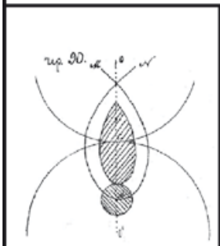
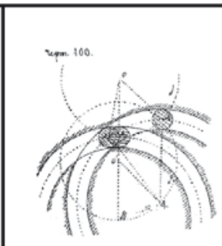
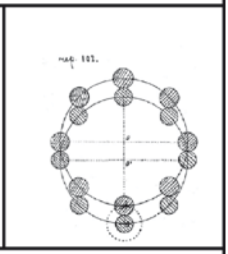
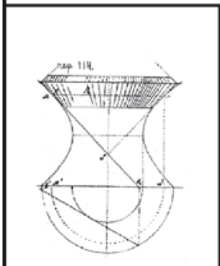
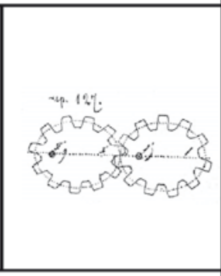
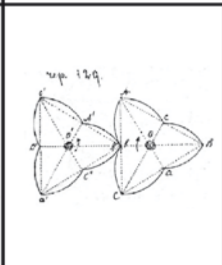
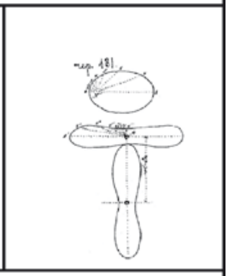
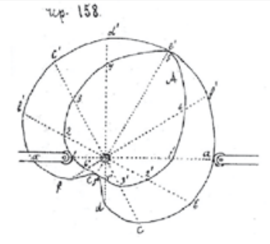
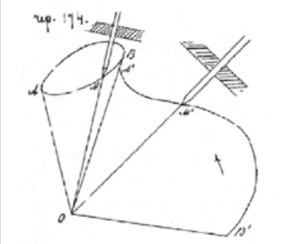
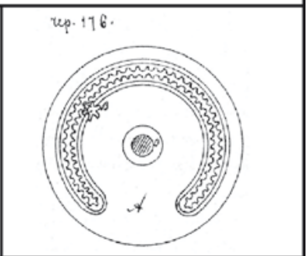
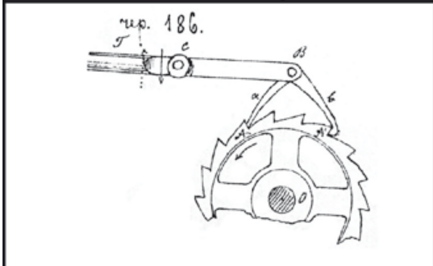
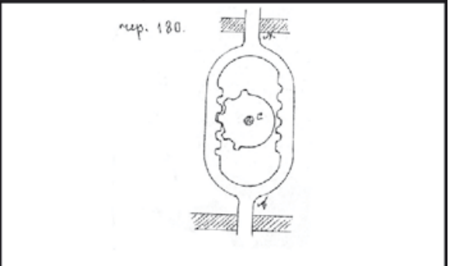
Examples of moving transmission by direct contact (gearing)			
			
Gears of Reaulaux		Orlov's gearing, fabricate in EMTS	
			
Hyperboloid wheels		Different gearings	

Table 3 Examples of moving transmission by direct contact (cams and other mechanisms)

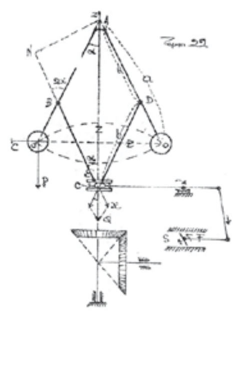
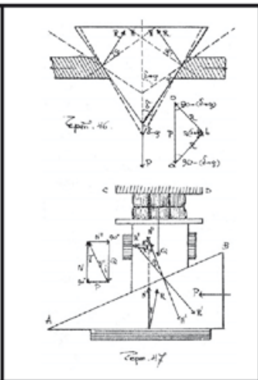
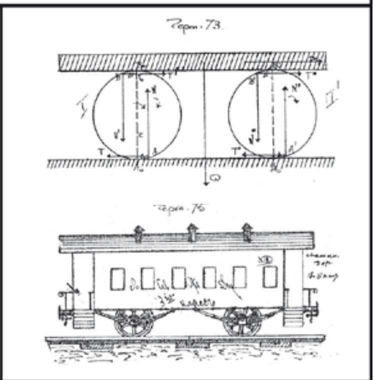
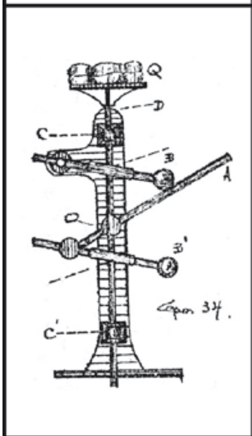
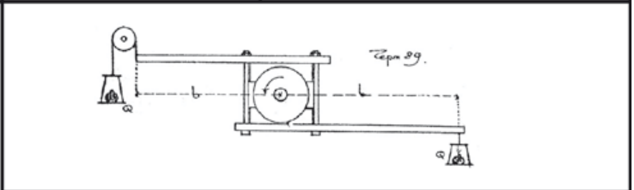
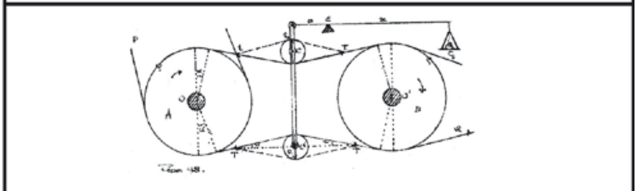
Examples of moving transmission by direct contact (cams and other mechanisms)		
		
Cams of Morin	3-D cams	Ratchet mechanism
		
Other mechanisms		

devices that use the friction effect. Determination of friction coefficient experiment. Prismatic pair: wedge, horizontal and vertical slider. Revolute pair. Screw pair. Teeth-wheels. Transmission of work by friction: friction wheels, friction couple etc. Rolling friction and its application. Friction of flexible bodies. Transmission of work by endless belt. Brakes. Dynamometer of Navier, Imre, Hachette, Watt, etc.

Examples illustrating the problems of friction and dynamic theory of machines can be seen in Table 4. Theory of motors. Living motors. Hydraulics. Hydrostatics. Mains pressure. Equilibrium of body submerged in liquid. Equilibrium of floating body. Determine of mains pressure ponderable liquid. Hydrodynamics. Flowing pressure. Liquid streaming from filler. Liquid moving in pipes. Liquid flow in rivers and canals. Water as motor, dams. Hydraulics machines. Water wheels. Turbines (eight types). Air as motor. Examples considering this part of the course are shown in Table 5.

Thermodynamics. General questions. About fallowes. Caloric machines. Work measuring of steam engine. Steam engines. Papin – Savary steam engines. Installation of Papin's steam engine in Peter the Great's garden in St. Petersburg in 1718. Newcomen and Kawlay. Watt's steam engine. Systems of steam engines and devices. Steam boxes. Furnace, steam boilers. Outfits of boilers (accessories). Manometers, float-gauges, float level gauges, safety valves, feed of boiler. Refrigerators. Examples considered this part of the course are shown in Table 6.

Table 4 Some examples from theory of machines

Some examples from Theory of Machines		
		
Watt's inertia governor	Horizontal and vertical slider	Rolling friction
		
	Prony's wheel brake	
		
Lifting jack	The belt dynamometer of Briggs	

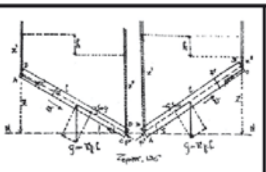
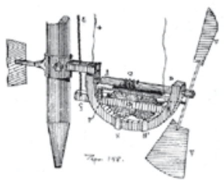
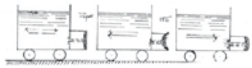
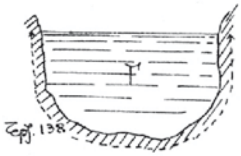
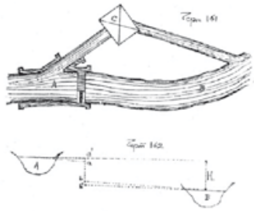
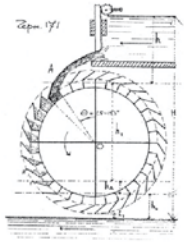
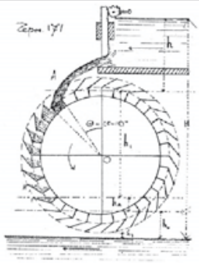
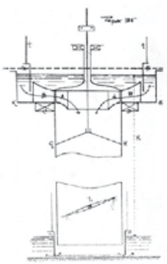
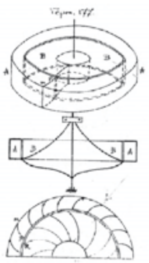
Theory of Resistance of Materials (Part 1) and Theory of Elasticity (Part 2)

Title page of the book published in 1880 reads as follows: "Excerpts from Prof. F. E. Orlov's lectures; Course of 1st Special class" (Fig. 3).

Contents of Part 1 (300 pages) corresponds to the classical contents of such courses. The following sections (in modern terms) are analysed consecutively:

Stress and strains, Hooke's law. Geometric properties of sections. Tension and compression. Pure bending. Tangential stress. Eccentric compression. Equation of deflection curve (now referred to as Krylov's method). All cases of two- and multi-support beams.

Table 5 Some examples from theory of machines (motors). Hydraulics

Some examples from Theory of Machines (Motors). Hydraulics		
		
Liquid moving in pipes	Voltman's propeller flowmeter	Water as motor
		
Liquid flow in rivers and canals	Dam, dyke	Overshot water wheels
		
Lovershot water wheels	Turbines	

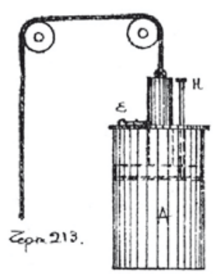
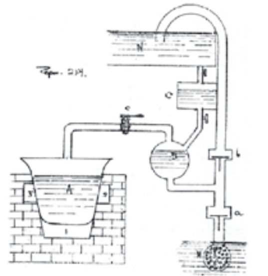
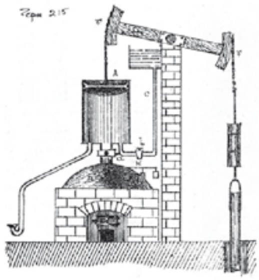
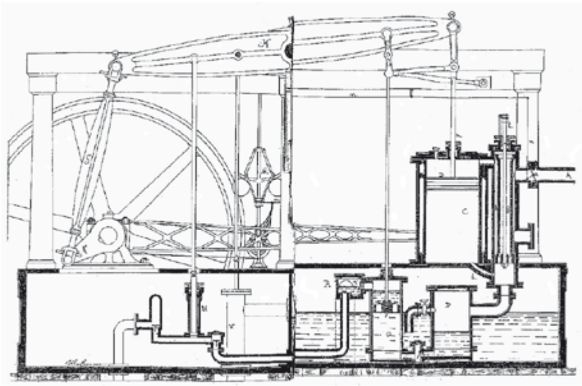
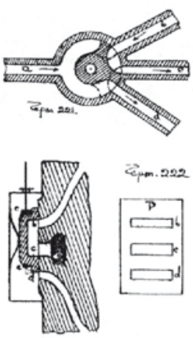
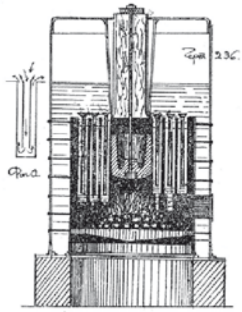
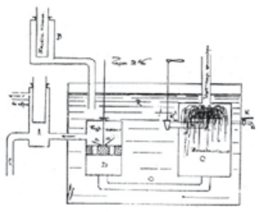
Stability of compressed beam. Flexure of curvilinear beam. Torsion. Momentless theory of shells.

Theory of elasticity – Part 2 (40 pages) is presented briefly. Actually (in modern understanding, too) the paper presents components of stress and strain tensors, Cauchy's surface, and Lamé's ellipsoid. Correspondence between theory of elasticity and resistance of materials is shown.

Theory of Steam Engines

Title page of the book published in 1881–1882 reads: "Prof. F. E. Orlov's lectures" (Fig. 4). In fact it is an extended course of thermodynamics presented in the

Table 6 Some examples from theory of machines (motors)

Some examples from Theory of Machines (Motors)		
		
Steam engine of Papin (1690)	Steam engine of Savary (1698).	Steam engine of Newcomen (1705)
		
Steam engine of Watt		
		
Steam box systems	Boiler of Fild	Refrigerator

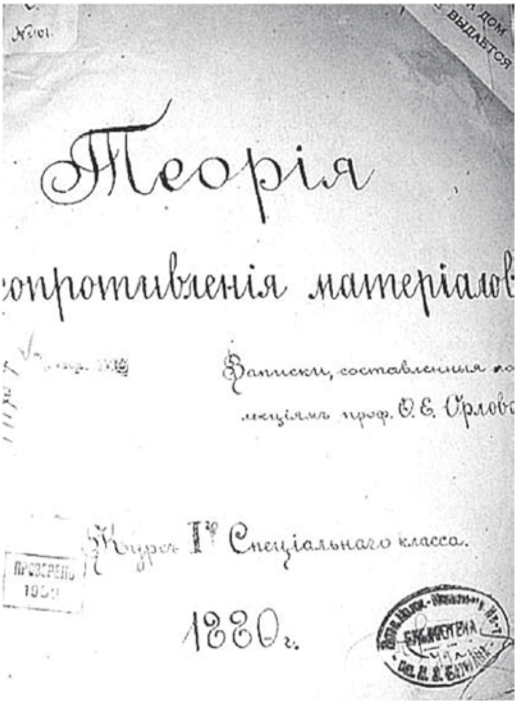


Fig. 3 Orlov's book of 1880

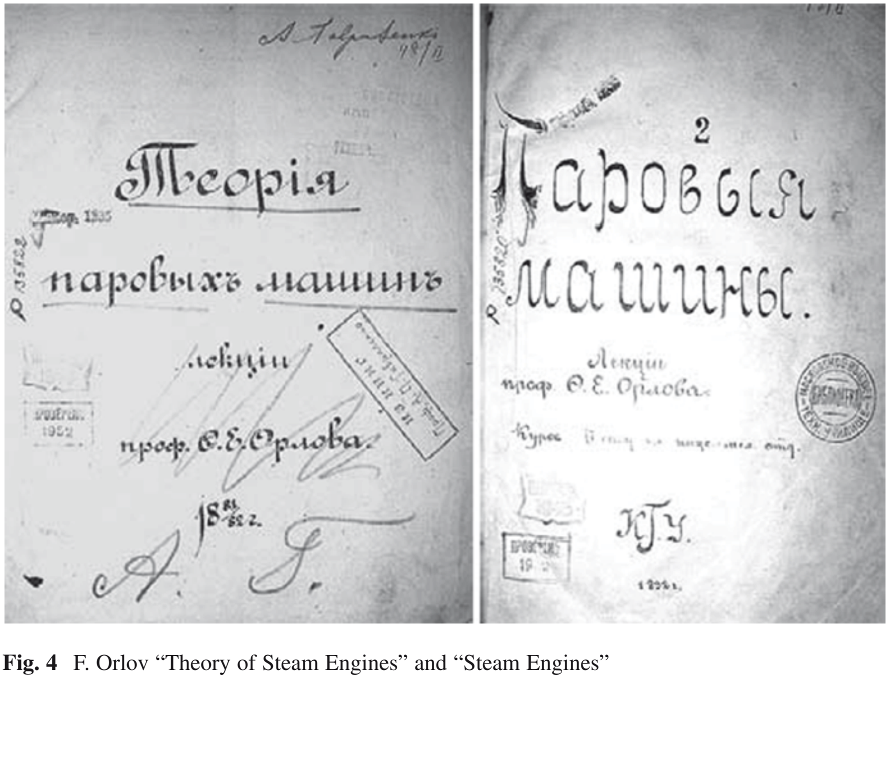


Fig. 4 F. Orlov "Theory of Steam Engines" and "Steam Engines"

course “Applied Mechanics, Part 2 – Theory of Machines”. The course is presented as 23 lectures on 197 pages. Part 1 (Thermodynamics, 91 pages) presents the fundamentals of thermodynamics, atmospheric and thermal machines. In the second section (on steam, 42 pages) steam types are considered. All then existing kinds of steam engines are analysed in the third section (theory of steam engines, 68 pages). History of steam engines: Hero of Alexandria, Solomon de Coos, D. Papin, T. Savery, T. Newcomen, J. Watt. Steam engines of Leupold and I. Polzunov are not considered.

Steam Engines. Title page of the book published in 1892 reads: “Prof. F. E. Orlov’s lectures, course for Mechanical Engineering Department” (Fig. 4). Book comprises 364 pages. Types of steam engines, indicators and their peculiarities (also defects), are analysed. Theory of double-acting steam engine with one cylinder of a complex steam engine, is presented. Analyses for all units of a steam engine are performed. Dynamic problems (travel adjustment, flywheels, maximum number of turns) are investigated. Railway engines: design, locomotive resistance (friction, air resistance, shocks on splice joints, etc.) steamships.

Hydraulics. Title page of the book published in 1882 reads: “Prof. F. E. Orlov’s lectures” (Fig. 5). In fact it is an extended course of hydraulics presented in the course “Applied Mechanics, Part 2 – Theory of Machines”. Book consists of 238 pages and two sections: hydrostatics and hydrodynamics. Problems of practical hydraulics: fluid flow in tube and channel, complex pipeline and manifolds, dams and embankments, methods to measure parameters of hydraulic systems, are solved.

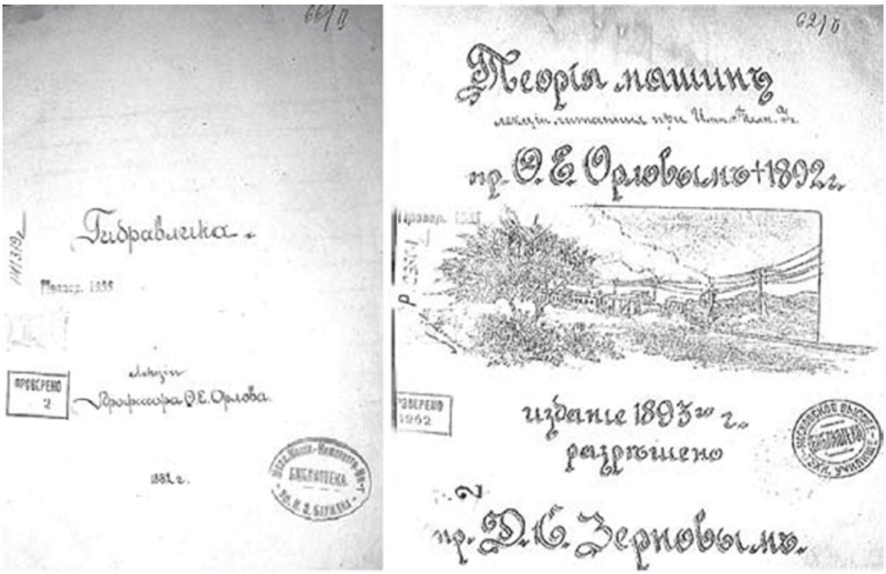


Fig. 5 F. Orlov “Hidraulics” and “Theory machines”

Theory of machines. The book was written in 1892 and published posthumously in 1893 (Fig. 5). It comprises 196 pages. Actually it is an arranged edition of Part 2 of Applied Mechanics.

