Chapter 2 Mechanism and Machine

One of the fundamental concerns in designing a machine is its mechanism for achieving a desired motion. The task of reconstruction design of lost ancient machines is mainly the design of mechanisms. This chapter presents the definitions of mechanisms and machines, the characteristics of mechanical members and joints, the definitions of kinematic link chains, the concept of constrained motion, the identification of the topological structure of mechanisms, and the process of mechanism and machine design [1, 2].

2.1 Definitions

A mechanism is an assembly of mechanical members connected by joints, and these members are so formed and connected such that they transmit constrained motions by moving upon each other. Four-bar linkages used in various applications for transmitting motions are typical examples of mechanisms. Figure 2.1(a) shows a four-bar linkage for guiding an automobile hood, and Figure 2.1(b) shows a four-bar linkage, named in ancient China the jie chi, for drawing parallel lines.

(a) (b)

Figure 2.1 Applications of four-bar linkages

A machine is a piece of equipment, mechanical in nature, designed for producing an effective work output or for conserving mechanical energy. In general, it consists of one or more mechanisms, has a certain type of power input, and has an adequate control system in order to serve a special purpose or perform a special function. Typical machines are working machines which convert mechanical energy to effective work outputs, such as machine tools, forklifts, generators, and compressors. Figure 2.2 shows a modern vertical machining center and its automatic tool changer. Prime movers like internal combustion engines, steam engines, turbines, and electrical motors are also machines which transform other forms of energy (such as wind, heat, water, electricity, and so on) to mechanical energy as the driving power of working machines. Figure 2.3 shows a jet-engine turbine for a commercial aircraft. Machines should have suitable controlling devices, such as human power control, hydraulic control, pneumatic control, electrical control, electronic control, and computer control for effectively producing the required motion and work. Figure 2.4 shows a hand-operated paddle machine used in ancient China [3]. It is a machine with human power as the input, and wooden paddle chains and sprockets as the mechanism.

A structure is an assembly of mechanical members connected by joints, and these members are so formed and connected that they transmit forces without any relative motion. A bridge is a structure. Aircraft-landing gears, for the purpose of absorbing impact forces during landing, are also structures; however, they become mechanisms during the period between gear up and gear down.

Figure 2.2 A machining center and its automatic tool changer

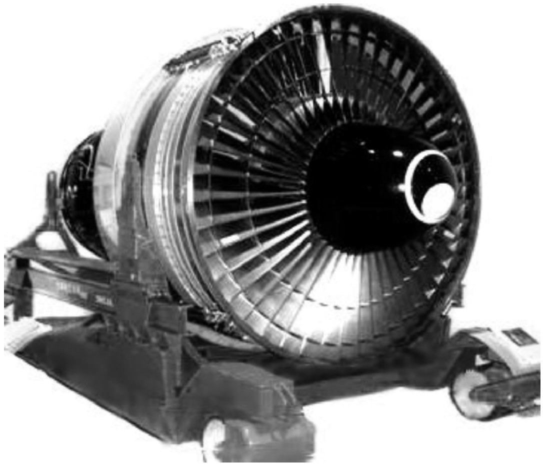


Figure 2.3 A jet-engine turbine

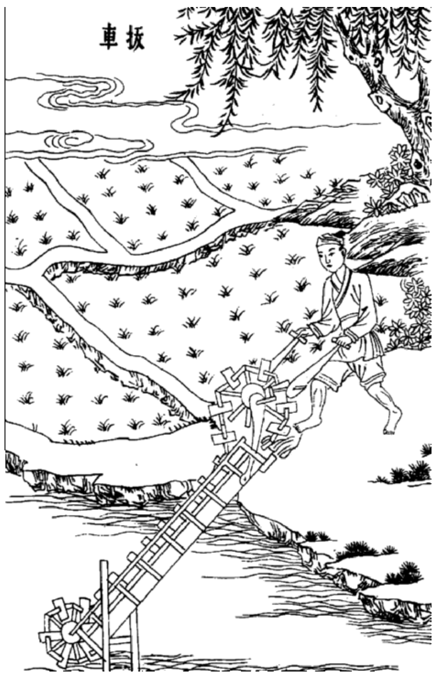


Figure 2.4 A hand-operated paddle blade machine [3]

Every mechanism and machine has a structure member known as the frame or ground link for guiding the motions of some mechanical members, for transmitting forces or for withstanding stresses. A frame can be a piece of a mechanical member or an overconstrained assembly of several mechanical members. For instance, the frame of a machine tool is the ground member and it is a structure.

2.2 Mechanical Members

Mechanical members are resistant bodies that collectively form mechanisms and machines. They can be rigid members, flexible members, or compression members. Compression members (such as airs or fluids) and those for the purpose of fastening two or more members together (such as shafts, keys, and rivets) that play no role in the reconstruction design of ancient machines are not of interest here. Only those members whose function is to provide possible relative motion with others are presented.

There are numerous types of mechanical members. The following are functional descriptions of basic mechanical members of machines.

Link

A link (K_L) is a rigid member for holding joints apart and for transmitting motions and forces. Generally, any rigid mechanical member is a link. Links can be classified based on the number of incident joints. A separated link is one with zero incident joints. A singular link is one with one incident joint. A binary link is one with two incident joints. A ternary link is one with three incident joints. A quaternary link is one with four incident links. An L_i-link is one with *i* incident joints. Graphically, a link with *i* incident joints is symbolized by a shaded, *i*-sided polygon with small circles on the vertices indicating incident joints. Furthermore, two binary links in a series is called a dyad.

Slider

A slider (K_P) is a link that has either rectilinear or curvilinear translation. Its purpose is to provide a sliding contact with an adjacent member.

Roller

A roller (K_O) is a link for the purpose of providing rolling contact with an adjacent member. A wheel is basically a roller.