Certainly, Orlov's main works were coherent with his teaching activity. However, he wrote several original works on abstract mathematics. Orlov the mathematician can be represented by two papers:

Proof of Euler's theorem (1867). The derivation is proposed for condition given by Euler for integrability of differential expression

$$f(y, x, y', y'', \ldots y^{n})\,dx,$$

Theorem defines necessary and sufficient conditions for the function integrability. Orlov proposed a more simple and elegant proof. His derivation may be extended to both direct and converse Euler theorems. On Reciprocity of Differential Equations (1868). This was his thesis on the Master Degree in mathematics. Along with the given autonomous differential equation

$$F\left(x, y, y'\right) = 0,$$

Orlov proposed one more equation which he refers to as one reciprocal to the given one

$$f\,(\omega', p\omega' - \omega p) = 0,$$

where ω is a straight line segment cut off by the tangent on the axis of ordinates, argument – slope of tangent to axis. It is proved in the paper that the integrals of these two equations are identical. The author gives integration examples for differential equations of various kinds, and notices the connection between the equation's reciprocity and the last multiplier theory. In the conclusion, the reciprocity idea is extended to partial derivative equations. Further development of this work was presented in Orlov's article "Finding the Integrating Factor" published in the fourth volume of the Moscow University Mathematic Collection in 1869.

Excerpts from the Roulette Theory. At the VII Congress of Russian naturalists and doctors, which took place in 1888 in the city of Odessa, Orlov gave the "Excerpts from the Roulette Theory" report. It was published in the Proceedings of the Novorossiysk Naturalists' Society. The problem of analysing movable and fixed centroids for a body whose one point describes a straight line, is solved in the report. This solution involves the theorem on acceleration centers for a body being in a uniform rotary motion, while one of this body's point moves in a straight line. Such a body has all its even order acceleration centres on the said straight line, while odd order acceleration centers are on another line perpendicular to the former one (Fig. 6). Orlov derived the second-order differential equation whose integration can lead to roulettes if the dependence between the radii of the curvature for the centroids is known.

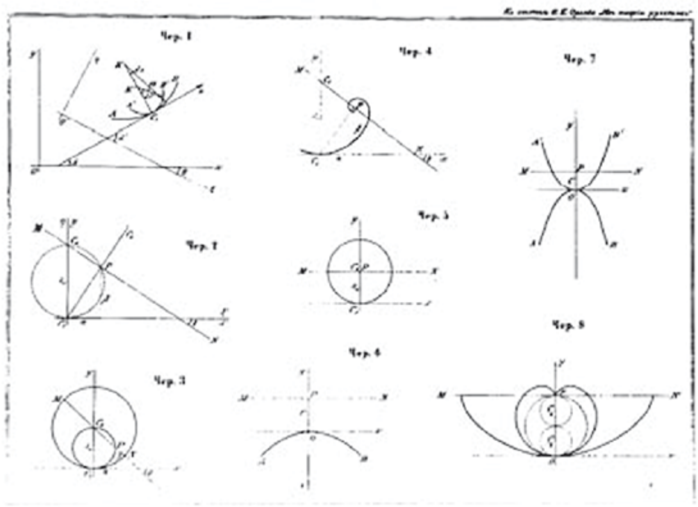


Fig. 6 Pictures from Orlov's article

The solution is illustrated by examples. In particular, on contacting the conjugate convex curves, both cetroids are parabolas and the point describing the straight line is the focus of the movable centroid. A wooden model of Cheby-shev's antiparallel link mechanism (Fig. 7) was fabricated in the IMTS workshop. In this model, the crank point moves along a line close to the straight one. The model also has a movable centroid linked to the crank, and a fixed one linked to the column. This model is supposed to be made by Orlov to visualize the theory presented in the report. This work was continued in the "On the Roulette Quadrature" article. This paper deals with interesting but little-known equations on the roulette quadrature derived in a more general form with the analytical methods being developments of Darboux's method. The said approach allows to define the area between some point's roulette, two perpendiculars constructed from its ends to a fixed centroid, and its contour. Orlov found that all points of the movable figure's plane whose roulettes have the same area, are on concentric circles. Orlov refers to the centre of these circles as the centre of roulette's area. With this point, the roulette areas can be represented by where r – distance from a point to the roulettes' area centre, E_0 – constant, ϑ – rotation angle of the figure under analysis.

Economic Role of Machines (1879). While abroad, Orlov took an interest in societies that supported workers. He visited meetings of these societies in Liège, Zürich and Berlin. The objectives of such societies were treated as follows: "…they are aiming at spreading education to the working class that is the first step towards socialism and the only way to solve the workers' problems". Impressed by these ideas, Orlov came to the conclusion that a scientist can help the working class by improving small thermal machines, and methods of long-distance power transfer from big machines. In his speech, he exploded a theory that the progress of technology and engineering worsens the workers' situation. On the contrary, he was sure

Fig. 7 Model of Chebyshev's "Excerpts from the Roulette theory" antiparallel link mechanism

that the machines would facilitate manual labour. Orlov presented these ideas in his inaugural speech in Moscow University on 21 October 1872. In the conclusion of the speech Orlov told students: "… they would not forget that their high calling is to facilitate human labour by natural force, and that power over this force is given by knowledge, and that knowledge is power".

Cabinet of Applied Mechanics in the IMTS and Moscow University

Orlov supervised offices of practical mechanics in Moscow University and the IMTS. Going abroad on business trip (Fig. 8), and satisfying requests from director of the IMTS V. Della-Vos, Orlov took an interest in collections of mechanisms in different European universities, and he acquired some models. During his trips, Orlov familiarised himself with collections of mechanisms, equipment of lecture halls, drawing offices, and workshops in universities and the technical schools of Zurich, Frankfurt, Berlin, Aachen, Margeburg, Karlsruhe, Liege, Paris, etc. This allowed him to form a clear picture of possible equipment for a mechanical office. Orlov wrote to Relaud "…about the mechanical laboratory organised at the Technical School aiming to be a necessary element of every special technical institution to acquaint students with methods and technique of experimental research".

Fig. 8 The show-window cupboards made in the nineteenth century at the beginning of the formation of the collection

Professor A. Yershov laid the foundation of mechanism collection at the IMTS. Orlov sufficiently updated and replenished the applied mechanics offices. Since the funds to acquire the models were modest, Orlov was thorough in selecting them to resupply the collections. In the 1880s, Hustav Voight in Berlin, Joseph Sröder in Darmstadt, Pierre and Alexandre Claire in Paris, started to manufacture models of mechanisms. Models by Reuleaux and Voight were the most perfect and thus they were preferably bought both for the IMTS and for the university. Some original models were elaborated by Orlov himself and manufactured in the IMTS workshops. Unfortunately, these models are now lost. But during Orlov's lifetime, the mechanism office was in perfect tune.

Toward the middle of the nineteenth century in Russia and abroad, engineering departments were formed at universities, and many higher technical schools and institutes were established (Rubio and Cuadrado 2000). Applied mechanics was one of the basic courses in their curricula. During that time, model offices were created in St. Petersburg (M.F. Okatov), Kiev (I.I. Rakhmaninov), Kharkiv (V.G. Ishmenitsky) universities and many technical institutes. Orlov had a great influence both on the contents of applied mechanics courses in these universities and on model selection for the mechanism offices. At the Polytechnic Society meeting devoted to the memory of Orlov, many spokesmen emphasised his merits of equipping applied mechanics offices. Orlov "…loved the Technical School and took great care to replenishing the main library with the best books in applied mechanics, and of acquiring valuable machines and instruments for the mechanical office under his supervision" (I.V. Aristov, IMTS director in 1883–1902) (Zhoukovsky 1893).

A.K. Eshliman: "Orlov inherited the mechanical office in an unenviable state. Despite the niggardly yearly allowance for office renewal, he succeeded in turning it into a highly valuable manipulative item, following his strict selection criteria. He acquired the collection of guides, models of recent steam distributors and inertia governors. A novice teacher would find strict order and rich content in the mechanical office" (Zhoukovsky 1893).

At the Polytechnic Society meeting on 23 November 1891, Orlov made his last report "On Astatic Governors" with a demonstration of new models from the mechanical office of the IMTS (Zhoukovsky 1893). Pictures of these governors are shown in Fig. 9.

Course of Lectures and Contemporaries

Together with Professors A. Yershov, N. Zhukovsky, D. Zernov, Orlov is by rights one of the founders of the Moscow School of Science of Machines. The great Russian engineer V. Shukhov, who had matriculated to the IMTS in 1876, listened to Orlov's course. Successors of Orlov were Professors L. Smirnov and N. Mertsalov whose pupil is the famous scientist academician I. Artobolevsky.

Courses established by Orlov, primarily of applied mechanics, and also courses of hydraulics, thermodynamics, and steam engines, corresponded to the modern state of engineering and scientific thought in Russia and abroad. Lithographic notes of Orlov's courses are extant. In fact these were the first Russian lectures designed for higher education. They laid the foundations of such disciplines as thermodynamics, steam engines, hydraulics and hydraulic machines, resistance of materials, theory of elasticity, theory of machines and mechanisms.

Fig. 9 The models of centrifugal governors, which were purchased by Orlov in Germany

Modern Interpretation of Main Contributions to Mechanism Design

In 1868, the Moscow Industrial Engineering School (MIES) was transformed into the Imperial Moscow Technical School (IMTS) whose administration established and developed the chairs on the basis of the MIES departments. First, the chairs of general mechanics (1868, Prof. F. Korolev), machine building (1868, Prof. D. Lebedev), general mechanics and machine building (1869, Prof. D. Lebedev; 1872, Prof. F. Orlov), were founded. In 1878, the general mechanics and machine building chairs were transformed into the applied mechanics chair headed by Orlov who is thus an acknowledged founder of the Applied Mechanics chair of the IMTS. In the same year, the theoretical mechanics chair headed by Professor N. Zhukovsky was organized. In the BMSTU, the official date of the applied mechanics chair foundation is regarded as 1873 when Orlov began to deliver a systemised course of applied mechanics. Friendship between Zhukovsky and Orlov greatly influenced the making of the applied mechanics course. The high level of the theoretical mechanics course allowed the improvement the theoretical level of the applied mechanics course. This level was maintained by Orlov's successors, Profs. D. Zernov and N. Mertsalov until the October revolution of 1917. Later, the level dropped due to the change in the student body.

The first systemised course of the theory of mechanisms in Russia is known to be Prof. A. Yershov's work "Foundation of Kinematics or Elementary Theory about Mechanisms of Machines Especially" published in the Moscow University printing house in 1854 (Yershov 1854). It was a kind of encyclopaedia of mechanisms organised according to Willis's classification (Golovin and Mkrtychyan 2007). Orlov's course was designed to a sufficiently advanced basic level and was replete with high theory. The course was perfected by Orlov's successors Profs. N. Mertsalov and D. Zernov whose textbook had several impressions over more than 30 years (Golovin and Tarabarin 2004). In the Theory of Machines and Mechanisms courses, especially since the 1940s of the twentieth century, much attention has been paid to various analyses. Mechanism properties lectures were essentially less attended. However, the very mechanism properties were thoroughly investigated in Orlov's course. For example, the quality analysis for components of the equation of motion is greatly influenced by the mathematical part of Orlov's talent. This tradition was continued in courses by D. Zernov, N. Mertsalov (also a graduate of the mechanical-mathematical department of the Moscow University), and others (Golovin and Tarabarin 2004).

Orlov's activity in the Polytechnic Society not only made a great contribution to the establishment of the Russian, later Soviet, engineering school, but also helped graduates of the IMTS and other technical schools to solve their problems. The society's activities (taking into account the time) can be compared to the modern activity of the ASME.

The collection of mechanisms is a special part of Orlov's work. The foundation of this collection was begun by Prof. A. Yershov who not only bought mechanism models from abroad, but also manufactured some models in the MIES (later IMTS) workshops (Golovin and Mkrtychyan 2007). Orlov continued this tradition, although funds to replenish the collection were limited. Orlov not only extended the collection, but also gave the problemoriented feature to it by taking into account the course needs. This work was continued by D. Zernov, N. Mertsalov, L. Smirnov, V. Gavrilenko (Golovin and Tarabarin 2004, 2005; Tarabarin et al. 2006). Actually, the collection consists of more than 600 exhibits, and is therefore one of the most comprehensive mechanism collections in the world. Moreover, it can be treated as an historical monument of science and technology. Besides, the collection is used as educational media. For example, the model of Watt's steam engine and its parts can demonstrate the common principles of machine design (multiple alternatives of engineering decisions), and of linkage design; fragments of a worn gear set serves to help understand the mechanism of the wearing of a kinematic pair of higher degree, etc. (Borisov et al. 2004).

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Todor Pantelić (1923–1999)

Aleksandar Veg

Abstract By transforming fundamental theoretical solutions into functional mechanisms, Todor Lazar Pantelić became a pioneer of innovative structural synthesis. Most of his work evolved to the level of patents and industrial products. Professor Pantelić's specialty was the four-bar chain in innumerable varieties such as walking, imprinting, and shutter mechanisms. The crown of his innovative work was the helical conveyor, theoretically established, patented, designed, and prototyped. Loved and admired by his students and colleagues, he made a point of introducing engineering talent and creativity into the science of machines and mechanisms. He was one of the founders of the International Federation for the Theory of Machines and Mechanisms (IFToMM) and the first president of its Commission for Collaboration of Science and Industry.

Biographical Notes

So much of who we are – we owe to our teachers. In the constellation of all the great masters I have met, shines brightly the giant star of Professor Todor Pantelić.

Todor Lazara Pantelić (Fig. 1) was born on 2nd July 1923 in Belgrade (then the capital of the Kingdom of Yugoslavia) to a family of a small merchant. He had a carefree childhood in a Belgrade suburb, spending every waking hour in his brother's workshop for mechanical calculators. His regular schooling at King Alexander's Lyceum was interrupted before he was 18 by the bombing of Belgrade on 6 April 1941, which was the beginning of the Second World War in Yugoslavia. Resourceful and restless, he soon took part in the antifascist resistance movement in occupied Belgrade. When the war finally ended in 1945, he was demobilised and became a student of the Belgrade Polytechnics.

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Fig. 1 Prof. Todor Pantelić at the international symposium machines and mechanisms, Belgrade, September 1997

His academic career started right after graduation: he became Junior Engineer in 1950, Teaching Assistant in 1954, Assistant Professor in 1960, Associate Professor in 1966 and, finally, Full Professor at the Faculty of Mechanical Engineering, University of Belgrade in 1971 (Evaluation report...).

He has published extensively at home and abroad (180 works and 4 books) and was the author or co-author of 23 national and five international patents. Marked by books, students, travels, patents, friends and family – his life was indeed an amazing one.

Prof. Pantelić was one of the founders of The International Federation for the Theory of Machines and Mechanisms (IFToMM). The decision was made in Varna (Bulgaria) in 1965, during the first Congress in that field, which assembled representatives of 16 countries. The committee including Prof. I. I. Artobolevskii (И. И. АртоболевскИй), Prof. F. R. E. Crossley, Prof. M. S. Konstantinov, Prof. W. Meyer zur Capellen, Prof. G. Bianchi, and Prof. Todor Pantelić, among others, organised the founding conference of IFToMM in Zakopane (Poland) in 1969. The next one was held in 1971 in Kupari (Yugoslavia), hosted by Prof. Pantelić (Fig. 2).

That grandiose gathering, with over 800 participants, has been considered a model of a successfully organised international scientific conference coloured by national charm. The exhibition of applied mechanisms was particularly successful: members of the Executive Board of IFToMM, very impressed, later pronounced Prof. Pantelić as chairman of the Commission for Collaboration of Science and Industry.

The Committee's seat therefore moved to Belgrade, to the Faculty of Mechanical Engineering. Innovative and brilliant, Prof. Pantelić established the Machine Mechanics Institute, and developed it into an incubator where scientists and innovators came for consultations and help with their evolving solutions and prototypes.

Many years later, in 1995, during the Ninth World Congress of IFToMM in Milan, I met Prof. J. R. Phillips who had travelled all the way from Australia to Belgrade in order to work with Prof. Pantelić on a model of mechanism analysed

Fig. 2 Kupari, Third IFToMM World Congress 1971. *Left* to *right*: (1) Ž. Nikolić [Yu], (2) I. I. Artobolevskii [USSR], (3) unknown, (4) P. Genova [Bul], (5) G. Boegelsack [GDR], 6) W. Roessner [GFR], 7) and 8) unknown, 9) N. I. Manolescu [Rom], 10) R. Unterberger [GFR]

in a doctoral thesis. At that time, the Machine Mechanics Institute was already renowned for application of the theory of machines and mechanisms.

The walls of the Institute still bear marks of the creative atmosphere of that time: a photograph (Fig. 3) taken at the Leonardo da Vinci Museum during the Congress in Milan shows the Yugoslav team led by Prof. Pantelić and accompanied by Prof. A. Morecki from Poland (the previous president of the IFToMM), Prof. B. Roth from USA, and Prof. A. P. Bessonov (А. П. Бессонов) from Russia. As I realised only recently, a model of Leonardo's helicoid stands out in the background of the picture, adding a touch of magic: in the preceding years, a helical conveyor had become the crown of Prof. Pantelić's innovative work.

Clearly, it was the Professor's idiosyncrasies that led to this patent conceived apparently contrary to the fundamental principles of mechanics. Namely, the only way to make a helicoid belt revolve around a central post without friction was to convert it into a solid body; for the belt as a floppy form, the task would be impossible. Many were sceptic, but Prof. Pantelić succeeded.

Recognition of creative powers and already achieved results of Belgrade's IFToMM centre came in 1974 with the Symposium on Application of the Theory of Machines and Mechanisms in Dublin (Ireland). Prof. Duffy from the Liverpool Polytechnic was chairing the Organising Committee, and Sir Crossley, president of IFToMM, personally entrusted Prof. Pantelić with chairing the event.

Fig. 3 Milan, Ninth IFToMM World Congress 1995. At the Leonardo da Vinci Museum (with a model of a hellicoid in the background), left to right: Lj. Miladinović [Serbia], A. Sekulić [Ser], A. Veg [Ser], N. Pavlović [Ser], M. Vukobratović [Ser], B. Roth [USA], A. Morecki [Pol], A. P. Bessonov [Rus], unknown, L. Cvetičanin [Ser], M. Pantelić (Prof. Pantelić's wife) [Ser], T. Pantelić [Ser]

In 1997, 26 professors from all parts of the world came to Belgrade Symposium on the Theory of Machines and Mechanisms, organised in his honour: Prof. M. Ceccarelli from Italy, Prof. T. Leinonen from Finland, Prof. E. J. Hahn from Australia, Prof. F. G. Dedini from Brazil, Prof. S. Kato from Japan, and Prof. G. Bőgelsack from Germany.

In 1999, while bombs were falling on Belgrade (again), Prof. Pantelić received an invitation to chair the Tenth World Congress of IFToMM in Oulu (Finland). He thanked for the honour but stayed at home.

Later that year, when he suddenly and unexpectedly died, his wife and three daughters received condolences from all over the world.

Main Works on Mechanism Design

Prof. Pantelić's main works include:

– A four-bar mechanism applied to operations on pieces on a conveying line (Pantelić 1974, 1977b). It represented a new type of mechanism that replaces intermittent mechanism, and it was used for manufacturing 120 pastry production lines (*Minel* Company, Pančevo, Serbia).