Cam

A cam (K_A) is an irregularly shaped link that serves as a driving member and it imparts a prescribed motion to a driven link called follower (K_{Af}). Cams can be classified as wedge cams, disk cams, cylindrical cams, barrel cams, conical cams, spherical cams, roller gear cams, and others.

Gear
Gears (K_G) are links that are used, by means of successively engaging teeth, to provide positive motion from a rotating shaft to another that rotates, or from a rotating shaft to a body that translates. Gears can be classified as pin gears, spur gears, bevel gears, helical gears, and worm and worm gears.
Screw
Screws (K_H) are used for transmitting motions in a smooth and uniform manner. They may also be thought of as linear actuators that transform rotary motion into linear motion.
Belt
Belts (K_B) are tension members for power transmissions and conveyers. They obtain their flexibility from material distortion, and motion is usually transmitted by means of friction between the belts and their corresponding pulleys (K_U). Belts can be classified as flat belts, V belts, and timing belts.
Chain
Chains (K_C) are also tension members for power transmissions and conveyors. They are made from small rigid parts that are joined in such a manner as to permit relative motion of the parts, and motion is usually transmitted by positive means, such as sprockets (K_K). Chains can be classified as hosting chains, conveying chains, and power transmission chains.
Actuator
An actuator (K_T) consists of a piston (K_I) and a cylinder (K_Y) with a kind of compression member bounded by the piston and the cylinder. Its purpose is to provide a damping action between the members adjacent to the actuator. Shock absorbers of vehicles are typical actuators.
Spring
Springs (K_S) are flexible members. They are used for storing energy, applying forces, and making resilient connections. Springs can be classified as wire springs, flat springs, and special-shaped springs.

2.3 Joints

In order for mechanical members to be useful, they must be connected by certain means. That part of a mechanical member that is connected to a part of another member is called a pairing element. Two elements that belong to two different members and are connected together form a kinematic pair or joint.

Kinematic pairs or joints are categorized according to the degrees of freedom, the type of motion, the type of contact, and the type of joints. These features are introduced as follows:

Degrees of freedom
The number of degrees of freedom is the number of independent parameters needed to specify the relative positions of the pairing elements of a joint. An unconstrained pairing element has six degrees of freedom including three translational and three rotational degrees of freedom. When a pairing element connects to another pairing element and forms a joint, a constraint is imposed and the motion of the original member is reduced by one or more degrees of freedom. Hence, a joint has a maximum of five degrees of freedom and a minimum of one degree of freedom. The topic on degrees of freedom and constrained motion will be further discussed in Section 2.5.

Type of motion
Type of motion refers to the motion of a point on a pairing element relative to another pairing element of a joint. The motion can be rectilinear or curvilinear, planar or curved, or spatial.

Type of contact
Point contacts, line contacts, and surface contacts are types of contact between two pairing elements.

Type of joints
In what follows, the functional descriptions of basic joints are introduced and the corresponding schematic representations of joints are shown in corresponding figures.

Revolute joint
For a revolute joint (J_R), Figure 2.5(a), the relative motion between two incident members is rotation about an axis. It has one degree of freedom with circular motion and surface contact.

Prismatic joint
For a prismatic joint (J_P), Figure 2.5(b), the relative motion between two incident members is translation along an axis. It has one degree of freedom with rectilinear motion and surface contact.

Rolling joint
For a rolling joint (J_O), Figure 2.5(c), the relative motion between two incident members is pure rolling without slipping. It has one degree of freedom with cycloid motion and line contact.

Cam joint
For a cam joint (J_A), Figure 2.5(d), the relative motion between two incident members is the combination of rolling and sliding. It has two degrees of freedom with curvilinear motion and line contact.