- Settlement of motion equivalence between four-bar and slider-crank mechanisms (Pantelić 1976, 1981b), which enabled synthesis of a family of extended slider-crank mechanisms with a member performing approximate curvilinear translation (Pantelić 1975a, 1975b , 1976, 1977b, 1980, 1981a, Stoimenov and Pantelić 1976). It was used for highly efficient pastry production lines, in which the translatory member carries the tools for executing individual operations. One of its inversions was applied to the model of the *walker* mechanism (Pantelić 1980, 1981a, 1981d, 1983a, Stoimenov and Pantelić 1981).
- Synthesis of six-bar linkage with three dwells in the motion of its driven bar (Martinović R and Pantelić 1975a, 1975b). It was the first practical solution of the problem since 1932. It was used to double or treble the number of rows in conveying lines, with the respective dwells in the motion phased by π, or $2/3\pi$.
- An advanced numerical method of the inertial forces harmonic analysis (Četić D and Pantelić and Sekulić 1971; Pantelić, 1981c) applying Bessel functions for balancing inertial forces of basic linkages. The results of this work were applied to balancing the new family of slider-crank mechanisms used for Prof. Pantelić's *walker*.
- Synthesis of four-bar with additional dyad (Pantelić 1977a, 1980, 1981). It generated a mechanism for a deep drawing machine press with very fast approach, relatively slow imprint, and fast return. Compared to the conventional machine presses, productivity of the new one was doubled.
- Research of kinematic chains with zero degrees of freedom, mainly for steel and chain conveyor belts, which contributed to optimisation of their drive and control (Četić D and Pantelić 1980).
- Helical conveyor and overcoming Euler friction (Bukumirović and Pantelić 1975a, 1975b), as the most serious challenge of Prof. Pantelić's career.

Neither a groundbreaking theorem nor a revolutionary new theory is what Prof. Pantelić is to be praised for. He did something else: he made a point of introducing engineering talent and creativity into the science of machines and mechanisms. His art was *simple and efficient transformation of an idea into a product*.

And to that vision he dedicated his whole career, his life too. Working with him, generations of students discovered the beauty of engineering creation, learned to love their profession and to enjoy every day of creative work and every achievement they made.

At the peak of his career, Prof. Pantelić found himself in a unique position to connect creative work of academic communities of all 17 members of the IFToMM within the Commission for Collaboration of Science and Industry, the so-called Commission C.

He invested all his talent and enthusiasm into realisation of the IFToMM *Programme on Collaboration of Science and Industry in the Theory of Machines and Mechanisms*.

Establishing of the Commission C was proposed in 1971 in Düsseldorf (Germany) at the meeting of the IFToMM Executive Council. An action plan in 12 steps was formulated, and Prof. Pantelić (nominated by Academician Artobolevskii) was elected President of the new commission (Fig. 4).

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IFTOMM

INTERNATIONAL SYMPOSIUM - MACHINES AND MECHANISMS, UNIVERSITY RESEARCH WORK AND ITS APPLICATION TO INDUSTRY.

ACKNOWLEDGEMENTS

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PROFESSOR T P PANTELIC

FACULTY OF MECHANICAL ENGINEERING

UNIVERSITY OF BELGRADE, YUGOSLAVIA

CHAIRMAN, IFTOMM COMMISSION "C".

Chairman of Organising Committee:

Dr. J Duffy
Reader in Mechanical Engineering
Department of Mechanical, Marine and Production Engineering
Liverpool Polytechnic, U.K.

Fig. 4 Proceedings Dublin 1974, front page

The first meeting of Commission C was held in 1971 in Kupari (Yugoslavia), the second one in 1972 in Miskolc (Hungary), the third one in 1973 in Bucharest (Romania). The pioneering job of harmonising creative work of university researchers and industry designers was soon in full swing, as can be seen from the proceedings of the 1974 IFToMM Symposium in Dublin.

Obviously, Prof. Pantelić was not leading such a creative army only because of his brilliant managerial skills; it was also because he had a gift for closing up the golden engineering triangle *idea → concept → product*.

An eye for harmony and beauty helped him create elegance without effort. "A beautiful construction is certainly a functional one, that's for sure," he used to say.

Design without effort came from the synergy of his exceptional visualisation, thorough understanding of fundamental sciences, and fascination with mechanisms.

Naturally, it resulted in axiomatic design. Although the following examples (chosen from among numerous successful constructions of Prof. Pantelić) seemed technically incomparable, he still found their common point and used it as a basis for conceptual design, which then led to two outstanding solutions (Pantelić 1965, 1983).

The first one is applied to an automatic bun production line (Fig. 5), and the second – to an orthopaedic device.

It all started with a mechanism for imprinting buns on a conveying line. A standard industrial solution widely applied in similar technologies was available: a configuration with coupled motions – horizontal, which follows a bun, and vertical, which imprints it in the process. The challenge was to simplify the configuration by implementing a single member with the resulting path.

The first attempt was synthesis of a four-bar chain where the coupler generates the desired path. But the search went on.

The same operation can be performed by adding new links to a kinematic chain, which follows the same path (Fig. 6). In that case, a link's endpoint in two inverted slider-crank mechanisms performs curvilinear translation, that is follows exactly the desired path. The solution was modified into an eight-link mechanism by omitting one slider and adding one link. The search for more efficient solutions continued.

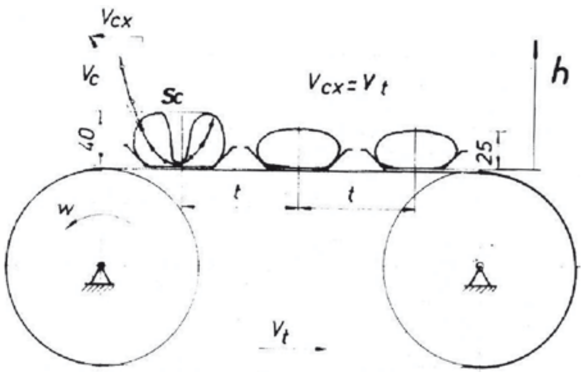

Fig. 5 Path analysis of the bun imprinting tool (Pantelić 1975b)

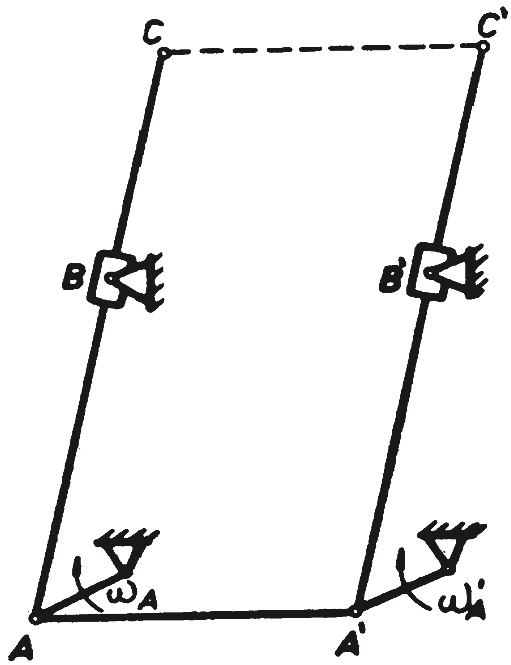

Fig. 6 Inverted slider-crank (Pantelić 1975b)

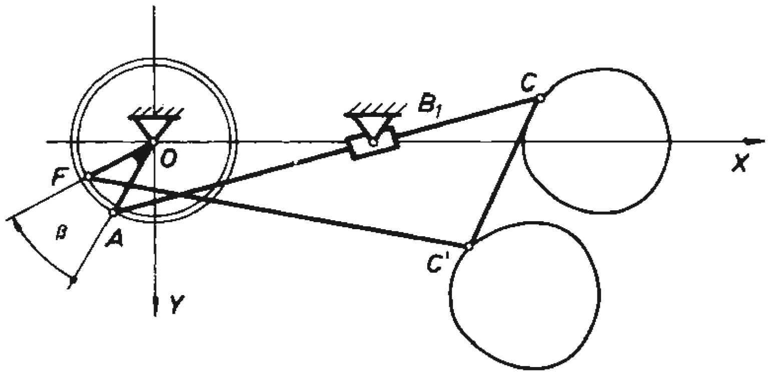

Fig. 7 Slider-crank mechanism with additional dyad – curvilinear translation (Pantelić 1975b)

Prof. Pantelić came up with a new task: to create a six-link inverted slider-crank mechanism with additional dyad, in which coupler CC’ performs curvilinear translation with the given path. It took quite a while to finalise the solution of this problem, which had not been solved up to that time.

In the inverted slider-crank mechanism with additional dyad (Fig. 7), translatory motion of the link CC' is due to points C and C' following approximately the same path. Such a simplified configuration was far more suitable for application to production lines.

Once established, synthesis of the extended inverted slider-crank mechanism with a member that performs approximately curvilinear translation, enabled a whole generation of innovative modifications.

The breakthrough occurred when Prof. Pantelić noticed hidden similarities in two apparently very different processes: bun imprinting and – human walking! In operational cycle of the imprinting mechanism (Fig. 8/1) there is a fragment with

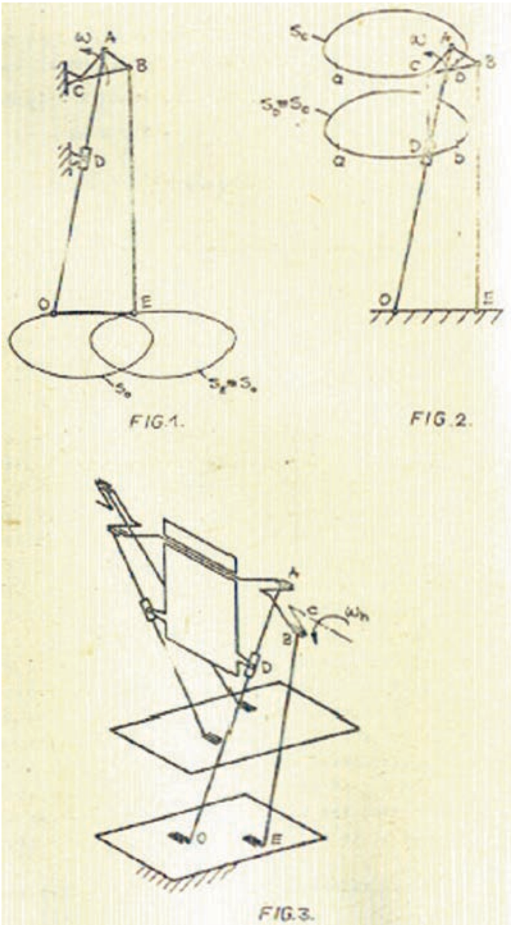

Fig. 8 Slider-crank mechanism with additional dyad: (1) imprinting inversion, (2) walker inversion, (3) walker composition (Pantelić 1981b)

no relative motion between the link CC' and the bun; similarly, from time to time, there is no relative motion between the foot and the floor.

Looking at the new inversion, the so-called *walker* mechanism (Fig. 8/2), one sees that its coupler CD performs curvilinear translation, which enables the *walker* to make a step forward relative to the floor. The basic structure of this mechanism is a four-bar OABE, extended with a coupler CD and a slider D. The transition from the raw concept to the actual "walking model" was long and winding, but Prof. Pantelić had a clear guiding vision.

Two identical walker mechanisms were placed in parallel planes, with cranks shifted for half a cycle and embedded in the point C (Fig. 8/3). The grounding of each walker acts as a foot; when one of them is firmly on the ground, the other is in the air and, due to rotation of the crank, performs a step forward. Alternating and synchronised lifting and dropping of the feet, and their curvilinear translation forward appears amazingly similar to human walking. A rocker also had to be added in the model in order to shuttle its centre of gravity from one plane to the other, enabling the foot in the air to walk freely.

The Walker (Fig. 9) was a revelation of the 1981 Bucharest Symposium *Theory and Practice of Mechanisms*: an intricate motion, similar the human walk, was realised in a very simple manner. Unfortunately, the avalanche of new, easily marketable ideas and patents at the Machine Mechanics Institute in Belgrade diminished the interest for this project, although it was recognised as striking and successful.

A special place in the creative opus of Prof. Pantelić belongs to his helical conveyor. He was persistently working on the idea despite the sceptic attitude expressed in some of the related disciplines. Unlike most of his works which were broadly published, he kept this one to himself, far from the international scene. Except for four master theses, one vague paper on the idea of the helical conveyor, one review paper at the 1997 Belgrade Symposium and a functioning model, there is no other technical evidence that usually accompanies projects of such relevance. Prof. Pantelić himself probably had his doubts: would everything work out as in his vision? All the elements necessary for a successful project were there – except a market boom.

There was a clear need in the food industry to transport pastry in the process of warming, baking, and cooling not through the endless line tunnels (30–70 m long!) but through a helicoid, inside a compact thermodynamically controlled space.

The main problem of this idea was obviously Euler friction; there was also the speed difference between the inner and the outer edges of the belt, as well as the inconformity of upward and downward motion of the helical belt.

The following overview is an attempt to reveal the path of the invention's evolution.

Prof. Pantelić's inspiration was an already existing idea of a helical transporting belt which ascends around the central post. It folds around the dragging roller at the top, then descends, and folds again around the tightening roller at the bottom. The problem is that friction between the stable post and the sliding belt, according to Euler's formula, grows exponentially.

There was also a version with a rotating post that drags the belt upwards; then, after a short linear part, the belt descends the second rotating post and proceeds linearly to the starting point.

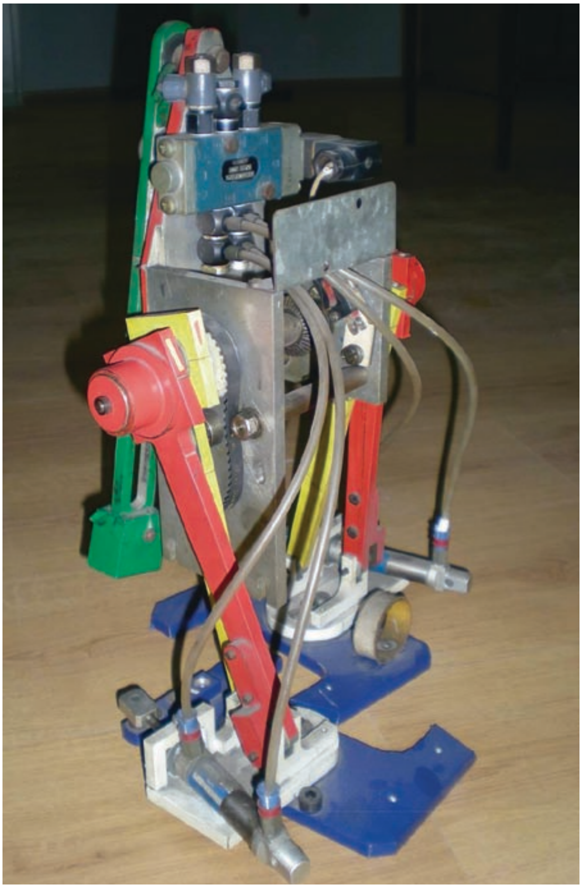

Fig. 9 Mechanical Walker (Photo A. Veg, 2008)

A serious disadvantage of the first solution was the enormous dragging force needed to overcome enormous friction. In the second one, combination of curved and linear paths of the belt, driven in free contact with rotating posts, caused various functional difficulties.

The creative illumination came when Prof. Pantelić wrote down all the necessary conditions and limitations for his helical conveyor:

– The helical belt should not touch the central post.
– Within the helical guides, belt chain members must loose all degrees of freedom, so the belt could rotate as a rigid helicoid (in such a way the dragging force of the helical conveyor becomes approximately equal to the dragging force of the correspondent line conveyor, (Miljković M. and Pantelić 1997)).
– The inner diameter of the solid helicoid must be significantly greater than the diameter of the central guiding cylinder.

– Coming out of helical guides, and also engaging with the driving rollers, belt chain members regain necessary degrees of freedom, so the belt could behave as a solid body.

This was the basis for Prof. Pantelić's new solution. In a consistent and focused developmental phase (Fig. 10), he defined the geometry of the belt; defined the

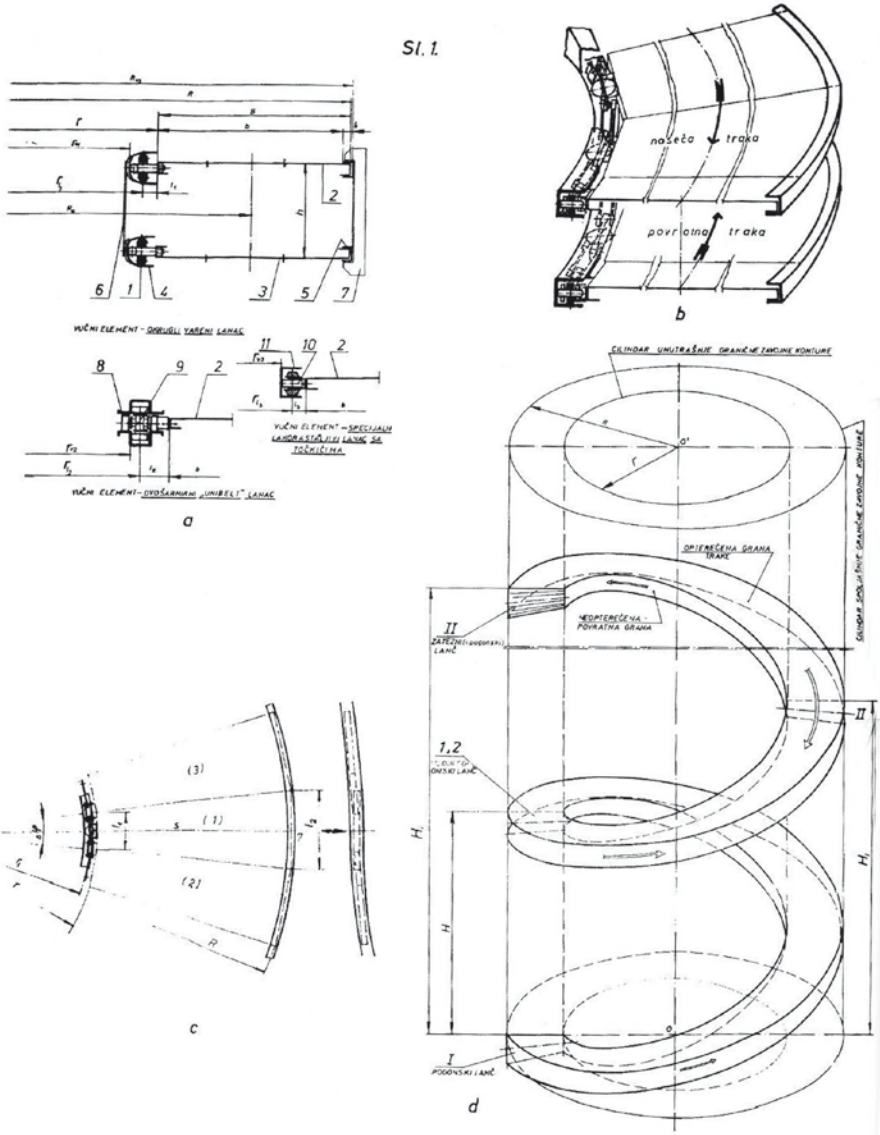

Fig. 10 Draft of the helical conveyor (Bukumirović and Pantelić 1975b)

upward and downward trajectories; constructed the helical guides; calculated contact radii of the driving roller; optimised speeds of the belt chains, that is developed a prototype (Fig. 11). Two models of the helical conveyor were made and they both fulfilled all the technical requirements.

Following the development of this project through documents, I concluded that it was the most serious challenge of Prof. Pantelić's career. Like a sport champion after achieving a record that will obviously stand for many years, he lost any further wish to compete.

The moment prototype of the helical conveyor came to life, all doubts of his colleagues disappeared and, even more importantly, his personal hidden doubts too. I think it was the last and the greatest creative flash of Prof. Todor Pantelić.

From then on, resigning the post of a great inventor, he focused on his teaching mission, leaving space for the upcoming younger colleagues.

Fig. 11 Helicoid prototype (Photo A. Veg 2008)

On the Circulation of Works

There are several aspects of Prof. Pantelić's conspicuously dynamic career.

Firstly, he did all he could to disseminate the theory of machines and mechanisms in the territory of former Yugoslavia. He had postgraduate and doctoral students from all the emerging Yugoslav centres – Niš (Serbia), Skopje (Macedonia), Mostar and Sarajevo (Bosnia and Herzegovina), Podgorica (Montenegro) – as well as from the centres which already had scientific reputation, only not in the field of mechanisms – Ljubljana (Slovenia) and Zagreb (Croatia). Most of those postgraduate and doctoral students became professors at their home universities, broadening the scientific community dedicated to the theory of machines and mechanisms and related fields.

He travelled and lectured extensively and organised symposia on the theory of machines and mechanisms in all those academic centres.

Another significant aspect of Prof. Pantelić's career was theoretical elaboration of insufficiently studied issues in the theory of machines and mechanisms which were needed for his technical innovations.

Application of those newly created mechanisms represents the third aspect of his career – undoubtedly its crown, since it has confirmed all his creative visions. An army of young enthusiastic engineers pursuing their dreams were involved in realisation of his projects. Prof. Pantelić offered a chance to all of them – 22 doctoral, 47 postgraduate, and more than 400 graduate students. They all worked towards their degrees in the innovative atmosphere of the Machine Mechanics Institute in Belgrade.

Prof. Pantelić was the intellectual and spiritual leader of his academic community, powerful, friendly, and informal. Working sessions at the Machine Mechanics Institute would start with his brief announcement: "Gentlemen, I signed a new contract, now let's make it happen." Ideas would come pouring in – what needs to be solved, done, connected, and in what way – from students, assistants, and researchers alike, who were all in a creative fever. At the end of a session, Professor would say: "If anything is still unclear or controversial, make the travel arrangements through the secretariat and go wherever they worked on it before, but come up with a solution in 20 days." And then there would be 20 days of hectic racing, sleepless nights, and excitement so much like the first romantic ones. Such was the creative magic of Prof. Pantelić.

But he did so much more.

He showed us there were no unconquerable fortresses; he showed us how to use a hook, how to catch small and big fish; what to wear to a business meeting; where to find the best men's shoes in the world; where to drink the finest espresso; that Volvo launched its Golden Series – small things like that, and so much more: how to enjoy every moment of life; how to sing in the company of friends; he even used to play for us if an accordion was somewhere in sight.

Finally, he directed his patent rights (1968) to the *Lazar Pantelić Foundation* (named after his father) in order to provide scholarships for excellent but poor students of machine engineering. It was indeed an honour to win them, as some 30 engineers who managed to do so still proudly point out (Contract on patents...).

Acknowledgement This text would have been impossible to write had it not been for the years I have spent learning, working, and forming scientific visions under the guidance of my teacher and mentor Prof. Todor Pantelić.

I wish to thank Prof. Pantelić's close friends and colleagues who helped me reconstruct his creative work and ideas (in random order): Prof. Gerhard Boegelsack (TU Illmenau, Germany), Prof. Života Živković (MEF Niš, Serbia), and Prof. Aleksandar Sekulić (MEF Belgrade, Serbia).

The documents I relied upon were mainly from the library of the Machine Mechanics Institute, as well as from the library and the archives of the Faculty of Mechanical Engineering, University of Belgrade. I am grateful to all the librarians and archivists who kindly helped me find my way around while preparing this text.

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Ferdinand Jakob Redtenbacher (1809–1863)

Jörg Wauer, Klaus Mauersberger, and Francis C. Moon

Abstract The rapid development of technology in the twentieth century, especially in the automotive and aircraft industries as well as machine tool and manufacturing engineering, is causally connected to the developments of the scientific principles of mechanical engineering in the nineteenth century. The transformation of mechanical technology from a mainly workshop-based profession into an engineering science, particularly in the area of design of machines and mechanisms, is closely related with the name of Ferdinand Redtenbacher. He was of eminent historical importance for this evolution of mechanical engineering to a technical science in the nineteenth century. Redtenbacher's role as the originator of mechanical engineering as a science in Germany is fundamental and of general interest since the introduction of science into engineering is a "sine qua none" for the development of a powerful high tech industry. As a professor and the director of the Polytechnic School in Karlsruhe, Germany – today the University of Karlsruhe (TH) –, Redtenbacher's influence therefore helped establish the German manufacturing systems engineering even today.

Biographical Notes

At the beginning of the nineteenth century, Germany and Austria were increasingly anxious to establish industries to counter the English manufacturing dominance. This beginning development of capitalist industrialization was accompanied by the

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Fig. 1 Lithograph of Ferdinand Redtenbacher (1809–1863)

institution of technical educational establishments modeled after the founding of the Ecole Polytechnique (1794) in Paris. Among the first polytechnic schools in middle Europe were the Vienna Polytechnic Institute (1815) in Austria and the Polytechnic School of Karlsruhe (1825) in Germany.

Early Years

Redtenbacher's childhood and early teens in Austria fell in the time of transition into the industrial age. The hustle of the iron and steel industry of his hometown, later known as the "Austrian Birmingham", were parts of the surrounding scenery for Redtenbacher, in which he was born into. But it was not the primary factor that became decisive for his later lifework. The ideals of education put forward by Vienna Polytechnic Institute and its director Johann Joseph Chevalier von Prechtl, influenced the young generation in Austria including Redtenbacher.

Ferdinand Jakob Redtenbacher (1809–1863) (Fig. 1) was born on July 25, 1809 in Steyr, Upper Austria. His parents' home was closely connected with the systems of acquisition and economy that had barely changed during the centuries. His father, Alois Vincent Redtenbacher, a scion of an old-established reputed dynasty of business magnates from Upper Austria, had inherited Voith's hardware shop in Steyr. Due to his economic wealth, Alois Redtenbacher belonged to the dignitaries of the small city. The father was described as a bright and likeable person, witty in his views and with affinities to literature and languages to pass them on to his children Alois and Ferdinand. Growing up in this contemplative atmosphere of the Biedermeier period, Ferdinand Redtenbacher had only sparse contact with engineering and technology in his young childhood.

The father wanted Ferdinand to become a merchant. At the age of 10 years he was put into a retail apprenticeship at his uncle's general store in Steyr. For 5 long years, Redtenbacher had to hold out and at the end of 1824 he had finished this first education step. It is difficult to say what these unloved years mattered for the adult intellect. However, it can be assumed that the young Redtenbacher could draw such advantages from this severe time as work discipline and practical understanding.

Besides his job, he took time to learn the basics of technical drawing and mathematics through private study, and this may certainly be interpreted as the first independent act to escape the retail career after the apprenticeship. The skills were definitely helpful and necessary when, after the end of the apprenticeship from January 1825 through September of the same year, Redtenbacher was employed by the building authority of Linz, Austria to draw construction plans and to help take geometrical measurements. Also during this time in Linz, Redtenbacher tried through private learning to come closer to becoming a capable engineer. In the fall of 1825, the free-thinking father let the single-minded son go to take up his studies at the Vienna Polytechnic Institute.

Education in Vienna

During Redtenbacher's time of studying in Vienna, reform of technical education began, but it was far from the result realized by Redtenbacher later at the Polytechnic School of Karlsruhe. However, the schools at that time cannot be compared with the technical universities of today. The Vienna school had an entrance age of 13 years for pupils. The preparatory junior school with its two annual classes, taught the subjects of religion, exercises in good reading, German grammar and style, element and (basics of) advanced mathematics, geography, history, drawing, good writing, Italian, French and the possibility to learn English, Czech and Latin. Only after taking these subjects would the technical section start with further instruction, depending on the career aspirations, in subjects today taught in the departments of mathematics, physics, chemistry, architecture, civil engineering or mechanical engineering. All this was certainly less thoroughly practiced than today but in its great variety and large extent, it was no less exhausting than the study of contemporary engineering.

Redtenbacher was studied not exactly a prodigy at the age of 16 years but, with his deficient elementary education, he faced up to the demands of the school. After successfully passing the junior school he studied technical drawing and design (with Arzberger), surveying and mapping, planimetry, drawing theory of maps, leveling and altimetry, drawing of geometrical layouts and maps, practical measuring (with Simon Stampfer), as well as road construction, hydrology, civil engineering economy, drawing of architecture layouts (with Josef Purkinje). He passed all exams with first-class grades and preference when he finished his engineering study. It is important to state that in the early nineteenth century, a mechanical engineering curriculum did not exist and engineering training was associated with what is called today civil engineering.

A special feature of Redtenbacher's studies in Vienna was that from the first school year, he participated, at his own option, in additional so-called "Tentamina", ceremonial public exams where the professors recognized a small selection of their outstanding students and the results of their work. Parallel to his study in the technical section of the Polytechnic Institute he enrolled at the University of Vienna for courses in advanced mathematics (with Andreas von Ettingshausen) and astronomy (with Karl-Ludwig von Littrow), passing the corresponding exams with excellent results.

The appreciation of bright students by his professors offered Redtenbacher, in 1829, an assistantship in mechanics and machine design. After studying with Arzberger for 2 years, his engagement was renewed in 1831 for a further 2 years. His natural teaching ability exhibited in his tutorials on the basics of machine design, became clearer simultaneously with his methodical intellectual power. Furthermore, he had to teach technical drawing and to sketch machines that were manufactured in the workshop of the Polytechnic Institute for the growing model cabinet. No doubt, the easy-going years of his assistantship represented the real student time in which Redtenbacher broadened his mind, through inquisitiveness and diligence.

In Vienna, Redtenbacher also stated for the first time that there is no real knowledge and no certainty excepting such that could be mathematically founded. In this period, Redtenbacher was also for the first time the co-author of a scientific contribution on a fire engine in a Technical Encyclopedia by Prechtl. From this article, it cannot be seen what portion of it was written by his professor and what part by him. Anyway, it is clearly and coherently written and deals with the technical matter in a thorough manner. These 4 years were accompanied by vacations of hiking trips in the vicinity of his homeland where he also inspected machine technology on route (e.g. the grand pumping station of Berchtesgaden, which delivered the brine over the mountain into the brewery of Reichenhall). He also trained himself in freehand drawing, composed outdoor sketches and started to paint, a hobby which he enjoyed for the rest of his life.

Zurich Appointment

The assistantship at the Polytechnic Institute was limited by imperial statute to 4 years and ran out irrevocably in September 1833. In the spring of 1834, his cousin, Dr. Joseph Redtenbacher, accidentally read of a job posting at the Higher Industrial School of Zurich. Dated April 26, 1834, the 25 year old Redtenbacher was appointed as a lecturer of mathematics and descriptive geometry at the Senior Industrial School, initially for 1 year, then finally as a professor.

The technical equipment and experience vital for Redtenbacher's new position was arranged by the Zurich company Escher, Wyss Cie. which started its business in 1805 as a spinnery, later going on to make manufacturing machines for spinning works in its workshop and, since 1836, changed over to the construction of steamboats and locomotives. The head of the company, Hans Caspar Escher, gave Redtenbacher the room to do multi-purposed and comprehensive tests to collect and to separate such data important for the practical daily work that became the starting point of all his subsequent publication activities. His results relating to mechanical engineering were so successful in the Zurich period that Redtenbacher purposed his first publication. However, the emergence of turbines instead of classical water wheels halted his work. Redtenbacher therefore first turned intensively to this new type of power engine, which then became the topic of his first book (in Karlsruhe) before his later work on water wheels and the general principles of mechanical engineering.

Redtenbacher's acuteness of mind grasped many helpful suggestions and practical experiences and amazing theoretical approaches for problems in machine technology. The factory of Escher-Wyss, under the influence of superior English technology with the leading engineers and technicians coming from England, guarded their know-how, which acted as a challenge for Redtenbacher. He wanted to strip off this knowledge secrecy and to place mechanical engineering as the foundation of new scientific principles. However, his main activities were focused on the school. In Zurich, Redtenbacher started thinking about the nature of the engineering school system which constituted the essential part of his lifework along with his scientific publications. Thus, it seems that the nearly 8 year-long restless occupation in Zurich constituted an important waystation for Redtenbacher's career. It let him mature and broaden his mind beyond mechanical engineering. The high reputation which he acquired very quickly brought him membership of the local association of Natural Science in 1834 and spread his reputation beyond Zurich. A token of increasing appreciation was, for example, the corresponding membership in the Lower Austrian association of industry in 1841. In Zurich, he also set the course of his private life: In 1836 Redtenbacher became engaged to his cousin Marie Redtenbacher and married her 1 year later. They had two children, a daughter Marie and a son Rudolf, to whom posterity owes a very informative biography (Redtenbacher 1879) of his father.

Appointment at Karlsruhe

In 1840, Redtenbacher received a call from the Polytechnic School of Karlsruhe. The basic concept of the new institution at Karlsruhe, the first of its kind in Germany, was to integrate the scientific and mathematical basics of engineering competence as an organic unity as part of the Polytechnic schools. The reform in 1832 enforced by Karl Friedrich Nebenius, merged the Civil Engineering School founded by Tulla, the Architectural School tracing back to Weinbrenner, the Industrial School initially domiciled in Freiburg, the School of Forestry, the Trading School and, above all, the Post School. Under Nebenius, the unity of these technical schools, on a unified basis with the preparatory had been much more elaborate than what was first formed when the Polytechnic School was founded in 1825. He had created a type of school somewhere between a grammar school and a university also spatially separated, possessing senate constitution, annular director election by the professors and featured an organization close to a department system of current universities.

Karlsruhe, the capital of the state Baden, with its 25,000 inhabitants, became the permanent home for Redtenbacher. By ministerial resolution of October 13, 1841, i.e. at the beginning of new school year, Redtenbacher was appointed as professor within the Mechanical Engineering Department. It was obvious that Redtenbacher was keen to play a part in Karlsruhe but, at the same time, to get flexibility and space for development to advance the school by pursuing the vision of his progressive concepts.

The subject of Redtenbacher's concern was the senior industrial school. When he started there, it was the technical section that was least developed of all and encompassed the same course of instruction in both engineering chemistry and mechanical engineering. There was no question that it was not mechanical engineering on a scientific basis. Everybody who was interested in becoming a mechanical engineer at that time, normally started with practical training. The industrial school taught theoretical knowledge quite apart from practical experience. One was content to become acquainted with machine elements, studied descriptions of machines and models of them. Dimensions were expected to be given by experience or were modified by empirical trial-and-error methods in the workshop. Strength calculations based on ideas of stress and strain were practically unknown.

During the 1830s of the nineteenth century, and also at the industrial section of the Polytechnic School of Karlsruhe, instruction primarily took place in the workshop in a handicraft-like fashion. Within a few years, Redtenbacher created a fundamental change in this type of education.

Considering the situation of industry in the German state of Baden at that time, the endeavor described in such a manner, at the beginning of Redtenbacher's tenure in Karlsruhe was definitely challenging for him. It is to Redtenbacher's credit that he introduced scientific methods in his lecture as a young 30-year old professor. The scientific treatment of practical engineering problems seemed to Redtenbacher to be not only more economic but also less erroneous than an investigation based on experience. At the same time, Redtenbacher knew that technical education was not sufficient with pure sciences alone, without attending to practical successes.

Herein, Redtenbacher differed from most Paris professors at Ecole Polytechnique. His lecturing was eventually directed to practice. What he had learned rudimentarily as a young student at the Vienna Polytechnic Institute, and what he had taken on as a successful link between science and application from the scientific work of the French polytechnician Jean Victor Poncelet (1826/1838) for his studies on water wheels and turbines during the Zurich time, was now combined by Redtenbacher into a far-ranging, coherent concept. Thus, the bottom line was to bring together both the education carried on by scientific study and practice. Therefore, Redtenbacher in 1846, began to separate the mechanical and the chemical program at the Industrial school into two single programs and in addition to the existing chemical laboratory, he installed a separate machine laboratory. Only after this step was mechanical engineering constituted as an independent department. This was the starting point for mechanical engineering under Redtenbacher and applied chemistry under Carl Weltzien for development into two autonomous and strong departments of international standing.

The fame of the mechanical engineering school of Karlsruhe propagated very fast. From everywhere, the prospective students came for an education at the Karlsruhe Polytechnic School in the mechanical engineering section under Redtenbacher. The number of students increased and at the zenith, Redtenbacher had 359 attendees, where 227 of them were regular students. After a while, Redtenbacher's work governed the scientific standard of his school. Accordingly, in 1857 he was elected as director. Under his directorship, the Karlsruhe Polytechnic School achieved international standing and was a model for the formation of other schools or re-organizations at home and abroad. As noted before, he received several calls from other institutions but he rejected them all. At the beginning of 1850, he received a call from the Austrian Department of Commerce with an offer of the directorship of a company which was the leading establishment of the Austrian railroad. About the same time, Redtenbacher received a prestigious offer for a professorship at the Royal Industrial Institute of Berlin. There were negotiations by letter over a long time, but on October 3, 1850 he decided to remain in Karlsruhe. On August 20, 1854, Redtenbacher also received an exceptionally prestigious call from the president of the Swiss education council, Dr. Kern, for a new professorship of mechanical engineering at the Swiss Polytechnic School of Zurich. It was planned that, under a generous general framework, Redtenbacher should not only undertake the direction of the mechanical engineering section but would participate in the organization of the whole school including the hiring of professors. Working conditions for Redtenbacher in Karlsruhe were already good before these recruiting calls, and the convenient life for him and his family in Germany (the economic situation obviously was further improved and he became privy counsellor so that in the future, some unpleasentnesses he could avoid) again caused him to stay. It must have given him the strongest satisfaction that for the internal organization of the Zurich school, Karlsruhe was taken as the prototype.

According to Redtenbacher's suggestions, the pre-school and the first annular mathematical course and also the Trade School, the Post School and the School of Forestry were abandoned. Instead, a Mining school was founded and philosophy, history, national economy and business, political science and law were included in the curriculum, besides literature and science which had been incorporated long before. The so-called "Education to Industry" already attested in the sense of Friedrich List by Karlsruhe's historian Franz Schnabel, was strongly promoted by these measures.

After the relocation of mechanical engineering in the new building was carried out in 1860, Redtenbacher was at the zenith of his productive life. By establishing humanities, a deeply felt desire of Redtenbacher had come true. Teaching the subjects of humanities at the Polytechnic School meant neither decoration nor luxury, they were a part of the technical studies themselves. What Redtenbacher demanded, or at least expected from his students, with respect to general education essentials beside the usual technical study, he did not excuse himself from either. He did not give up his artistic intentions in painting, music, theatre, poetry until his last years. In connection with his own research, he was inspired by the classical French mathematicians who were seen far above all their contemporarities, especially the English who focused more on practice. The logic and the methodologies of French science were the closest to his heart. From Justus von Liebig he learned to grasp beyond chemistry into adjoining areas. Kuno Fischer who was a recognized philosopher in Jena, gave him an understanding of the newer philosophy, from which he studied Kant and Hegel as well as the much noticed main opus of Hermann Lotze, “Micro Cosmos”, and the writings on aesthetics by Friedrich Theodor Vischer. In addition to all the time-consuming teaching and adminstration work and his own literary activities, he even got round to the reading of contemporary historians.