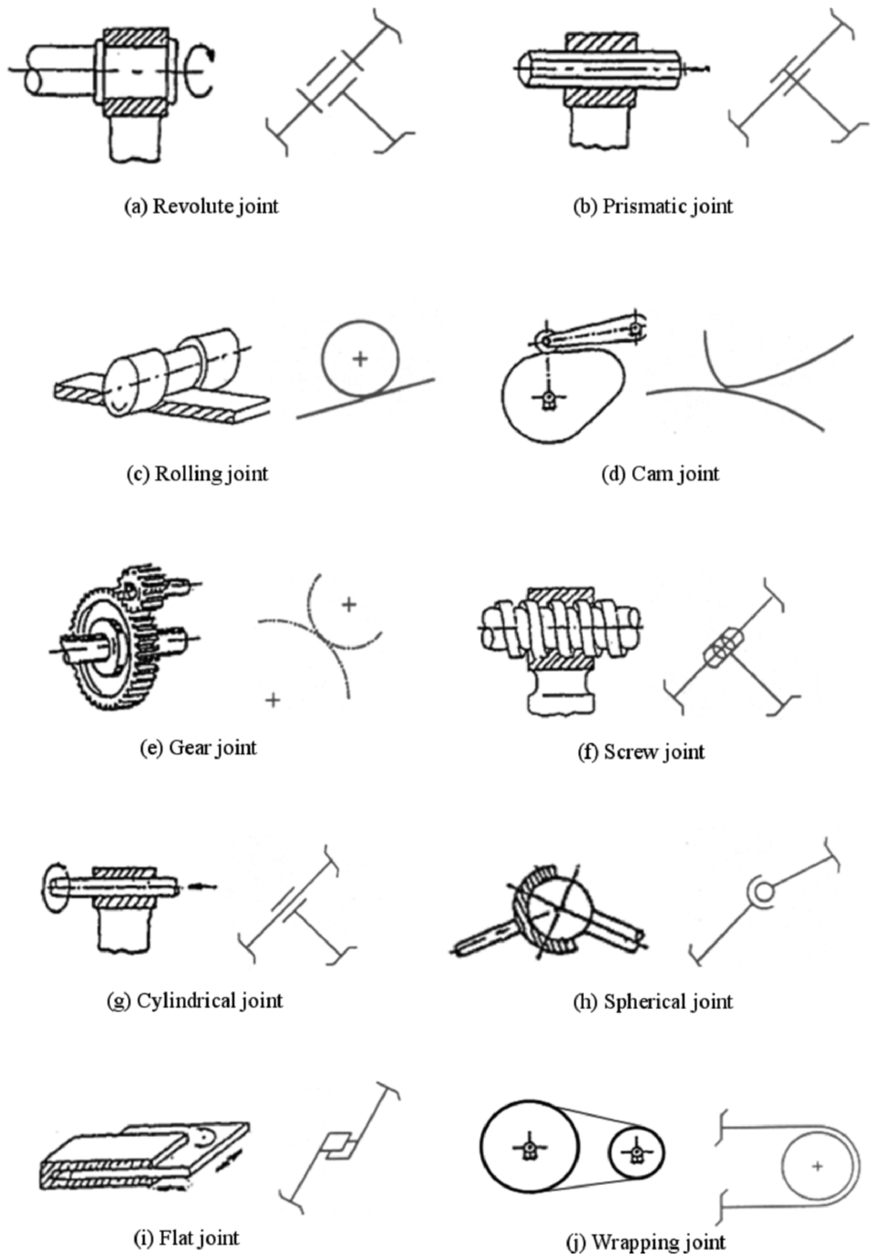


Figure 2.5 Types and schematic representations of joints

Gear joint
For a gear joint (J_G), Figure 2.5(e), the relative motion between two incident members is the combination of rolling and sliding. It has two degrees of freedom with curvilinear motion and line contact.
Screw joint
For a screw joint (J_H), Figure 2.5(f), the relative motion between two incident members is helical.
Cylindrical joint
For a cylindrical joint (J_C), Figure 2.5(g), the relative motion between two incident members is the combination of a rotation about an axis and a translation parallel to the same axis. It has two degrees of freedom with curvilinear motion and surface contact.
Spherical joint
For a spherical joint (J_S), Figure 2.5(h), the relative motion between two incident members is spherical. It has three degrees of freedom with spherical motion and surface contact.
Flat joint
For a flat joint (J_F), Figure 2.5(i), the relative motion between two incident members is planar. It has three degrees of freedom with planar motion and surface contact.
Wrapping joint
For a wrapping joint (J_W), Figure 2.5(j), there is no relative motion between two incident members. However, one of the members (pulley or sprocket) rotates about its center.

2.4 Mechanisms and (Link) Chains

When several links are connected together by joints, they are said to form a link chain, or just a chain in short. An (N_L, N_J) chain refers to a chain with N_L links and N_J joints.

A walk of a chain is an alternating sequence of links and joints beginning and ending with links, in which each joint is incident with the two links immediately preceding and following it. For example, for the (5, 4) chain shown in Figure 2.6(a), link 1 – joint *b* – link 4 – joint *d* – link 3 – joint *d* – link 4 is a walk. A path of a chain is a walk in which all the links are distinct. For example, for the (5, 4) chain shown in Figure 2.6(a), link 1 – joint *b* – link 4 – joint *d* – link 3 is a path. If any two links of a chain can be joined by a path, the chain is said to be connected; otherwise the chain is disconnected. Figure 2.6(a) shows a (5, 4) disconnected chain with a separated link (link 5), and Figure 2.6(b) shows a (5, 5) connected chain with a singular link (link 5). If every link in the chain is connected to at least two other links, the chain forms one or several closed loops and is called a closed chain. A connected chain that is not closed is an open chain. A bridge-link in a chain is a link whose removal results in a disconnected chain. Figure 2.6(c) shows a (6, 7) closed chain with a bridge-link (link 4). The connected chain shown in Figure 2.6(b) is also an open chain.

A kinematic chain generally refers to a movable chain that is connected, closed, without any bridge-link, and with revolute joints only. If one of the links in a kinematic chain is fixed as the ground link (K_F), it is a mechanism. Figure 2.6(d) shows a (6, 7) kinematic chain, and Figure 2.6(e) shows its corresponding mechanism obtained by grounding link 1 in the

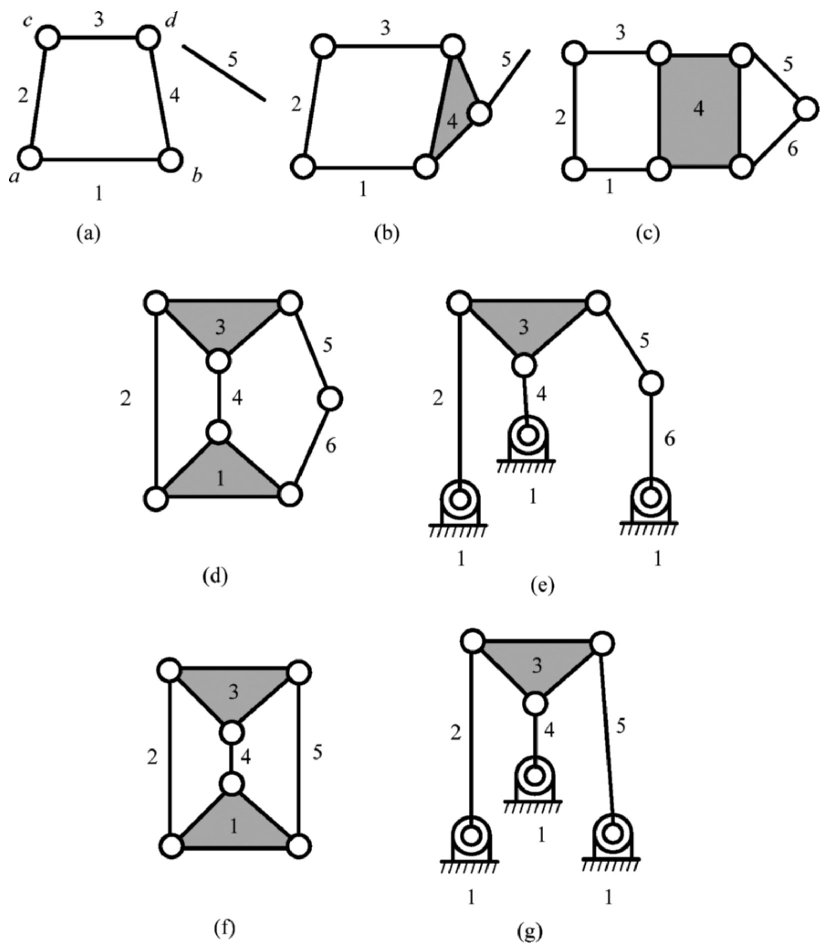


Figure 2.6 Type of (link) chains, mechanisms, and structures

chain. A generalized kinematic chain consists of generalized links connected by generalized joints, i.e., the types of links and joints are not specified. For example, if the types of links and joints for the (6, 7) kinematic chain shown in Figure 2.6(d) are not specified, it becomes a (6, 7) generalized kinematic chain. The concept of generalized kinematic chains will be presented in detail in Section 4.4.

A rigid chain refers to an immovable chain that is connected, closed, without any bridge-link, and with revolute joints only. If one of the links in a rigid chain is fixed or grounded, it is a structure. Figure 2.6(f) shows a (5, 6) rigid chain, and Figure 2.6(g) shows its corresponding structure by grounding link 1 in the chain.

2.5 Constrained Motion

The number of degrees of freedom (F) of a mechanism determines how many independent inputs the design must have in order to fulfill a useful engineering purpose. A mechanism with a positive number of degrees of freedom and with the same number of independent inputs has constrained motion. Constrained motion means that when any point on an input member of the mechanism is moved in a prescribed way, all other moving points of the mechanism have uniquely determined motions.

2.5.1 Planar mechanisms

For planar mechanisms, a member has three degrees of freedom consisting of translational motions along two mutually perpendicular axes and a rotational motion about any point. The number of degrees of freedom, F_p, of a planar mechanism with N_L members and N_{Ji} joints of type *i* is:

$$F_p = 3(N_L - 1) - \Sigma N_{Ji} C_{pi} \tag{2.1}$$

where C_{pi} is the number of degrees of constraint of *i*-type joint.

[Example 2.1]
Calculate the number of degrees of freedom for the device jie chi shown in Figure 2.1.

This is a planar mechanism with four members and four revolute joints. Therefore, $N_L = 4$, $C_{pR} = 2$, $N_{JR} = 4$, and $C_{pP} = 2$. Based on Equation (2.1), the number of degrees of freedom, F_p, of this mechanism is:

$$\begin{aligned} F_p &= 3(N_L - 1) - (N_{JR}C_{pR}) \\ &= (3)(4-1) - (4)(2) \\ &= 9 - 8 \\ &= 1 \end{aligned}$$

Therefore, the motion of this mechanism is constrained.

[Example 2.2]
Calculate the number of degrees of freedom for the (5, 6) planar mechanism shown in Figure 2.7. The actuator (members 4 and 5) is the input and the follower (member 2) is the output link.

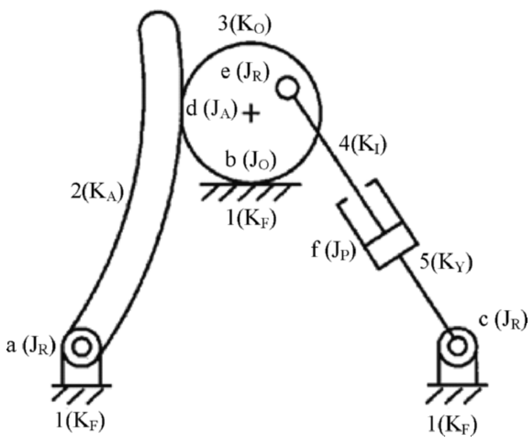


Figure 2.7 A (5, 6) planar mechanism

This is a planar mechanism with five members (ground link K_F, link 1; follower K_{Af}, link 2; roller K_O, link 3; piston K_I, link 4; and cylinder K_Y, link 5) and six joints consisting of three revolute joints (J_R; *a*, *c*, and *e*), one prismatic joint (J_P; *f*), one rolling joint (J_O; *b*), and one cam joint (J_A; *d*). Therefore, $N_L = 5$, $C_{pR} = 2$, $N_{JR} = 3$, $C_{pP} = 2$, $N_{JP} = 1$, $C_{pO} = 2$, $N_{JO} = 1$, $C_{pA} = 1$, and $N_{JA} = 1$. Based on Equation (2.1), the number of degrees of freedom, F_p, of this mechanism is:

$$\begin{aligned} F_p &= 3(N_L - 1) - (N_{JR}C_{pR} + N_{JP}C_{pP} + N_{JO}C_{pO} + N_{JA}C_{pA}) \\ &= (3)(5 - 1) - [(3)(2) + (1)(2) + (1)(2) + (1)(1)] \\ &= 12 - 11 \\ &= 1 \end{aligned}$$

Therefore, the motion of this mechanism is constrained.

[Example 2.3]
Calculate the number of degrees of freedom for the horizontal tail control mechanism with two independent inputs of an aircraft shown in Figure 2.8 in which member 2 is an input (I) from the control stick, the actuator (members 8 and 9) is another input (II) for the purpose of stability augmentation, and member 7 is the output link to the horizontal tail.