To his admirable self-discipline that he mustered during his studies, during his later years there was added an authoritarian rigorousness towards particular lecturers who became obstinate and were not inclined to follow his plans. He was not always a congenial colleague. He never made a secret of his convictions and he could mercilessly pack a punch in a faculty meeting when mediocrity and small-mindness emerged and when people clung to out-of-date and bureaucratic regulations instead of pursuing the objective requirements. All the time, however, he was backed up by the state authority which was needed to push through his reforms with both meticulousness and impatience against restrictions and obstructions of all kinds, sometimes surely with a good deal of obstinacy as well. Self-willed traits emerged when, for the school year 1861/62, there was simply no re-election of the director – since 1857 year after year, the faculty meeting had voted for him – but he directly pursued his official duties because, to his mind, it would be in the interest of the school to eliminate the previous annular director election by the lecturers of the school by a director appointment for life. The ministry had this opinion of Redtenbacher to prolong his directorship for life which was not explicitly confirmed but condoned and did not urge a re-election. Though some colleagues grumbled, they hesitated to undertake actions against this infringement of their perceived rights, especially because Redtenbacher was at this time starting to be troubled with a stomach illness which developed little by little into a deadly disease. Despite his malady, Redtenbacher still continued his classes during the whole school year 1861/62. In the fall of 1862, after a recuperation journey which should bring recovery, the illness exacerbated such that he had to cease lecturing at Christmas 1862 and also resign the directorate. On April 16, 1863 he silently departed this life blessed by restless work and great success.

These biographical notes, which are a shortened version of Wauer et al. (2008) substantially follow Mauersberger (1989a) and Fuchs (1959) with regard to personal biographical details by Ferdinand Redtenbacher himself (Bader 1858), as well by historical appraisals in Mauersberger (1980, 1985) and Schnabel (1925 and 1938).

List of Works

Theorie und Bau der Turbinen und Ventilatoren, 1844
Theorie und Bau der Wasserräder, 1846
Resultate für den Maschinenbau, 1848
Prinzipien der Mechanik und des Maschinenbaus, 1852
Die Luftexpansionsmaschine, 1852
Die calorische Maschine, 1853
Die Gesetze des Lokomotivbaues, 1855
Die Bewegungsmechanismen, 1857
Das Dynamiden-System. Grundzüge einer Mechanischen Physik, 1857
Die Bewegungsmechanismen, neue Folge, 1861
Die ursprüngliche und jetzige Temperatur der Weltkörper, 1861
Der Maschinenbau, 3 Bände, 1862–1865

Review of Main Works on Machine Science

Within the limits of this contribution, it is hardly possible to completely do justice to Redtenbacher's groundbreaking scientific work; it is too voluminous, too manifold in content and so broad in its scope. Lasting results concern the institutional establishment of mechanical engineering as a science and the formulation of trend-setting methodical design principles. They represent the German way to find a synthesis between the workshop-oriented English technical education close to practice and the highly theoretical machine science of French provenance. Above all, there was the final goal to combine theoretical knowledge, especially of mechanics, with extended practical experience in an appropriate manner. Within this approach, the intention was perceived to extend the brilliant successes of analytical mechanics, in particular to predict the planetary motions. Bearing in mind the fact that machine motion is dictated by terrestrial effects, Redtenbacher aspired to incorporate friction, impact restitution forces and other "noise terms" in a scientific method for predicting the behavior of machines. This could be accomplished not only through reliable knowledge of the mathematical-scientific fundamentals but also through firm workshop experience know-how.

As much as he planned to apply scientific methodology ideals, he did not forget the empirical basis of technology. Intuitively, he developed his knowledge stepwise and started both with the exploration of determinant phenomena and with the examination of different types of machines. In his opinion, every science should begin with induction and end with deduction. His debut publication was in 1844, a book on "Theory and Construction of Turbines and Ventilators" (Redtenbacher 1844), second edition 1860, followed 2 years later by "Theory and Construction of Water Wheels" (Redtenbacher 1846), second edition 1858. This unexpected order had essentially no technical reason. In a letter from his publisher Bassermann of

Mannheim (August 30, 1844), we learn that the "Water Wheels" at that time were ready to print but there was a time lag due to the time consuming production of 30 lithographic tables. Much of the material for both treatises can be traced back to his Zurich time and the collaboration with the company Escher-Wyss, but it was also advanced by study trips 1842 to the industrialized Alsace, 1843 down the Rhine till Cologne, in February 1844 to the Baden Black Forest and in August 1844 to Amsterdam and Haarlem via Cologne, back via Belgium (Figs. 2 and 3).

In the creation of new machines, conventional technical knowledge and the inherited wealth of workshop experience often failed. Therefore, analyses as exact as possible had to be found, in particular for further advancement of such machine innovations. In exemplary form, Redtenbacher tackled the problem. Even though, in the case of turbines, for example the constructions of Fourneyron, Jonval or Schott, seemed to be designed in all details but with respect to limited water resources, there was a need to look for an increase of power or a reduction of energy losses. Additionally, there was the demand for specific dimensioning rules depending upon the application and to harmonize the power requirements with the driven machinery. By his detailed calculation rules based on fundamental hydrodynamic balance equations, Redtenbacher helped to overcome tentativeness in launching such driving aggregates and presented lasting, acceptable construction standards for them.

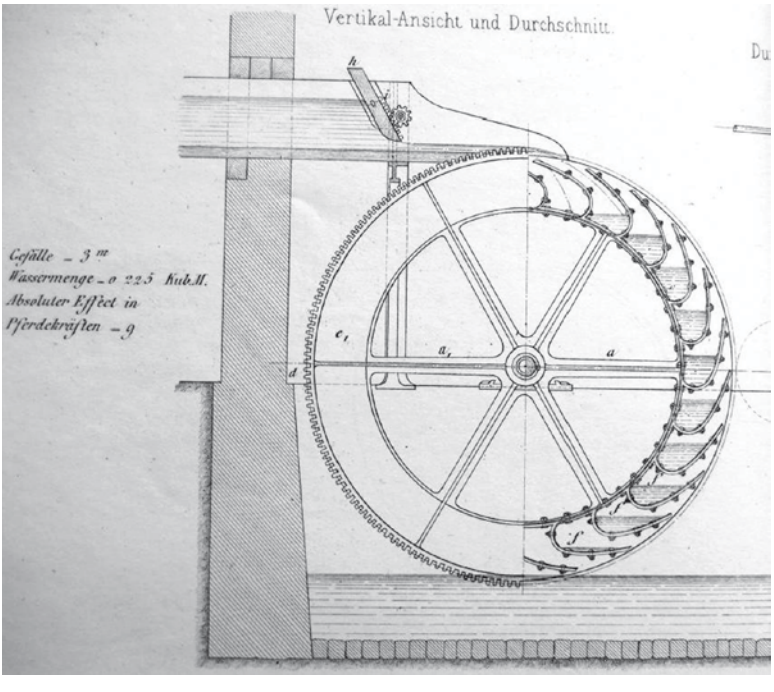


Fig. 2 Water wheel design of Redtenbacher

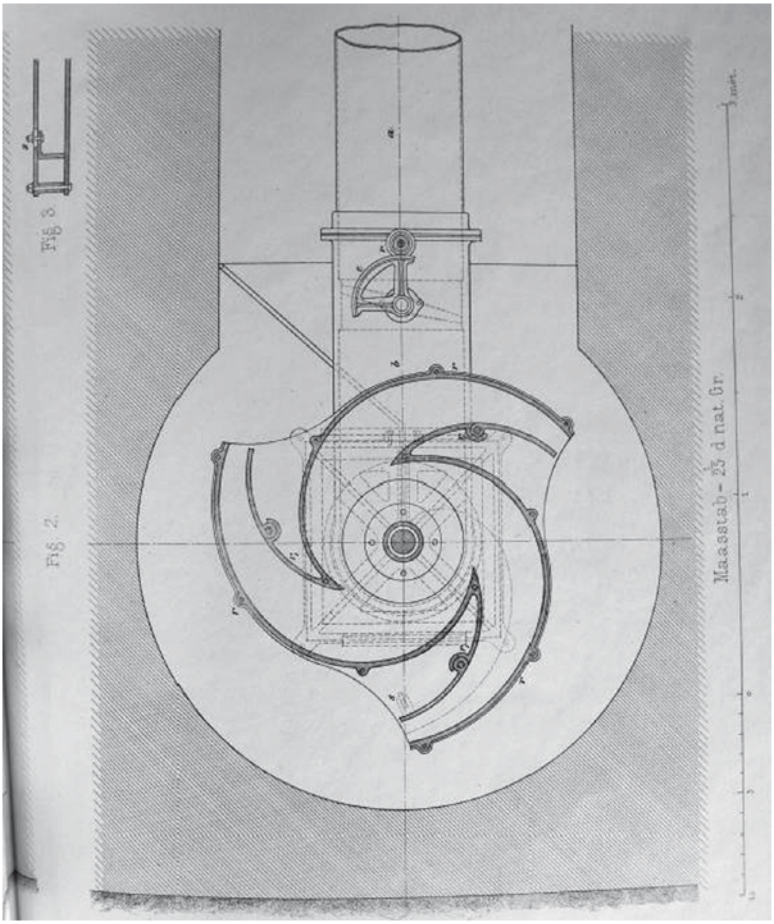
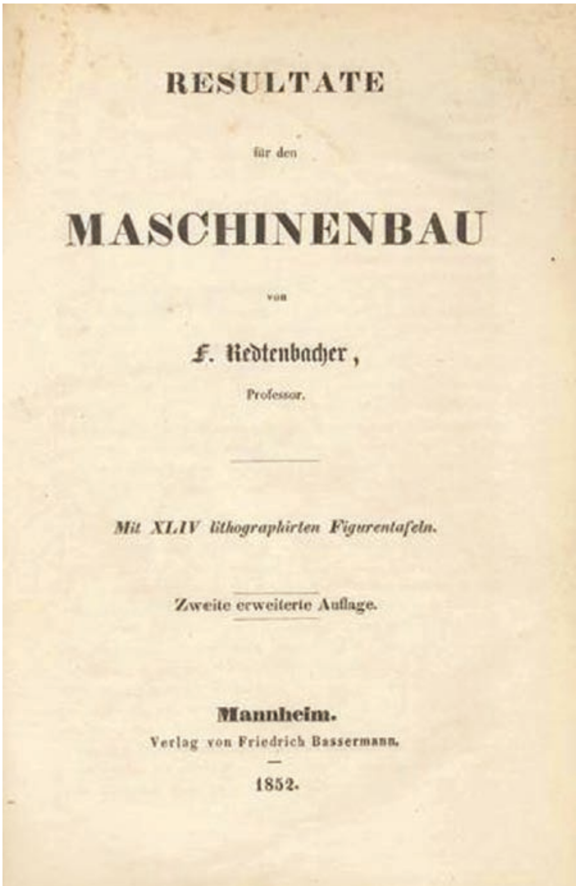


Fig. 3 Water turbine design of Redtenbacher

Moreover, he showed, by comparing issues regarding energy aspects, the advantages and drawbacks of the different designs.

In a report strongly structured according to basic scientific principles, he succeeded in coming up with such effects and to take into account such economic-technical determinants not yet exactly computable in the sense of confirmed scientific knowledge. In this way, Redtenbacher's understanding of sufficiently accurate approximation results was formed to bring them through further research experiments, step by step to a higher level of generality and closeness. Of course, the analytical machine theory vis a vis the French deductive method, was still in its infancy, and there were still too many unknowns in the knowledge basis of the young engineering sciences. For the time being, only use of well-proven technology helped. Recourse to a reliable reference book was among the popular instruments in engineering during that time, as is still true today.

The completion of a design reference book was realized by Redtenbacher in 1848 in his most popular work "Results for Mechanical Engineering" (Redtenbacher 1848) (see Fig. 4) a real manual for students, practically working engineers, designers and industrial managers likewise. It had four German editions and one French edition in his lifetime and two other German ones posthumously. In this work, he presented all those tools and rules in a half-empirical manner, multiply tested and well-established for the practical applications to be indepensible for a beneficial design. He referred therein to accepted standards to dimension all essential machine elements such as gearwheels, pulleys, chains, screws, cables and belts, journals, shafts, rivets and bolts, linkages, stuffing boxes and pistons and transferred them to other scales. This "method of ratios", once borrowed from architecture and, already applied during the time of James Watt, was an elementary method of calculation characterizing scientific mechanical engineering during the early stage of the field.


RESULTATE

für den

MASCHINENBAU

von

F. Redtenbacher,

Professor.

Mit XLIV lithographirten Figurentafeln.

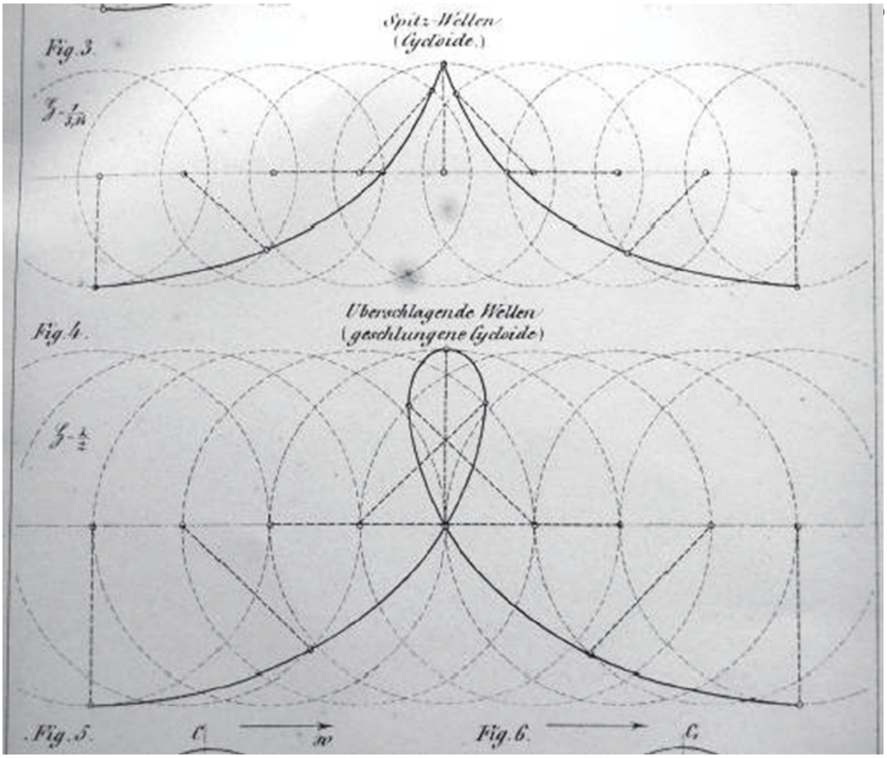
Zweite erweiterte Auflage.

Mannheim.

Verlag von Friedrich Bassermann.

1852.

Fig. 4 (**a**) Book facing page "Results for Mechanical Engineering". (**b**) Cycloid mathematical curves from "Results". (**c**) Kinematic mechanism design from "Results"



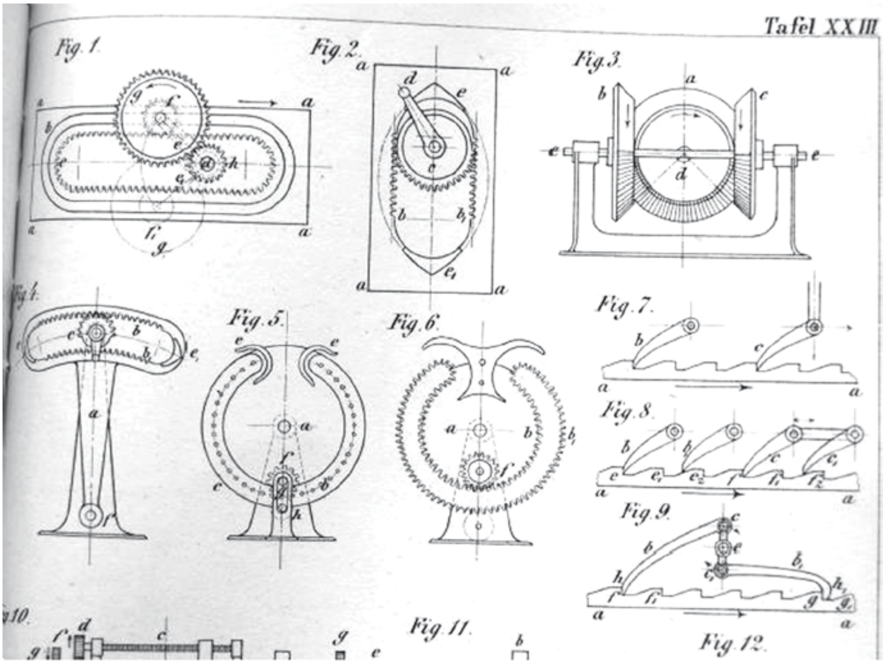


Fig. 4 (continued)

Besides Redtenbacher, the French polytechnician Artur Morin had succeeded cultivating this calculation type theoretically and using it as a practicable tool. Its publication motivated Redtenbacher, for the most part, to retreat from his high scientific ideals but it corresponded to the actual needs of mechanical engineering to have available a large variety of new mechanisms and design concepts for power and work machines fully functional in the developing industry. It helped to define mechanical-constructive orientation of the machine design.

Mechanics was omnipresent in Redtenbacher's work: "All-around where something budges, mechanics has a finger in the pie but the spirits do not stir by mechanics", could be read in the 1856 caption of a Redtenbacher portrait. During his time in Zurich, Redtenbacher had indicated that he was not interested in leaving design to half-empirical recipes. Already, his objective was aimed at a machine science that would match the achievements of modern mathematics and mechanics. The French experts of mechanics were so highly distinguished in his mind that their shining example inspired him to emulate them. He had manifested, for a long time, the desire to comprehend the machine problems totally in their highest generality.

His scientific ideas were published in 1852 in the book "Principles of Mechanics and of Mechanical Engineering" (Redtenbacher 1852a) (see Fig. 5). This became a

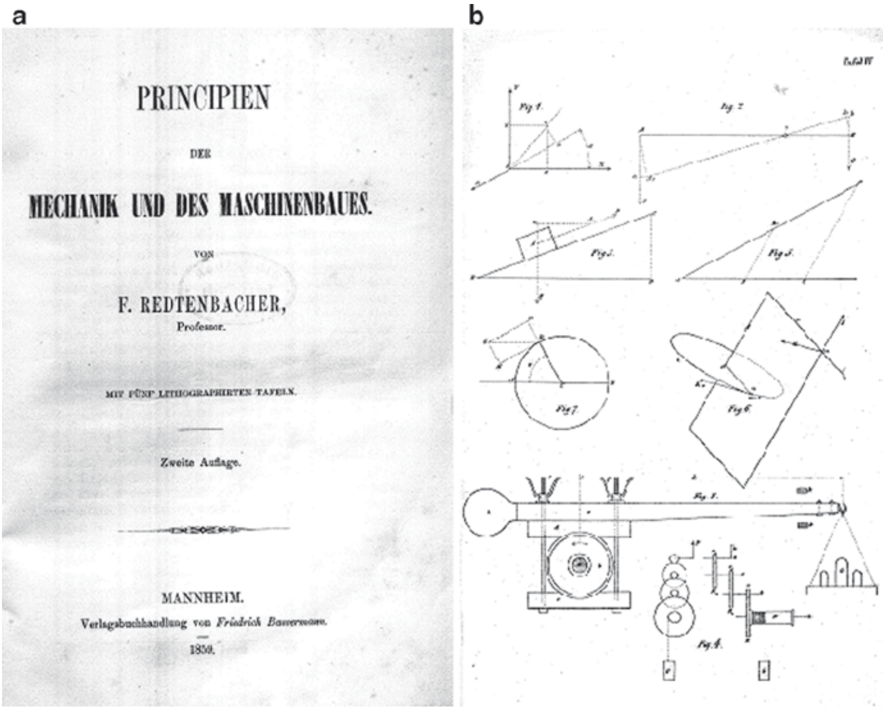


Fig. 5 (**a**) Book facing page "Principles of Mechanics and of Mechanical Engineering". (**b**) Drawings of equilibrium problems from "Principles"

principal part of his machine theory and a milestone in composing technical-scientific theories. In the book, he compellingly developed the modeling ideas for the design of a machine. With a consequent orientation to the interactions of technical function, constructional shape forming and economic feasibility, he broke new ground in design methodology. Consequently, he incorporated that vocabulary which had already heralded a specific dynamic-energetic dimension of approach under the French triumvirate Louis Marie Henry Navier, Gustave Gaspard Coriolis and Poncelet, starting with Charles A. Coulomb and his theory of simple machines during the second half of the eighteenth century. Work, energy and efficiency factor were among the main properties within the structure of categories of his machine theory, where he always tried to explain the context descriptively. By avoiding cumbersome mathematical expansions, straightforward and applicable procedures were his ultimate goal. Herein, the specific usefulness of technical coefficients outcropped, e.g., describing the strength behavior of machine elements made of metallic material or concerning the outflow of fluids from containers or reservoirs but also such geometrical properties of shape and cross-section tabularly ascertainable as moments of inertia, etc. Such comparisons gave directions to the engineer for an effective design.