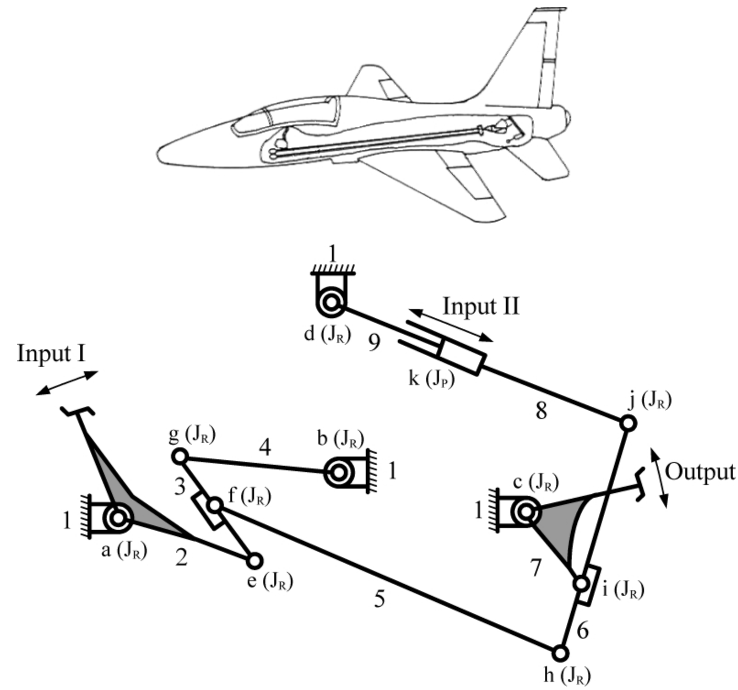


Figure 2.8 An aircraft horizontal tail control mechanism

This is a planar mechanism with nine members (links 1–9) and eleven joints consisting of ten revolute joints (*a*–*j*) and one prismatic joint (*k*). Therefore, $N_L = 9$, $C_{pR} = 2$, $N_{JR} = 10$, $C_{pP} = 2$, and $N_{JP} = 1$. Based on Equation (2.1), the number of degrees of freedom, F_p, of this mechanism is:

$$
\begin{aligned}
F_p &= 3(N_L - 1) - (N_{JR}C_{pR} + N_{JP}C_{pP}) \\
&= (3)(9 - 1) - [(10)(2) + (1)(2)] \\
&= 24 - 22 \\
&= 2
\end{aligned}
$$

Therefore, the motion of this mechanism is constrained.

If the stability augmented system, that is, input II, is not activated, links 8 and 9 have no relative motion to each other. It then becomes a mechanism with eight members and ten revolute joints, and its number of degrees of freedom, F_p, is:

$$\begin{aligned} F_p &= 3(N_L - 1) - N_{JR}C_{pR} \\ &= (3)(8-1) - (10)(2) \\ &= 21 - 20 \\ &= 1 \end{aligned}$$

Therefore, the motion of this mechanism is still constrained.

2.5.2 Spatial mechanisms

For spatial mechanisms, a member has six degrees of freedom consisting of translational motions along three mutually perpendicular axes and three rotational motions about these axes. The number of degrees of freedom, F_s, of a spatial mechanism with N_L members and N_{Ji} joints of type *i* is:

$$F_s = 6(N_L - 1) - \sum N_{Ji}C_{si} \tag{2.2}$$

where C_{si} is the number of degrees of constraint of *i*-type joint.

[Example 2.4]
Explain if the McPherson strut suspension mechanism (Figure 2.9) commonly used in automobiles has constrained motion. The input of this device is from the wheel to member 3.

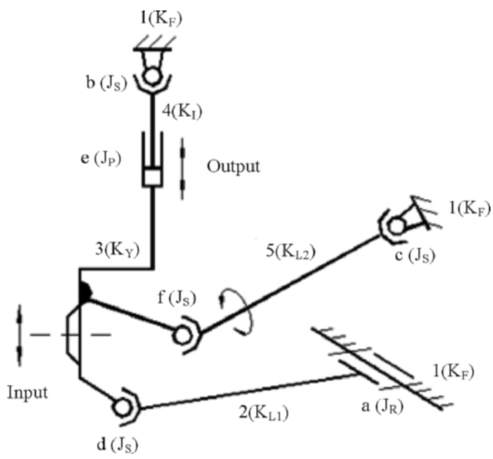


Figure 2.9 McPherson strut suspension mechanism

This is a spatial mechanism with five members (frame K_F, link 1; connecting link K_{L1}, link 2; wheel link and cylinder K_Y, link 3; piston K_I, link 4; connecting link K_{L2}, link 5) and six joints consisting of one revolute joint (*a*), one prismatic joint (*e*), and four spherical joints (*b*, *c*, *d*, and *f*). Therefore, $N_L = 5$, $C_{sR} = 5$, $N_{JR} = 1$, $C_{sP} = 5$, $N_{JP} = 1$, $C_{sS} = 3$, and $N_{JS} = 4$. Based on Equation (2.2), the number of degrees of freedom, F_s, of this mechanism is:

$$\begin{aligned} F_s &= 6(N_L - 1) - (N_{JR}C_{sR} + N_{JP}C_{sP} + N_{JS}C_{sS}) \\ &= (6)(5-1) - [(1)(5) + (1)(5) + (4)(3)] \\ &= 24 - 22 \\ &= 2 \end{aligned}$$

This is still a useful device, since the rotation of member 5 about the axis through the centers of spherical joints *c* and *f* is an extra degree of freedom that does not affect the input–output relation of the system.

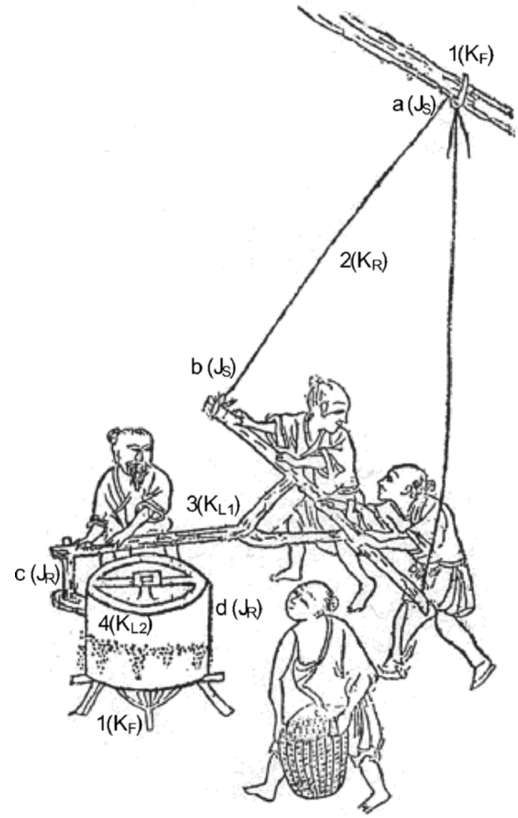
[Example 2.5]
Calculate the number of degrees of freedom for the ancient Chinese mill for removing rice hulls shown in Figure 2.10.

Since the two ropes are designed for the purpose of providing an efficient input through human power and are symmetrical, this device can be analyzed as a spatial mechanism with four members (the ground link K_F, member 1; the rope K_R, member 2; the horizontal bar and connecting rod K_{L1}, member 3; and the crank and the grinding stone K_{L2}, member 4). There are four joints consisting of two spherical joints (J_S; joint *a* and joint *b*) and two revolute joints (J_R; joint *c* and joint *d*). Therefore, $N_L = 4$, $C_{sR} =5$, $N_{JR} = 2$, $C_{sS} = 3$, and $N_{JS} = 2$. Based on Equation (2.2), the number of degrees of freedom, F_s, of this mechanism is:

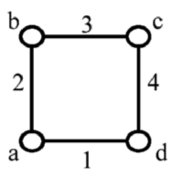
$$\begin{aligned} Fs &= 6(N_L - 1) - (N_{JR}C_{sR} + N_{JS}C_{sS}) \\ &= (6)(4-1) - [(2)(5) + (2)(3)] \\ &= 18 - 16 \\ &= 2 \end{aligned}$$

2.6 Topological Structures

Two mechanisms are said to be isomorphic if they have the same topological structures. The topological structure of a mechanism is characterized by its types and numbers of links and joints, and the incidences between them. The isomorphism of mechanisms can be identified based on the concept of a matrix named topology matrix, which is a powerful tool for the representation of the topological structures of various chains.



(a)



(b)

Figure 2.10 An ancient Chinese mill [4]

The topology matrix, M_T, of an (N_L, N_J) chain or mechanism is an N_L by N_L matrix. Its diagonal element is $e_{ii} = u$ if the type of member i is u. Its upper off-diagonal entry is $e_{ik} = v$ ($i < k$) if the type of the joint incident to members i and k is v, and its lower off-diagonal entry is $e_{ki} = w$ if the assigned name of the joint is w; and $e_{ik} = e_{ki} = 0$ if members i and k are not adjacent.

[Example 2.6]
Identify the topological structure of the (5, 6) planar mechanism shown in Figure 2.7.

This mechanism has five members and six joints. K_F (member 1) is the ground link, K_{Af} (member 2) is the output link, K_O (member 3) is a roller, K_I (member 4) is a piston, and K_Y (member 5) is a cylinder. The joint (*a*) incident to K_F and K_{Af} is a revolute joint (J_R); the joint (*b*) incident to K_F and K_O is a rolling joint (J_O); the joint (*c*) incident to K_F and K_Y is a revolute joint (J_R); the joint (*d*) incident to K_{Af} and K_O is a cam joint (J_A); the joint (*e*) incident to K_O and K_I is a revolute joint (J_R); and the joint (*f*) incident to K_I and K_Y is a prismatic joint (J_P).

The topology matrix, M_T, of this mechanism is:

$$M_T = \begin{bmatrix} K_F & J_R & J_O & 0 & J_R \\ a & K_{Af} & J_A & 0 & 0 \\ b & d & K_O & J_R & 0 \\ 0 & 0 & e & K_I & J_P \\ c & 0 & 0 & f & K_Y \end{bmatrix}$$

[Example 2.7]
Identify the topological structure of the McPherson strut suspension mechanism shown in Figure 2.9.

This mechanism also has five members and six joints. Member 1 (K_F) is the ground, member 2 (K_{L1}) is a connecting link, member 3 (K_Y) is the wheel link and the cylinder of the shock absorber, member 4 (K_I) is the piston of the shock absorber, and member 5 (K_{L2}) is another connecting link. The joint (*a*) incident to K_F and K_{L1} is a revolute joint (J_R); the joint (*b*) incident to K_F and K_I, and the joint (*c*) incident to K_F and K_{L2} are spherical joints (J_S); the joint (*d*) incident to K_{L1} and K_Y is also a spherical joint (J_S); the joint (*e*) incident to K_Y and K_I is a prismatic joint (J_P); and the joint (*f*) incident to K_Y and K_{L2} is another spherical joint (J_S).

The topology matrix, M_T, of this mechanism is:

$$M_T=\begin{bmatrix} K_F & J_R & 0 & J_S & J_S \\ a & K_{L1} & J_S & 0 & 0 \\ 0 & d & K_Y & J_P & J_S \\ b & 0 & e & K_I & 0 \\ b & 0 & f & 0 & K_{L2} \end{bmatrix}$$

[Example 2.8]
Identify the topological structure of the ancient Chinese mill shown in Figure 2.10.

This mechanism has four members and four joints. Member 1 (K_F) is the ground, member 2 (K_R) is the rope, member 3 (K_{L1}) is the connecting link, and member 4 (K_{L2}) is the crank. The joint (*a*) incident to K_F and K_R is a spherical joint (J_S); the joint (*b*) incident to K_R and K_{L1} is also a spherical joint (J_S); the joint (*c*) incident to K_{L1} and K_{L2} is a revolute joint (J_R); and the joint (*d*) incident to K_{L2} and K_F is also a revolute joint (J_R).