Redtenbacher's approach was captured in a systematic method that was based on the machine's type of motion – changing the position and deformation of machine parts led to the determination that beneficial layouts and culminated in an analytical machine theory. Its framework was geared to a technical–economic optimal solution, the essential determining properties were then represented by a set of primary and secondary equations. With respect to the purpose of the machine and the technological process, considerations were finally given to the dependencies between the constructional elements and their technical functions. This part of Redtenbacher's procedure to design machines is the one that is based the least on scientific principles but on economic, industrial and societal issues. Here mechanical design practice totally dominates.

With the development of mass production, scientific mechanical engineering became more intensively devoted to the manufacturing processes. The temporary priority of the design process as an object of scientific examinations was emphasized by the key role which Redtenbacher attributed to technical drawing. Despite all specialization, he still considered engineering activities as an organic procedure, also involving a certain artistic creativity. The recognition that the design abilities of technicians as well the aesthetic appeal of their product were part of the process began to emerge within the evolving engineering sciences. The use of aesthetics in machine design was later embraced by Redtenbacher's student Franz Reuleaux (see, e.g., Moon 2007).

Redtenbacher saw the conscious use of engineering thinking as an expression of human power, and a chance to create a bridge between nature, technology and society and, furthermore, a basic approach for a reconciliation between the differences of the neo-humanistic and technical education. The psycho-emotional moment in the process of an original design became a central part of the inventive process of an engineer as well as the basic principles of mechanics.

Redtenbacher believed that, among the important virtues of a mechanical engineer, should be an artistic nature, including phantasy, play instinct, artistic abilities and virtuosity. Incidently, he felt that technical drawing would considerably advance keenness and clarity of thoughts of an engineer. Without it, many a trend-setting idea might be pushed ahead of its time, many a keen approach could not completely be realized. The use of descriptive geometry and technical drawing was introduced by Gaspar Monge of the Ecole Polytechnique showing again the French influence on Redtenbacher.

On the one hand, advances in the theory of machine sciences were so notable that they were beyond the means of the engineering practice, on the other hand, there were huge gaps of knowledge in such elementary problems as lubrication, tightness or fit accuracy of machine components. Increasing the speed rates and the pressure as well the enlargement of the reciprocating masses were other factors accounting for such discrepancies between theory and design rules. Only the next generation of engineering scientists could overcome the hiatus between program and reality. Nevertheless, Redtenbacher tried to verify his guiding principles during the fifties. By his essay "The Air Expansion Machine" (Redtenbacher 1852b), which was already published as a second edition in an extended form and new title "The Caloric Machine" (Redtenbacher 1853) 1 year later, he could manage a validated conformation of his conceptions from Redtenbacher (1848) in a original format. Using the example of Ericson's air expansion machine, a strange forerunner of the combustion engine and strongly debated in the literature, Redtenbacher – surely knowing the contributions of the French polytechnician Sadi Carnot – raised the question on the perfect motor. During that time, the thermal behavior of heat-power engines came more and more the vision of the engineers. Increasing the power by higher cylinder pressures and temperatures, multi-utilization of steam, minimal fuel consumption and advantageous arrangement of the thermal process were the focal points of many scientific debates.

In contrast to his student Reuleaux, Redtenbacher's contribution to machine theory therefore moved into the forefront of technical thermodynamics. Starting with fundamental considerations in which, strongly following his principles, he formed a theory of an effective hot air engine, he optimized its main parameters. However, the problem was not yet completely solved and he addressed the key question of the practicability under which the required high temperature gradient brought back down to earth all speculation to exceed the limits of the classical steam engine. With less resonance, the work "Laws of the Locomotive Construction" (Redtenbacher 1855) was addressed in 1855, even though there was an urgent need for such a book of rules. Railroad construction had been a catalyst for the growth of powerful machine factories. The novelty and complexity of this technical system required scientific principles and from March 1854, he declared in several letters that this technology, driven by the English with their long empirical knowledge, would require a scientific basis. He thereby entered the new field of interia forces, vibrations and impact loading, but was not able to cope with the complex driving system, called a locomotive, in all details. Critical comments by experts in this field could not be ignored.

His series of books was extended in 1857 by the contribution "Motion Mechanisms" (Redtenbacher 1857a), a book of detailed designs for models of kinematic mechanisms. In 1861, it was expanded by a new issue (Redtenbacher 1861a), to be collected in 1866 as one volume (see Fig. 6) which essentially presented and explained the teaching model aids collection of the mechanical engineering section constructed in the workshops of the Polytechnic School under Redtenbacher. These models (see Figs. 7 and 8) supported his lectures to the professional community from models of a simple pair of wheels or a slider crank mechanism through kinematic models of the complex non-uniformly transmitting gear boxes.

a


DIE

BEWEGUNGS-MECHANISMEN

Darstellung und Beschreibung eines Theiles der

MASCHINEN-MODELL-SAMMLUNG

der polytechnischen Schule in Carlsruhe.

von

F. REDTENBACHER

Großherzoglich Badischer Hofrath u. Director an der polytechnischen Schule in Carlsruhe.

Neue Auflage.

Mit 80 lithographirten Tafeln.

HEIDELBERG

VERLAGSBUCHHANDLUNG VON FRIEDRICH BASSERMANN.

b

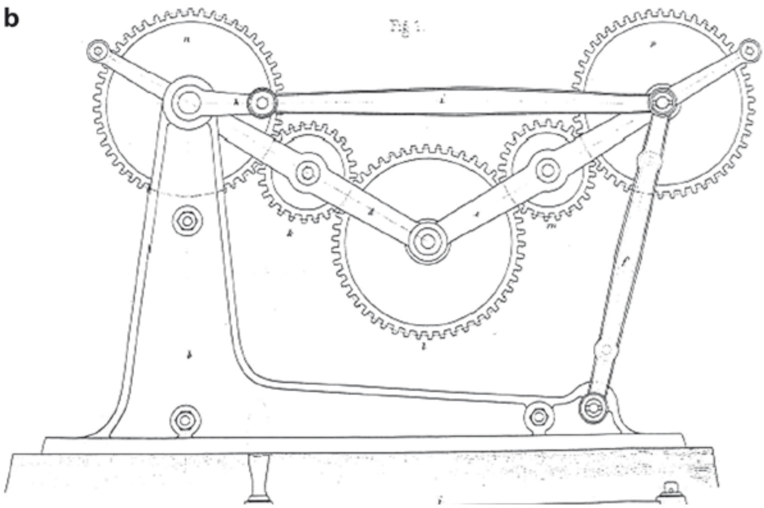


Fig. 6 (**a**) Book facing page of Redtenbacher's "Motion Mechanisms". (**b**) Drawing of gear train mechanism from "Motion Mechanisms".

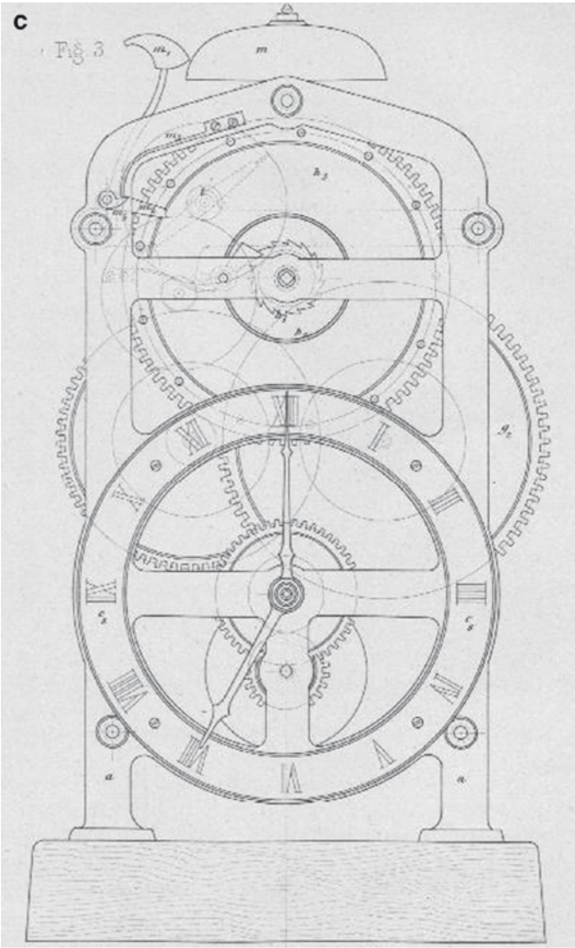


Fig. 6 (continued) (**c**) Drawing of gear train mechanism from “Motion Mechanisms”

Again and again, Redtenbacher was interested putting his explanation of the interaction between nature and technology on a consistent basis. Such wide-ranging thinking permanently inspired his research activities and led him to a complex and variable methodology. His world picture was particularly rooted in the predictability and in the logical precision of classical mechanics. Redtenbacher, who contemplated writing a history of mechanics, picked up nature-philosophical discussions and tried to translate them into a technical-scientific question. His intentions in 1857 culminated in the presentation of his opus “The System of Dynamides, Main Features of a Mechanical Physics” (Redtenbacher 1857b). What he already had implied in his “Principles”, here it attained the most mature expression: an attempt

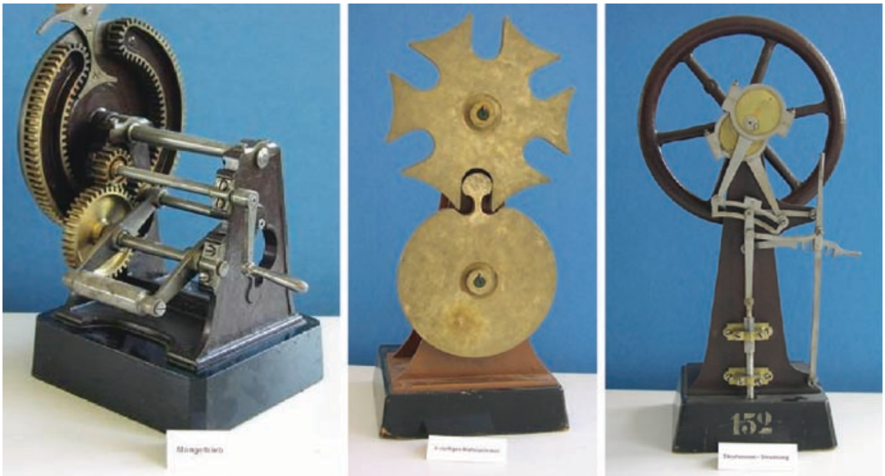


Fig. 7 Photographs of kinematic models from the Redtenbacher Model Collection of Karlsruhe University. (**a**) Reciprocating gear mechanism. (**b**) 6-part Geneva wheel intermitted mechanism. c. Stephenson valve gear mechanism

to yield a contribution to the scientific and philosophic progress of knowledge. Therefore, evidence of the theoretical influence of the flourishing technical-scientific thinking should be furnished. In the process of fermentation between different concepts of nature which loomed in the course of the accomplishment of the classical physics, Redtenbacher's contribution to continue the thoughts of Dalton Poisson and Augustin Louis Cauchy was an attempt to match the existing atomistic molecular-theoretical models with the specifics of technical-scientific styles of thinking. The center of his ideas were the so-called "Dynamides", i.e., body atoms with its enclosing aether hull, he aspired to explain graphically the connection between micro- and macro-cosmos, a venture which must fail on the mathematical explanation of complex processes of aether oscillations. By this "System of Dynamides" which was denoted a patchwork theory by Redtenbacher – obviously he appreciated the deficiencies of his constructs – he wanted to set a marker to bring forward – beyond the attempt to the self-image – the acceptance of the status of engineers. In this respect, the book had deserved broader attention from his contemporaries, especially as it dealt with important ideas in physics, e.g., such of James Clerk Maxwell. His affinity to natural-philosophical topics was expressed in 1861 a second time in his work "The Initial and the Actual Temperature of the Heavenly Bodies" (Redtenbacher 1861b). Both books are important in understanding the broadness of Redtenbacher's scientific work, but for the development of machine science, they are contributions with no impact.

Obviously, several factors came together to inspire Redtenbacher's final masterwork "Mechanical Engineering" (Redtenbacher 1862). As Redtenbacher himself explains in the preface to the first volume, the complete three volumes should summarize the essentials of all his lectures on mechanical engineering at the Polytechnic

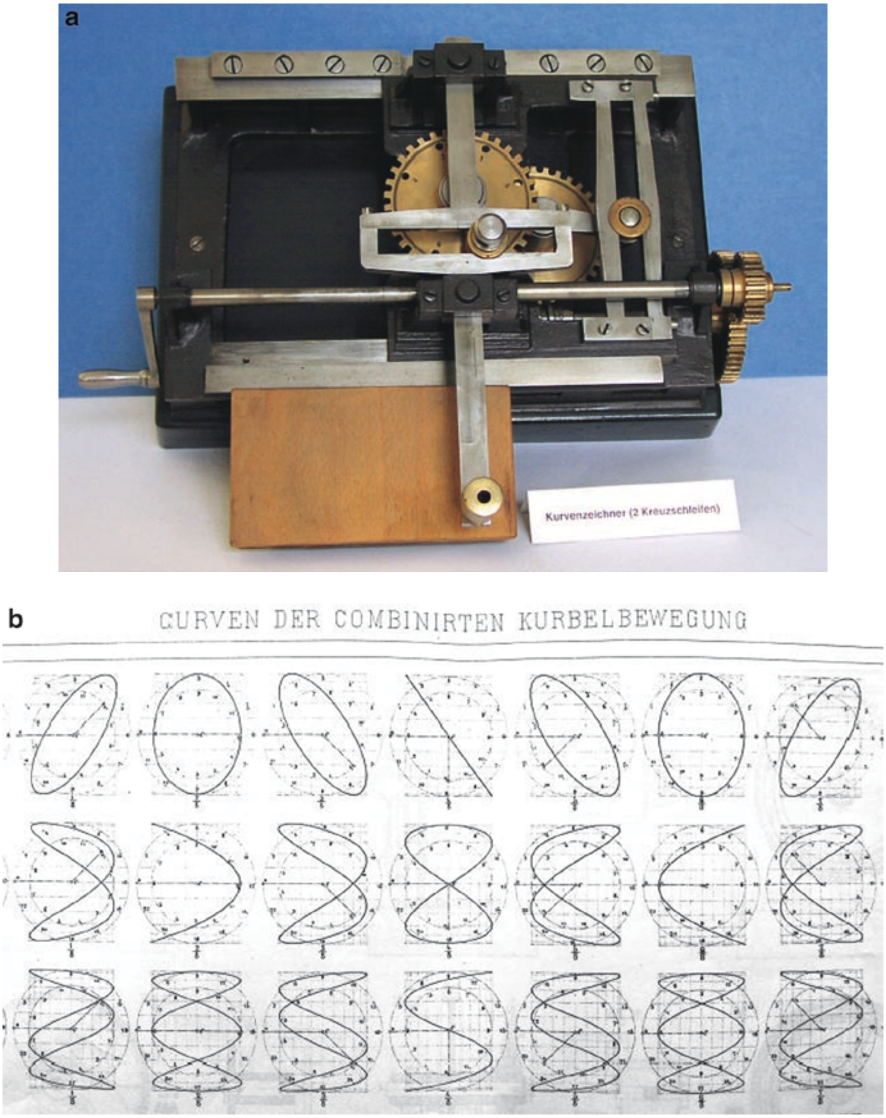


Fig. 8 (**a**) Photograph of kinematic model of a function synthesizer from the Redtenbacher Model Collection of Karlsruhe University. (**b**) Lissajous curves drawn with Redtenbacher's kinematic function generator

School of Karlsruhe. "This work composes for all students of mechanical engineering the bridge between the other works which I have published many years ago, namely the 'Principles of Mechanics and of Mechanical Engineering' and the 'Results for Mechanical Engineering'. The present work shortly called 'Mechanical Engineering' essentially is the derivation of the results from ‘Principles’ for application. This means that the ‘Principles’ are a general formalism describing what the essence of every machine is, how the motions and operations work, what conditions influence the machine and how these constraints can be traced, what ideas are important in order to develop the design to a real machine that functions in practice. With one word: The ‘Principles’ try to tell and to teach everything what is necessary for understanding, for design and for realization of machines, i.e., the ‘Principles’ are the general machine science which is taught within the first three months of engineering study. On the other hand, ‘Mechanical Engineering’ is intended to teach all specialities which are necessary for practical realization of all general principles and treats a series of concrete work and power machines.” But Redtenbacher’s desire to write this summary work, however, was urgent due to the misus of his ideas by others and the exploitation of his lectures. The final statement within the foreword to Volume 1 states explicitly “that the publisher already often was impelled to intervene against this circulation of my work and that hopefully this misapplication will not happen again in future”. Only the first volume was published in Redtenbacher’s lifetime. Volume 2 was ready to print when he died, volume 3 was finished according to available notes by his co-worker Josef Hart; the publication took place in 1865.

Following the intentions mentioned, the first volume spanned a wide selection of topics including strength of materials, design of machine elements, friction in machine elements, kinematics of mechanisms, clock escapements, and the design of construction cranes. His second and third volumes cover hydraulics, water wheels and turbines, locomotive design, steam engines and mining machines. The structure of the text consists of short descriptions of each topic, many formulas, some derived using differential and integral calculus, and a few line drawings at the end of each volume.

On the Influence of Redtenbacher’s Works

For the evolution of mechanical engineering in central Europe from its workshop-oriented tradition into a science, Redtenbacher’s three books “Results”, “Principles” and “Mechanical Engineering” composed a type of comprehensive framework. To understand concrete applications, the publications “Water Wheels”, “Turbines” and with some restrictions “Caloric Machines” and “Locomotives” are useful, too. To understand how Redtenbacher taught his students, explaining to them theoretical and methodical connections with the use of real models, the book “Motion Mechanisms” had additional significance. Therefore, these works will be included in the following discussion.

The influence and the renown of Redtenbacher’s works were already wide spread during his lifetime. Six German editions and an additional French edition (from 1848 through 1875) of his most popular work “Results” as well three editions of “Motion Mechanisms” (between 1858 and 1866) give evidence for his wide reputation. In addition, there were two editions of “Water Wheels”, “Turbines” and the “Principles” while, on the other hand, there was only one edition of the large three-volumed comprehensive work “Mechanical Engineering”. The latest edition of “Results” edited by Redtenbacher’s successor, Franz Grashof, in 1875 was in the library of the well-known American engineer-professor Robert Thurston of Stevens Institute and later Cornell University, i.e., Redtenbacher’s work also circulated in America as well as in Germany and France. We can obviously conclude that practical handbook knowledge, rules of thumb and tabular results were most important for engineers and technicians during that time of early industrialization. But even nowadays such collections of scientific and technological facts in a short form without proofs are very important for students and practicing engineers as compendia as “Hütte” or “Dubbel” show. And a comparison with the early editions of “Hütte” in the nineteenth century verifies that it was definitively based on Redtenbacher’s “Results”.