The topology matrix, M_T, of this mechanism is:

$$M_T=\begin{bmatrix} K_F & J_S & 0 & J_R \\ a & K_R & J_S & 0 \\ 0 & b & K_{L1} & J_R \\ d & 0 & c & K_{L2} \end{bmatrix}$$

2.7 Mechanism and Machine Design

The process for designing mechanisms and machines can be divided into the following seven steps as outlined in Figure 2.11.

Step 1. Problem definition

The first step in the design process is to define the problem, which includes listing all the specifications for the mechanism and the machine to be designed. The specifications are the input and output quantities such as the type of driving power, the required motion of the output member, the strength and rigidity of the members, and the amount of effective work produced. These should be systematically written down by designers to further enhance the functional design of the machine.

Step 2. Structural synthesis

After the output function and input type of a machine have been defined, the next step is to synthesize feasible topological structures based on the characteristics of the mechanism, and the design requirements and design constraints for achieving a constrained motion.

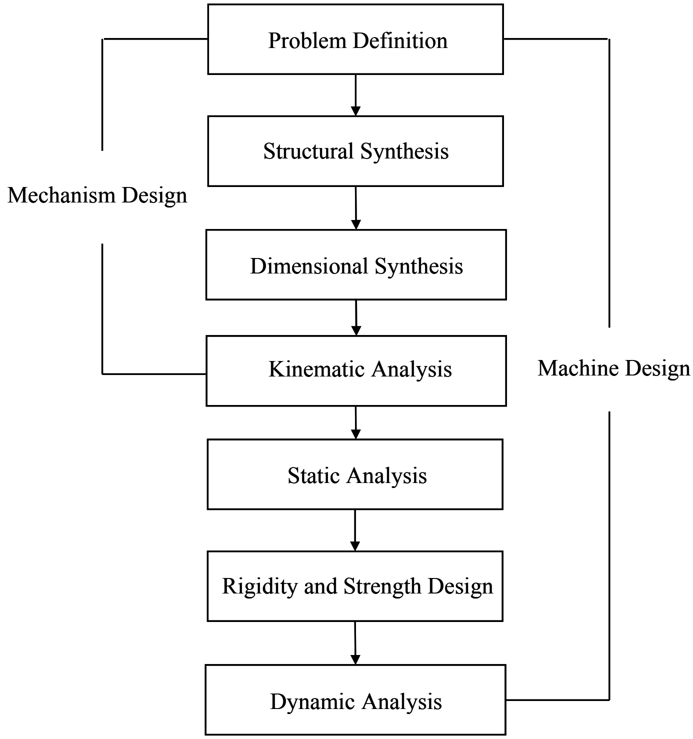


Figure 2.11 Process of mechanism and machine design

Step 3. Dimensional synthesis

The purpose of this step is to synthesize the geometric dimensions of members between joints such that the input state of motion (position, velocity and acceleration) corresponds to the required output state of motion. The key issue of this step is to determine the geometric relation and the relative motion of the machine members without considering the size, the mass, and the loading condition.

Step 4. Kinematic analysis

This step validates the synthesized mechanisms from Step 3 by determining if the input and output motion relations satisfy the requirements. These include the angular and the linear position, velocity and acceleration of the machine members and points of interest in the mechanisms. And, they are used for dynamic analysis.

Step 5. Static analysis
Based on the theory of statics and known static loading, this step is to analyze the static forces acting on every joint of the machine members in all possible positions. It also studies the required force or torque of the input members.

Step 6. Rigidity and strength design
Based on the theory of the strength of materials, known static loading and selection of materials, this step is to determine the size of machine members for ensuring that the members are sufficiently strong and rigid to safely withstand the imposed loading.

Step 7. Dynamic analysis
This step studies dynamic problems that arise with the motion and the mass of machine members. These problems include dynamic loading, inertia force, shaking force, shaking moment, dynamic balance, and dynamic response, etc. In this step, the strength and rigidity of the designed machine members from the previous steps are rechecked to ensure that they are within safety limits.

Mechanism design concerns only the first four steps, and machine design includes all seven steps. No step is independent since in the process of design, if any of the steps does not satisfy specifications, the results from the previous steps would have to be suitably revised. Other than the above-stated seven steps, the complete machine design process includes selection of a driving power, design of a control system, industrial design, the selection of material and treatments, thermal and fluid effect consideration, assembly and testing, and so on. The reconstruction design of lost ancient machines focuses on Steps 1 and 2, i.e., the problem definition and structure synthesis of mechanisms.

2.8 Structural Synthesis of Mechanisms

The reconstruction design of lost ancient machines is basically to synthesize all possible topological structures of mechanisms. Structural synthesis is the process of synthesizing the topological structure of mechanisms including the number of degrees of freedom, the numbers and types of machine members and joints, and the atlas of (generalized) kinematic chains. The process for the structural synthesis of mechanisms can be divided into the following steps as outlined in Figure 2.12.

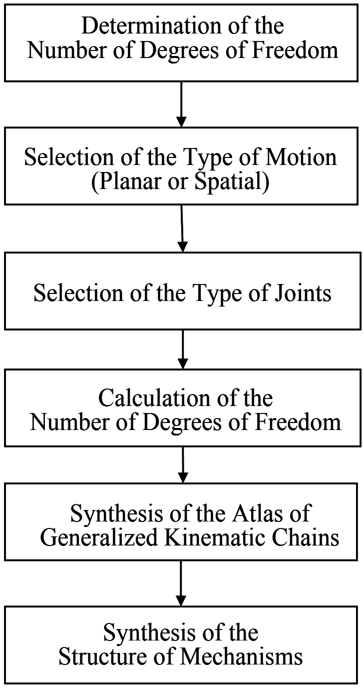


Figure 2.12 Process of structural synthesis of mechanisms

Step 1. Determination of the number of degrees of freedom
The number of inputs is a known condition and is decided by the purpose of the task. If no special requirement is specified, the number of degrees of freedom is taken as the number of independent inputs of the mechanism.

Step 2. Selection of the type of motion
To determine whether the mechanism is planar or spatial, various factors such as specifications, design requirements, design constraints and the designer's own judgments (e.g., the positions and the type of motion of the input and output members) have to be taken into consideration. If a planar mechanism is chosen, Equation (2.1) should be applied for the structural synthesis. Conversely, Equation (2.2) is applied for a spatial mechanism.

Step 3. Selection of the type of joints
This is based on the objective of the task, the type of motion, and the designers' judgments. Generally, a joint with one degree of freedom is chosen if no special requirement is specified.

Step 4. Calculation of the numbers of members and joints
Once Steps 2 and 3 are accomplished, Equation (2.1) or Equation (2.2) is employed to calculate the required numbers of members and joints.

Step 5. Synthesis of the atlas of generalized kinematic chains
The synthesis of the atlas of (N_L, N_J) generalized kinematic chains with N_L links and N_J joints is beyond the scope of this book. Figures 4.7–4.17 provide commonly used atlases of generalized kinematic chains.

Step 6. Synthesis of the structure of mechanisms
The last step is to synthesize the structure of mechanisms by assigning specific types of members and joints in every (N_L, N_J) (generalized) kinematic chain obtained in Step 5 subject to design requirements and constraints.

[Example 2.9]
Carry out the structural synthesis of a planar mechanism with one independent input and calculate the number of required links and joints.

1. Since the mechanism has one independent input with no other specifications, the number of degree of freedom is taken as one.
2. Since the mechanism is specified as planar, based on Equation (2.1),

$$F_p = 3\,(N_L - 1) - \Sigma N_{Ji} C_{pi} = 1 \tag{2.3}$$

3. Since joints in a planar mechanism with one degree of freedom are revolute joints (C_{pR} = 2), prismatic joints (C_{pP} = 2) or rolling joints (C_{pO} = 2), based on Equations (2.1) and (2.3),

$$N_{JR} + N_{JP} + N_{JO} = (3N_L - 4)/2 \tag{2.4}$$

4. Solving Equation (2.4) for the case of the smallest number of links, i.e., N = 4, results in the following solutions:

N_{JR}	0	0	0	0	0	1	1	1	1	2	2	2	3	3	4
N_{JP}	0	1	2	3	4	0	1	2	3	0	1	2	0	1	0
N_{JO}	4	3	2	1	0	3	2	1	0	2	1	0	1	0	0

Therefore, the number of joints is $N_J = N_{JR} + N_{JP} + N_{JO} = 4$.

[Example 2.10]
Carry out the structural synthesis for motorcycle rear suspension mechanisms with planar six-bar linkages and a shock absorber.

1. The only input to the rear suspension mechanism of a motorcycle is from the motion along the ground. As such, the number of independent input is one and the number of degree of freedom is also one.
2. It is a planar mechanism.
3. To simplify the design and construction of the mechanism, the joints are chosen as revolute joints. Since a suspension mechanism must have a prismatic joint for the shock absorber, based on Equation (2.1), the number of revolute joints, N_{JR}, is:

$$N_{JR} = (3N_L - 4)/2 \tag{2.5}$$

4. If the number of members does not exceed eight, based on Equation (2.5), the following solutions can be obtained,

N_L	4	6	8
N_J	4	7	10
N_{JR}	3	6	9
N_{JP}	1	1	1

5. For the design with six links (N_L = 6) and seven joints (N_J = 7), from Figure 4.13(a) and (b), there are two (6, 7) kinematic chains as shown in Figure 2.13.

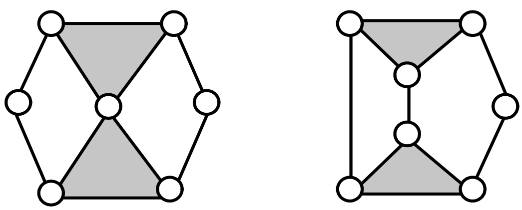


Figure 2.13 Atlas of (6, 7) kinematic chains

6. By assigning one link as the frame (link 1), one link as the swing arm for linking to the tire (link 3), and two binary links in series (dyad) with revolute joints at both ends as the shock absorber (link 5 and link 6) to each (6, 7) kinematic chain shown in Figure 2.13, all possible topological structure of the mechanism for the six-bar planar motorcycle rear suspension can be synthesized. Figure 2.14 shows six of them in which Figure 2.14(b) is the design of the Kawasaki uni-trak, Figure 2.14(c) is that of the Suzuki full-floater, and Figure 2.14(e) is design of the Honda pro-link.

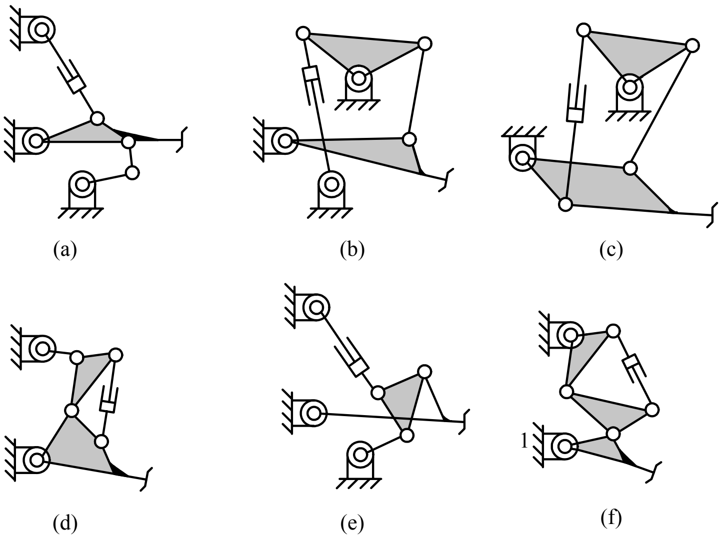


Figure. 2.14 Rear suspension mechanisms of motorcycles

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