The design experience represented by his precise technical drawings one can find both within the “Results” and also the tables accompanying the text of “Motion Mechanisms”, and are a further step in the didactic realization of the practical-mechanic knowledge of his time. Machines and their components were visualized in all details where the machine elements and even the motion of mechanisms were displayed in their statical and strength constitution. The kinematic principles that governed machine engineering was the typical style of the French Monge school in which they demonstrated the conversion of motion and represented a catalog of mechanisms for intuitive selection of proper gear shapes for example. It was far away from a modern mathematical–geometrical analysis or even a synthesis of such units.

Redtenbacher’s Kinematic Models

There is evidence that Robert Willis used such models as early as 1840 in Cambridge, as did Johann Andreas Schubert at Dresden around the same time (see, e.g., Moon 2003a, b, Mauersberger 1989b, 1997). Likewise, Redtenbacher developed one of the most extensive model collections of his day at Karlsruhe with as many a 100 different models which was only surpassed after his death by his student Franz Reuleaux at Berlin. Most important for the evolution of mechanical engineering is the fact that Redtenbacher documented the construction of these teaching models in his two monographs. This offered an opportunity for others to copy these models as did a famous commercial model-maker of the time, the Schroeder Company of Darmstadt. Unlike Reuleaux’s original 800 model collection at Berlin that was destroyed in World War II, the Redtenbacher Collection is remarkably preserved at the University of Karlsruhe. Recently, has become the entire collection available on the web, appropriately alongside the Reuleaux Collection, at the website KMODDL (http://kmoddl.library.cornell.edu). Reuleaux’s designs for models survived because he set Gustav Voigt to copy and make reproductions of around 350 of his models. However in competition with Voigt, I. Schröder of Darmstadt, Germany, also produced copies of Ferdinand Redtenbacher's models from (Redtenbacher, 1857a, 1861a) as well as copies of models based on Reuleaux's books. The Schröder-Redtenbacher models were quite popular because they came in two sizes, small and large. Several museums such as the Science Museum in London and the Musée des Arts et Métier in Paris purchased the larger models. A large collection of these copies of Redtenbacher models can be found in Italy at the Foundation for Science and Technology (FST) in Florence. Another large collection can be found at the University of Porto in Portugal. Cornell University has about 18 Schröder models to be found illustrated in Redenbacher's textbooks. Schröder exhibited these at many world exhibitions including the Centenial Exhibition in Philadelphia in 1876 at which Reuleaux was on the judging panel that awarded Schröder's models a prize. Thus unwittingly, Redtenbacher's influence extended beyond Karlruhe through his designs for teaching models of machines. The Redtenbacher models largely consist of kinematic mechanisms including linkages, gear systems and straightline mechanisms. However, there are cutaway models of steam-engine valve systems as well as mathematical function synthesizers.

The representation of engineering knowledge in the mid-nineteenth century began with mathematical codification in the form of coefficients, tables, dimensionless characteristic numbers, etc., and was typical for the methodical approach in the evolution phase of mechanical engineering science. In particular for the instruction of the early mechanical engineers, this type of procedure introduced drastic simplifications, and was the only practicable method. Within the conflicting goals of practicability and scientific content, Redtenbacher tended to propose a didactically-illustrative method – similar to his contemporary colleagues Julius Ludwig Weisbach at the Mining School of Freiberg in Saxony and the Scottish engineer William John Macquorn Rankine – but the scientific background had to be foremost. The benefits of such a unity of exact scientific conceptions and a realization intelligible to all were obvious: The different demands on scientific methods in research, education and engineering practice became apparent. Even in that period, the emerging of these levels of engineering-scientific activities within a scientist personality such as Redtenbacher proved its worth. Excellence in science mainly occurred where new technologies pioneered and technical problems could not be solved via conventional aids. However, it cannot be ignored that, essentially, engineering practice could be handled very well by handbooks and know-how and also workshop traditions.

Redtenbacher's posthumous fame was considerable at least in the German-speaking regions of Europe. A notable number of students alone has ensured that his name would not fall into oblivion. Already within early writings in the history of engineering science, Redtenbacher's lifework was acknowledged by well-known historians. He made history not only for his pioneering work in scientific mechanical engineering, but also as one who brought about its realization in the training of engineers. There was some continuity within the work of Gerstner (Vienna), Schubert (Dresden), Weisbach (Freiberg) and Redtenbacher (Karlsruhe) to introduce scientific methods into mechanical engineering where Redtenbacher possibly outstood and had in Grashof a coequal successor. Grashof was successful in continuing Redtenbacher's educational intentions and plans. One year after his relocation to Karlsruhe, at the annual meeting of VDI (Association of German Engineers), he delivered a lecture, "On the basic principles for the organization of polytechnic schools". Based on this speech, a new organization status for the Karlsuhe Polytechnic School was granted in 1865 as the first institution in Germany holding a university constitution with self-management and appeal proceedings to be equated in rank with the state universities.

But it is also correct to say that Redtenbacher's work is clearly less spectacular and less controversal than that of his most famous student, Reuleaux. Based on a solid disciplinary development of the scientific mechanical engineering, Reuleaux and others tried a theoretical consolidation that spurred strong pedagocical debates. The major subjects were sufficiency of theoretical models, practical relevance of theory, the role of mathematics and the variety of methods within the flourishing engineering science. Therefore, it is not surprising that Reuleaux's work received much more attention in America than Redtenbacher's although the latter's work was wider in scope than either of Reuleaux's two major works including his "Kinematics of Machinery".

Modern Interpretation of Main Contributions

To appreciate Redtenbacher's contributions to machine science, it is helpful to read the opinions of his colleagues and later educators in similar institutions.

What Redtenbacher achieved for the mechanical engineering cannot be stated more incisively than by the words of Professor Kammerer within his directorate speech discoursed in 1908 at the Technical University of Berlin, i.e., in a time when his school had become the largest and most important institution of this kind in the German empire: "…in the emergence of a mechanical engineering art from mechanical engineering craft, scientific methods had to be found to determine machine dimensions as well as economic efficiency. The leadership was firstly taken by the Karlsruhe Polytechnic School. There, in the year 1841, Ferdinand Redtenbacher started his lectureship who had got to know the mechanical engineering undertaking from his own personal experience and at the same time also governed the scientific mechanics. In place of aimless rules he placed a theory based on experience… Justifiably, he may be seen as the originator of machine science in Germany" (Keller 1909).

As another person of importance in this context, Franz Reuleaux has to be surely named as one of Redtenbacher's master students. Reuleaux was also impressed and influenced by Redtenbacher in his 2 years of study at Karlsruhe, 1850/51 and 51/52, where he had learned from Redtenbacher's books published between 1844 and 1857 and summarized in the three-volumed opus "Mechanical Engineering" in 1862–65. In his famous work of 1875 "The Kinematics of Machinery: Outlines of a Theory of Machines" (Reuleaux 1875), within the third paragraph of chapter 1, Reuleaux puts machine science in the framework which was filled out by Redtenbacher 30 years earlier in Karlsruhe. Thereby, he ascertained that the general basics of machinery, the theory of machines, machine design and kinematics, in a sense, could be extended compared to that of Ampere in order to define a machine as a whole. Reuleaux explicitly credited Redtenbacher with a key role in promoting the first three ingredients for scientification of mechanical engineering departing from the traditionals stating for example, “that in the general basics of machinery a descriptive representation was usual until the thirties and Redtenbacher first removed the stigma of indistinctness from the matter.”

There is some debate among historians of machine engineering as to the relative contributions to mechanical engineering of Reuleaux and his professor Ferdinand Redtenbacher who, as noticed before, has been called one of the pioneers of German engineering education. Both men published influential books in machine design and both developed kinematic model collections for teaching. Redtenbacher’s summarizing three volume work “Mechanical Engineering” followed a year after Reuleaux’s own “The Constructor” (Reuleaux 1861) was published. The Redtenbacher work is wider in scope than either of Reuleaux’s two major works, including his “Kinematics of Machinery” (Reuleaux 1875) of 1875/76. However, unlike his pupil, Redtenbacher did not attempt to develop a general kinematics theory of machines or mechanisms. His chapter on kinematics classified mechanisms as to the type of motion they performed and was clearly influenced by the earlier French classification schemes of Monge. Nor did Redtenbacher review the history of machines and there are not many references to the literature or machine practice.

Lasting effects emanated from Redtenbacher’s main theoretical work “Principles”. However, it is difficult to find his name associated with theorems, methods or even formulas in mechanical science and engineering. Examples of his theoretical paradigms showing his use of definitions and names in the sense of Newton’s *Principia* were introduced in the development of machine theories and are still found in the framework of modern machine theory, albeit in a modified and extended form. In this meaning, Redtenbacher might be compared with Euler who had a similar impact on natural science. Redtenbacher reinterpreted the theorems of theoretical mechanics in such a way that they could be readily applied to problems in engineering. With regard to progress in knowledge and development of methods, Redtenbacher’s “Principles” constitute a milestone in the history of mechanical engineering and are, at the same time, a credo for scientific methodology. It was not sufficient to simply mathematize problems, but the development of theoretical models took a key role in engineering science. The complexity of real machine problems and the large number of parameters within the design process preclude exact methods according to the ideals of natural science and require a limitation to the use of essential principles. The modelling has to consider the concrete purpose of use, the function and the boundary conditions. Practical experience, specifically for mechanical engineering, is the reference field for setting up of adequate theories. Nevertheless, the developing machine sciences borrowed their methodical approaches from natural science. Failing self-contained methods this approach was legitimate at the time. Deductive methods and the search for closed-form solutions were the long-term objective of all attempts for scientification by Redtenbacher and his students. At the same time, it was intuitively clear to them that the path for generalization could only be followed inductively, studying the specific features of the individual case.

How should such a theory of machine science finally look, what factors had to be taken into consideration within the modelling? In general, according to the principles of Galilei, the essentials had to be distinguished from the non-essentials. For this purpose, practical judgment and experience were required. However, the main parameters for an analytical machine theory were fixed; mostly there were key economic constraints on designing a machine as related to function, weight, power and costs. In his concept of a machine theory where one had to find efficient design proportions and the choice of appropriate machine elements and materials, Redtenbacher began with design parameters which he described as functions of geometric secondary quantities. The solution of a specific dimensioning problem then arose from maximizing or minimizing the main design parameters by step-by-step elimination from the governing system of equations.

Some fruitful approaches were created but there were some limits to such a strictly composed deductive theory. Often the economic solution could not be technically realized; due to the complexity of the machine problem, simplifications had to be introduced which diminished the applicability. Furthermore, mathematical solutions existed which avoided a technical interpretation. Altogether, Redtenbacher therefore stuck to approximate approaches. The basic principle of transfer of proven traditions onto new circumstances and, in parallel, the balancing of possible factors and disturbances, was in accordance with the requirements of that time. It is to Redtenbacher's credit, that he used the "method of ratios" borrowed from architecture for mechanical engineering and cultivated it. Initiated by practical problems, Weisbach and Redtenbacher maintained the introduction and the use of technical parameters. These had the advantage of being measurable and could be calculated. The tabulation of such coefficients provided a basis to consolidate the structure of the concept of machine science and, by the permanent usage in reference books, it became the prevalent tool of the working engineer. Such practicable parameters also conveyed their theoretical background. Redtenbacher committed himself to establish non-dimensional parameters which had the advantage of being independent of specific measurements. Furthermore, such ratios were easily committed to memory and formed the intensive thinking of engineers for the correct design rules. Such a simplified machine calculation began in the first place with the geometry of motion of the mechanisms (later object of kinematics and gearings). The second step in the design process was the consideration of the strength of materials which resulted in the specification of design rules for machine elements.

Although Redtenbacher, who had a distinct appreciation for the theoretical formulation, attached great importance to their verification, he continually tried to improve them. With a view to approaching the high aims of his "Principles", at least partially, he formulated modified specific theories for special machines. For corresponding optimization problems, he even discarded the "exclusive computing method". Consequently, Redtenbacher proposed a deductive-axiomatic procedure, e.g., treating the design of hydraulic machines where he structured the calculation as follows:

1. Listing the requirements
2. Definition of the variables
3. Development of theory
4. Formulation of constraint equations maximizing a certain effect
5. Derivation of dimensioning rules
6. Consideration of constraints (noise, losses)
7. Generation of general laws for construction and operation of the machine by comparison with experiments
8. Selection of material and cost calculation

Taking into account the imperfection of the introduced ratios which were based on static principles, Redtenbacher again and again evaluated the pros and cons of approximate methods. But ultimately he had only one essential criterion of his scientific theory which was to accurately describe real conditions in a machine. The necessary simplifications of theoretical formulations led to the practical realization that these models were not precise but which were consciously accepted. But Redtenbacher did not stop with a new theory, he tried to improve it by error estimations and reflections on the neglected effects. Such a procedure sharpened his ability to deal with existing technical solutions and to judge and to estimate trends of mechanical engineering. Even today, such a procedure seems to be very modern and shows how strong his methodical thinking influenced the later theory of mechanisms and machines. But an explicit example may be difficult to find.

Contemporary “mechanism and machine theory” was originally defined within the English-speaking area as a conglomerate of machine-scientific disciplines focused on machine kinematics and only included dynamics and design in recent years. Willis seemed to advance the view of machine theory as largely kinematics, see, e.g., Moon (2003a, b)). Rankine, however, see Rankine (1887), seems to have pursued a wider vision of the theory of machines. Redtenbacher in his time, pursued by all means a very modern concept of machine science looking much more from a holistic perspective. Traditionally, constructive and technological aspects were approximate and one tried to evolute the established machine engineering into a machine science. To realize it, Redtenbacher and his students brought together kinematics and gearings as Reuleaux did, as well as strength of materials with an intensive study of the machine elements as did Bach and fluid dynamics/thermodynamics as did Weisbach, Zeuner and Stodola.

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Wang Zheng (1571–1644)

Baichun Zhang and Miao Tian

Abstract Wang Zheng was a Chinese official interested in machine design from a young age. In the 1620s, he became familiar with European missionaries and the knowledge they brought to China. Together with Johannes Schreck Terrenz (1576–1630), a German Jesuit missionary, he compiled *Yuanxi Qiqi Tushuo Luzui* (*A Record of the Best Illustrations and Descriptions of Extraordinary Devices of the Far West*) to introduce European mechanics and machines to China. This remained the most authoritative book on mechanics and machine design in China until the 1860s. Wang Zheng published two further books on machine design and constructed several devices himself. In 1644, he committed suicide because of the fall of the Ming Dynasty.

Biographical Notes

Wang Zheng (Fig. 1), who styled himself Liangpu, was born on May 12, 1571, in Jingyang County, Shanxi Province, China. His father, Wang Yingxuan, was an erudite village teacher with an interest in ancient books, skilled in calculation, methods for preserving health, geography, and astrology. His mother came from a family of scholar-officials (Wang Zheng 1987a, pp. 252–258).

Wang learned from his father from a very young age. In 1577, he went to live with his maternal grandfather and began to study with his uncle, Zhang Jian, a brother of his mother. Zhang, who held various official positions during his lifetime, was proficient in the Confucian classics and history, well acquainted with military knowledge, and had extensively studied arcane knowledge such as the arts

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Fig. 1 Wang Zheng Portrait (anonymous painter, modern imitation, preserved in Wang Kejü's home)

of astrology and divination. He was also good at making devices. Zhang exerted great influence on Wang, who later highly praised his morality and profound learning, claiming that his skill in crossbow and chariot-making was remarkable (Wang 1987a, p. 208).

In 1587, Wang became a student in the county school. In 1594, he successfully passed the imperial examinations at the provincial level. Over the following years, he took the highest imperial examination ten times, finally succeeding in 1622. Soon after, he was appointed an official in charge of juridical affairs in Guangping Prefecture. At the end of the autumn of 1622, he reached Guangping to take up the post. He was an able and dutiful official. According to his own account, during 1 year he inspected the army and its armaments and led the reform of the military, compiling the *Bing Yue* (Soldiers' Rules); he quelled local unrest and released innocent persons falsely accused of belonging to a rebellious sect, the White Lotus Society; and he ordered the construction of canals and embankments and designed water-gates for the Qinghe river. With the death of his step-mother in March, 1624, he left Guangping for his hometown to observe the prescribed 3-year period of mourning.[1]

[1]After the death of a parent, a son should observe a 27-month period of mourning at home, eschewing all social intercourse. If an official, he must leave his job.

At the beginning of 1627, he was appointed an official in charge of juridical affairs in Yangzhou Prefecture. He arrived at his post in July of 1627. During his tenure of office, besides his juridical duties, he reconstructed floodgates, improved irrigation systems, introduced military methods, built Confucian temples and painted.

In 1628, he again had to leave his post and return to his hometown to observe the prescribed period of mourning after the death of his father. In 1629, he organized local militia to fight against insurgents in his hometown and neighboring areas. In 1631, he was promoted to supervisor of military affairs. However, he was soon removed from his post due to a rebellion by low-ranking military officers and returned to his hometown. From then on, he invested his efforts in serving his hometown and writing. In 1643, the town was overrun by one of the rebelling armies. Refusing to serve them, he committed suicide.

As a result of this act, he was highly regarded as a loyalist and martyr by his contemporaries. However, subsequently he became famous as a member of the first generation of Chinese converts to Catholicism, and for his achievements in the history of the transmission of knowledge between Europe and China, especially machine design and mechanics.

There is no solid evidence to tell us exactly when Wang converted to Catholicism. He was attracted to it when he met the Spanish Jesuit missionary, Diego de Pantoja (1571–1618), in 1616. During 1625 and 1626, Wang helped the Jesuit missionary Nicolas Trigault (1577–1628) to compile and publish the first Chinese phonetic dictionary using transcriptions in the Latin alphabet. Interestingly, in his preface to this book, he stressed that, through the study of Western writing, he had come to understand why the ancient Chinese classic, the *Yi Jing* (*Book of Changes*), was the origin of all written characters. In 1634, he established a Catholic society, "Ren Hui" (Benevolence Society), framing its "Rules" and building a church.

Influenced by his uncle Zhang Jian, from his youth he took an interest in ingenious mechanisms and devices, especially those for military use. In 1622, he presented a memorial to the throne to introduce several military devices, and became known as an expert in machine design and military affairs. Between 1623 and 1626, he used his devices for various purposes such as dredging rivers, flood defense, and military defense. All the machines constructed by him were concerned directly with farming, daily life, or military affairs.

Thus it was that he was able to appreciate the machines that he saw brought by missionaries to China and recorded in their books. Inspired by the mechanisms of European clocks, he invented a weight-driven quadricycle in imitation of an ancient device he had sought to reconstruct for many years (Zhang Baichun 1996). In 1626, he wrote *Xinzhi Zhuqi Tushuo* (*Illustrations and Descriptions of Several Newly-built Devices*), which included eight kinds of machines. In 1627, together with the German Jesuit misssionary Johann Terrenz (1576–1630), he composed *Yuanxi Qiqi Tushuo Luzui* (*A Record of the Best Illustrations and Descriptions of Extraordinary Devices of the Far West*), which systemically introduced European mechanics and machines to China. Terrenz interpreted the Western texts in spoken Chinese while he illustrated Terrenz' interpretations and formulated them in written Chinese. After that, he used European technology to make more devices, playing a central role in the transmission of knowledge about Western machines to China.

In his old age, he was still interested in constructing devices based on Western knowledge and Chinese technology. At the end of 1640 or the beginning of 1641, he integrated his old writings and new ideas into a new book entitled "*E La Ji Ya You Zao Zhuqi Tushuo* (*Illustrations and Descriptions of the Devices Created by Gratia*)". This book described 24 kinds of devices, all of which he thought practical. Unfortunately, as the book was lost during the twentieth century, little is known of the specific content.

Wang lived the ordinary life of a low ranking scholar-official. His interest in machine design and the transmission of European mechanics was not widely shared by his contemporaries, though his endeavors were in accordance with the Confucian doctrine of serving society (Jami 1999, Huang Yi-Lung 2005). However, converting to Catholicism was definitely unusual in the seventeenth century. Nevertheless, an open attitude toward non-Confucian knowledge was not so unusual among Chinese scholars at that time. In fact, both his father and uncle, Zhang Jian, were interested in non-orthodox Confucian thought and knowledge, and he was open to knowledge from different traditions from early on in his life (Zhang Baichun and Tian Miao 2006). In his preface to *Yuanxi Qiqi Tushuo Luzui*, he claimed: "[As for] learning, [I] originally do not ask whether [it is] fine or coarse, [but] always expect [it] to be of benefit to the world; [as for] a person, I also do not ask whether [he is] a Chinese or a Westerner, [but] always expect him not to disobey Heaven" (Terrenz and Wang Zheng 1830). In his various works, he tried to incorporate Catholic ideas into Confucianism. We believe that this was an effort to legitimize Western knowledge and Catholicism in China. His satisfaction with the fact that Western knowledge and religion did not violate Confucian tradition was the basis for his adoption of Western knowledge and for his conversion to Catholicism. In fact, he believed that both European knowledge and thought were in accordance with Confucianism. Even though he was interested in Daoism, and converted to Catholicism, he remained a Confucian scholar (Tian Miao and Zhang Baichun 2007). In his *Liang Li Lüe* (*An Outline of Two Administrations*), he mentions that whenever "I arrived at a county, I would first pay homage at the temple of Confucius. I would examine the sacrificial utensils and books. Obeying the Sage, esteeming (his) *Dao* and respecting (his) learning are the main acts of righteousness of a country" (Wang Zheng 1987b, p. 27). His suicide in 1644, displaying such loyalty to the Ming emperor, is proof of his life-long commitment to Confucianism (Zhang Pengfen 1830). Loyalty toward the emperor was one of the prime principles of Confucianism, while suicide was strictly forbidden by Catholicism.

List of Wang Zheng's (Main) Works

Xinzhi Zhuqi Tushuo (新制诸器图说, *Illustrations and Descriptions of Several Newly-built Devices*), written in 1626, first published in 1628.

Yuanxi Qiqi Tushuo Luzui (远西奇器图说录最, *A Record of the Best Illustrations and Descriptions of Extraordinary Devices of the Far West*, written in 1627, first published in 1628.

Liang Li Lüe (两理略, *An Outline of Two Administrations*), written in 1637.
E La Ji Ya You Zao Zhuqi Tushuo (额辣济亚牖造诸器图说, *Illustrations and Descriptiions of the Devices Created by Gratia*), written in the 1640s.

Review of Wang Zheng's Main Works on Mechanism Design

In his *Xinzhi Zhuqi Tushuo* (*Illustrations and Descriptions of Newly-built Devices*, hereafter *Zhuqi Tushuo*), Wang Zhang illustrated and described nine devices, including a single-cylinder siphon-pump, a flume-beamed swape, a crank-operated man-powered mill, a wind-driven mill, a weight-driven geared mill, a weight-driven quadricycle, a combined clock, a mechanical cable plough, and a multiple crossbow (Wang Zheng 1830a, b, pp. 1–21). The single-cylinder siphon-pump (Fig. 2), which consists of a pipe and a single-cylinder pump, may be used to lift water.

The flume-beamed swape (Fig. 3) is a long water-lifting flume. The crank-operated man-powered, mill is not a particularly special mill, but he emphasized its two gear wheels. The wind-driven mill was drawn by him on the basis of a mill described by Nicolas Trigault. He also imitated the transmission and power mechanisms of European clocks, namely combined gear wheels and driving weights, with millstones or quadricycles in order to design a weight-driven geared mill and a weight-driven quadricycle (Fig. 4). For his combined clock, he made a copy of the transmission and power mechanisms of a European clock and combined them with a drum, a bell, and puppets (Fig. 5). The mechanical cable plough (Fig. 6) is driven by a windlass with handspikes. The multiple crossbow is a traditional Chinese device, which he tried to assemble on the basis of an unearthed trigger.[2]

Yuanxi Qiqi Tushuo Luzui (远西奇器图说录最, *A Record of the Best Illustrations and Descriptions of Extraordinary Devices of the Far West*, hereafter *Qiqi Tushuo*, see Fig. 7) is the first monograph on Western mechanics and machines in Chinese (Terrenz and Wang Zheng 1830), most of which was new for the Chinese of the seventeenth century. Following the introduction to the art of force or science of weights, there are three chapters that selectively expound Western mechanics and machines from Archimedean times to the early seventeenth century. The first chapter, which consists of 61 sections, is called *Explanations of Weight*. It discusses such topics as weight, center of gravity, geometrical center, specific gravity, buoyancy, etc. The second chapter of 92 sections, *Explanations of Devices*, discusses principles and calculations concerning simple machines such as the balance, steelyard, lever, pulley, wheel, screw, etc. The third chapter consists of illustrations and explanations of 54 Western machines, including devices to hoist and move heavy objects, water-lifting devices, wind-mills, water-mills, wood-sawing machines, and so on. This chapter also describes such mechanisms as the worm wheel and the ratchet wheel.

[2] The trigger unearthed from the ground tells us that there was no cross-bow trigger available for Wang Zheng.

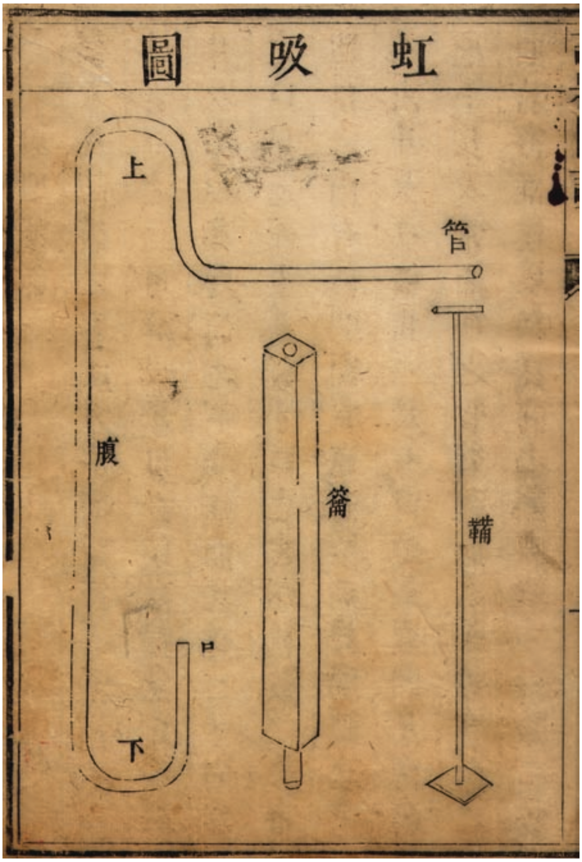

Fig. 2 Single-cylinder siphon-pump (*Xinzhi Zhuqi Tushuo*, Lailutang edition)

The first and second chapters of *Qiqi Tushuo* are probably derived mainly from Simon Steven's *Hypomnemata Mathematica... Mauritius, Princeps Auraicus, Comes Nassoviac...* (1608), Guidobaldo del Monte's *Mechanicorum liber* (1577) (Damerow and Schoepflin 2006). All the mathematical proofs in the Western sources were left out by Terrenz and Wang. The third chapter is obviously derived from Agostino Ramelli's *Le Diverse et Artificiose Machine del Capitano* (1588), Faustus Verantius' *Machinae Novae Fausti Verantii Siceni, cum Declaratione Latina, Italica, Hispanica, Gallica et Germanica* (written *c*. 1595), Jacques Besson's *Théatre de Instruments Mathématiques et Mécaniques* (1578) and Vittorio Zonca's *Novo Teatro di Machini e Edificii* (1607). Terrenz and Wang integrated knowledge from these books into a new system of mechanical knowledge and machines (Tian Miao and Zhang Baichun 2007).

The most outstanding invention Wang made is the design of a weight-driven quadricycle (Fig. 4), which he called a Self-motion Vehicle. He made a great effort to reconstruct the famous transporting device known as the Wooden Ox and Gliding Horse, created by Zhuge Liang (181–234). He was unsuccessful until he learned

Fig. 3 Flume-beamed swape (*Xinzhi Zhuqi Tushuo*, Lailutang edition)

about the mechanism of mechanical clocks transmitted from Europe (Wang Zheng 1987b, pp. 81–82). The weight-driven quadricycle is the result of his application of such a mechanism.

According to Zhang Pengfen, it was believed in Wang's hometown that he made wooden models for farming and other purposes, such as making fire and operating bellows. It was also believed that he used his weight-driven quadricycle to help with binding and transporting stalks (Zhang Pengfen 1830). However, modern historians no longer believe such accounts.

On the Circulation of Wang Zheng's Works

Qiqi Tushuo is the most important publication that Wang Zheng was involved with. *Zhuqi Tushuo* was published attached to it. *E La Ji Ya You Zao Zhuqi Tushuo* was never published, remaining in manuscript form, and is now lost.

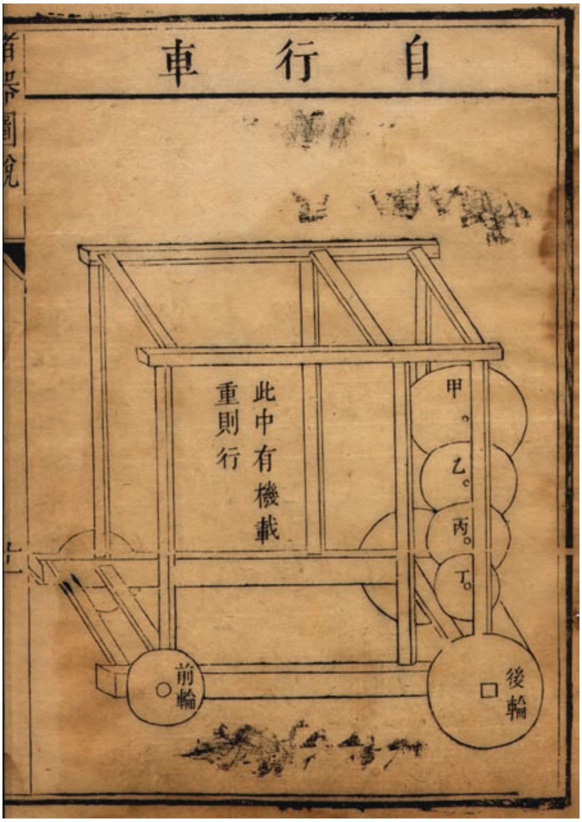

Fig. 4 Weight-driven quadricycle (*Xinzhi Zhuqi Tushuo*, Lailutang edition)

In 1628, Wu Weizhong, one of Wang's friends, printed a woodblock edition of *Qiqi Tushuo* with *Zhuqi Tushuo* in Yangzhou. Subsequently, Wang Yingkui copied the blocks and reprinted the two works in order to make them more widely available. Wang Yingkui's edition introduced some new errors and simplified a few of the illustrations. On the basis of this edition, Wu Huaigu reprinted them again in 1631. The content of this edition is the same as Wang Yingkui's, except that all the Western characters used as markers are replaced by Chinese ones.

Later, new editions of the two books based on these were reprinted in such collections as *Gujin Tushu Jicheng* (*GJTSJC, Collection of Ancient Chinese Books*, 1728), *Siku Quanshu* (*SKQS, Complete Collection in Four Treasuries*, 1781–1782), *Shoushange Congshu* (*Shoushange Book Series*, 1844) and by the Lailutang printing house (Zhang Baichun et al. 2006). *GJTSJC* and *SKQS* were compiled on imperial order. The editors of *GJTSJC* left out the first and second chapters, while the editors of *SKQS* added a short introduction to *Qiqi Tushuo*, remarking that Johann Terrenz and Wang's explanations of the art of force (science of weight) "exaggerated the marvellousness of these methods. Most of them are preposterous and

Fig. 5 European-styled clock (*Xinzhi Zhuqi Tushuo*, Lailutang edition)

excessive, not worthy of investigation. However, the skill of the manufacture of the machines is, in fact, the finest of any age" (Ji et al. 1983). This paragraph demonstrates the attitude of some Chinese scholars towards theoretical mechanics.

Shoushange Congshu and *GJTSJC* were repeatedly copied by other publishers so that *Qiqi Tushuo* and *Zhuqi Tushuo* were widely transmitted in the nineteenth and twentieth centuries not only throughout China, but also to Japan and Korea. The publishers and editors of new editions selected and changed their content based on their interests in Western knowledge about mechanics and machines. The majority of the errors in the first edition were repeated in subsequent ones. Though some revisers improved the content or added new misunderstanding, all the editions played a role in the acceptance and transmission of western scientific knowledge in China before the twentieth century.

Prior to the 1860s, *Qiqi Tushuo* was the most authoritative book on mechanics and machine design in China. Its content was repeatedly cited and discussed by later Jesuit missionaries and Chinese Scholars (Tian Miao and Zhang Baichun 2006a, Tian Miao and Zhang Baichun 2006b). Xue Fengzuo (1600–1680),

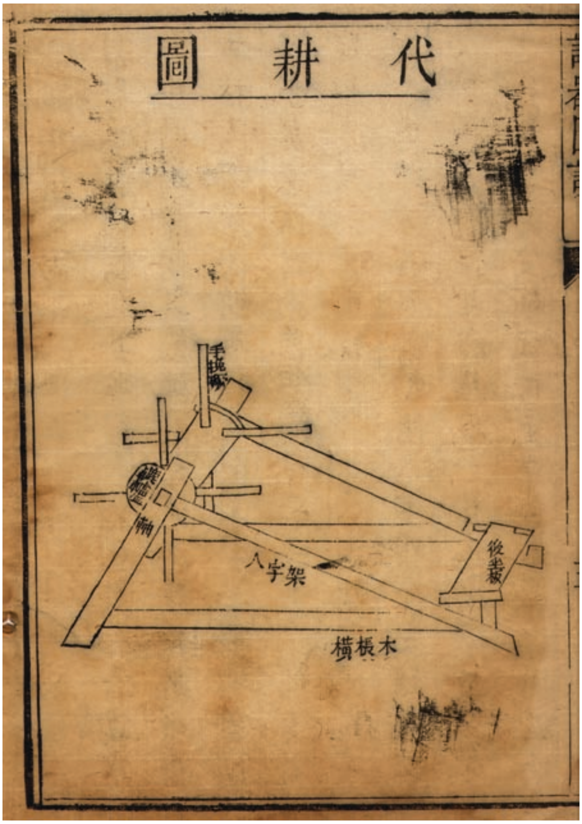

Fig. 6 Mechanical cable plough (*Xinzhi Zhuqi Tushuo*, Lailutang edition)

an astronomer and mathematician, completed a book entitled *Zhongxue* (*The science of weights*) in 1664 based on the two works (Tian Miao and Zhang Baichun 2006a). Xue had a good understanding of Western mechanical knowledge and abridged and summarized their original texts and illustrations, though he completely left out the second chapter of *Qiqi Tushuo*. He thought that the science of weights and mathematics would help people to understand the purpose and principles of machine construction, though some of the illustrations he redrew were of poor quality and he deleted some important mechanisms.

In the 1680s, another mathematician, Mei Wending (1633–1721), made a study of *Qiqi Tushuo*, contributing a commentary to its first chapter and supplementing its third chapter with some illustrations and explanations of traditional Chinese machines (Tian Miao and Zhang Baichun 2006b). He also tried to provide mathematical proofs for the mechanical knowledge in the first chapter of *Qiqi Tushuo*. A Jesuit missionary, Ferdinand Verbiest (1623–1688), compiled a book in Chinese entitled *Qiong Li Xue* in 1683, which includes mechanical theory from *Qiqi Tushuo* rather than knowledge about machines.

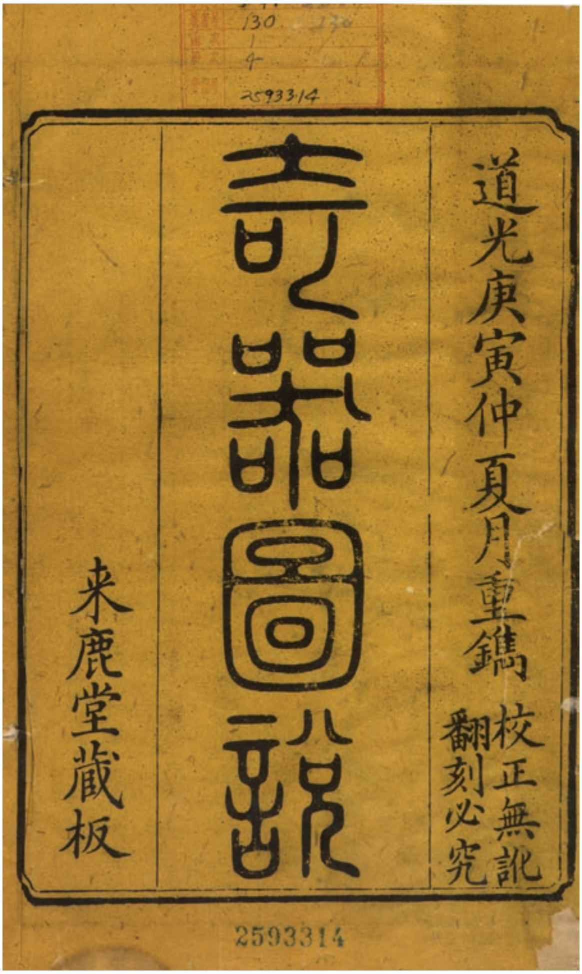

Fig. 7 The Cover of *Yuanxi Qiqi Tushuo Luzui* (Lailutang edition)

Although *Qiqi Tushuo* and *Zhuqi Tushuo* were circulated among Chinese scholars and other readers, we have not found any Chinese scholar from the eighteenth to mid-nineteenth century who made a further study of mechanics and mechanism design on their basis.

Modern Interpretation of Wang Zheng's Main Contributions

The weight-driven quadricycle was Wang Zheng's most important design (Fig. 4). A model of this kind of quadricycle could run for more than 10 m. Its mechanism was based on a system of gear wheels. Such gear wheels enable a crank-operated man-powered mill to be turned quickly and the design was used in water-powered, gear-driven mills in ancient China. Using it to make a transportation device was Wang's own invention. He surmised that a big weight-driven quadricycle could run for three *li* (one li is approximately equal to 0.5 km). However, in order to make a quadricycle or a mill run over and over again, the operator has to intermittently lift a weight that provides the power. In fact, his designs are feasible in principle, but they cannot be used to construct a large functioning quadricycle or mill (Liu Xianzhou 1958).

His main contribution to mechanism design is his role in the earliest transmission of Western knowledge about mechanics and machines into China. He also used his skill in Chinese painting to create a traditional Chinese pictorial representation of Western machines, for instance changing all the machine operators in the illustrations from European figures to Chinese ones.

His work laid the foundation for the further introduction of modern mechanics and knowledge about Western devices into China prior to the twentieth century. From the 1840s, the door to China was pushed open and Western military and other related technology was introduced, including mechanical knowledge. Mechanical terms used in *Qiqi Tushuo* had an influence on such books as *Zhong Xue* (Science of Weights, 1859) by Li Shanlan and Joseph Edkins (1823–1905), which was a Chinese translation of *An Elementary Treatise on Mechanics* by W. Whewell (1794–1866), as well as some textbooks on machines. When the Republic of China's Ministry of Education standardized technical terms, Liu Xianzhou adopted terms from *Qiqi Tushuo* when compiling a dictionary on mechanical engineering.

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