MACHINE DESIGN

Volume 1

Mechanism Design

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Collage of Mechanical and Electric Engineering
in China University of Petroleum, Beijing

PETROLEUM INDUSTRY PRESS

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Abstract

This textbook is intended for students beginning the study of mechanical engineering design, and used for bilingual (Chinese and English) teaching. The contents of this textbook (Machine Design) include two parts: *Mechanism Design*, and *Design of Mechanical Elements*. *Mechanism Design* may be divided into three parts. Part 1 is the methods of analysis of mechanism which is composed of an introduction to kinematics and mechanism, and the analysis methods of velocity, acceleration, force, etc. Part 2 is the methodolgy of mechanism design including the basic methodology of mechanism design, the methodology of design of overall scheme, executive system of machine, etc. Part 3 is the detail of design of various mechanisms including planar linkage design, cam design, design of gears and gear trains, design of intermittent motion mechanism and miscellaneous mechanisms, etc.

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Preface

This textbook is intended for students beginning the study of mechanical engineering design. It is known that a course in the curriculum of mechanical engineering in China, is *machine design*, which is a very important major course for the mechanical engineering disciplines. The contents of this course include two parts: *mechanism design*, and *design of mechanical elements*.

The bilingual teaching (Chinese and English) is a useful form and method of teaching in higher education. The Ministry of Education of China desires to popularize the bilingual teaching in universities of China quickly in recent years. The Collage of Mechanical and Electrical Engineering in China University of Petroleum, Beijing decides to change the form of teaching of course of Machine Design into bilingual teaching, and thus the task of writing a textbook in English of Machine Design is put forward. This textbook will consist of two volumes, Volume 1 is *Mechanism Design*, and Volume 2 is *Design of Mechanical Elements*.

Mechanism Design may be divided into three parts. Part 1 is the methods of analysis of mechanism which is composed of Chapters 1, and 2, including an introduction to kinematics and mechanism, the analysis methods of velocity, acceleration, force, etc. Part 2 is the methodology of mechanism design which is composed of Chapter 3, and Chapter 8, including the basic methodology of mechanism design, the methodology of design of overall scheme, executive system of machine, etc. Part 3 is the detail of design of various mechanisms which is composed of Chapters 4 ~ 7, including planar linkage design, cam design, design of gears and gear trains, design of intermittent motion mechanism and miscellaneous mechanisms, etc. *Design of Mechanical Elements* covers the design of specific machine components. The topics covered are: 1) Screw fasteners, and the design of nonpermanent joints; 2) Welding bonding and the design of permanent joints; 3) Mechanical springs; 4) Rolling – contact bearings; 5) Lubrication and journal bearings; 6) Gearing introduction; 7) Spur and helical gears; 8) Bevel and worm gears; 9) Clutches, brakes, couplings, and flywheels; 10) Flexible mechanical elements, etc.

When writing this textbook, the author has considered the following points:

(1) To establish a new system of this course

I think that the main body of this course is design, but the analysis and synthesis are the foundation, and the scheme design of mechanical system is the standpoint. In order to train the ability of mechanical design of students, the relationships of main body, foundation, and standpoint about mechanical design must be handled correctly. In this book, the overall scheme design and mechanical system design of machine are added, the basic theory and method of analysis and synthesis are strengthened, and the methods and steps of design of various mechanisms and mechanical elements are emphasized. All these arrangements strive to establish a new system of this course for the training

of students.

(2)To make use of the advantages of the textbooks from both China and other countries

This is the advantage which relationship must be correctly handled, when selecting the contents of this book. For example, the contents of overall scheme design and mechanical system design of machine are selected from reference books of China; the contents of methodology of mechanism design are selected from textbook of America; the contents of design of intermittent motion mechanisms are chosen from textbooks of China, and part of contents of planar linkage design is adopted from the text of Oxford University of England. In a word, advantages from all sources must be adopted.

(3)To satisfy the special requirements of bilingual teaching

There is a table of contrasting English – Chinese technical terms in this course in the appendix of this book, and also there are guides of reference books for students given in the rear of each Chapter in order to guide students to contrast the Chinese and English references, and to deepen the study of some interesting details. In short all this measures serve for the convenience of teachers in teaching and students in studying in the course of bilingual teaching. It means that the taking peoples as the basis is very important.

These are the features of this textbook if these measures taken in the above three points are successful.

The book is written by Fang Huacan, professor of the College of Mechanical and Electrical Engineering in China University of Petroleum, Beijing.

I am grateful to the authors whose books have been partly chosen to be partial materials in this book. I am also grateful to my colleagues who made contributions to this book: Professor Huo Laijian, professor of Department of Foreign Language of China University of Petroleum, Beijing, who has checked the English manuscript of the book.

The author is also indebted to the leading cadre of administration of China University of Petroleum, Beijing, its Department of teaching affairs, and professors in the Collage of Mechanical and Electrical Engineering, who made contributions to this book: Professor Zhang Laibin, Professor Wu Xiaolin, Professor Zhai Yinghu, Professor Zhang Hong, Professor Hu Pinhui, Professor Tong Xinghua, Professor Qi Mingxia, etc.

The author thanks the following individuals for their contributions in making the manuscript of this textbook: Ye Zhongzhi, graduated student; Lu Xiumei, Director of Office of Collage of Mechanical and Electric Engineering in China University of Petroleum, Beijing, etc.

Please oblige me with valuable opinions of readers.

Fang Huacan

Beijing, PRC, July 7, 2004

Contents

Chapter 1 Introduction to Kinematics and Mechanism

1.1 Basic Concepts

1.1.1 Linkage

A linkage consists of links (or bars) (see Table 1 – 1), generally considered rigid, which are connected by joints (see Table 1 – 2), such as pins (or revolute), or prismatic joints to form open or closed chains (or loops). Fig. 1 – 1 shows that the mechanical linkages are employed to pump oil from wells.

Table 1 – 1 Planar link types

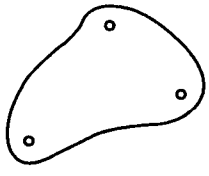
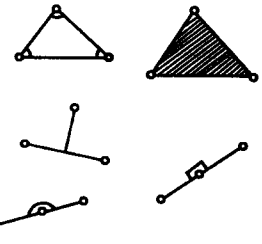
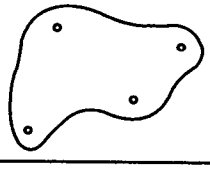
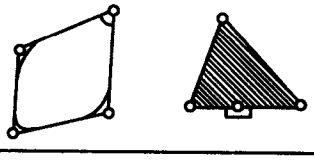
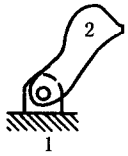
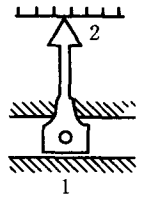
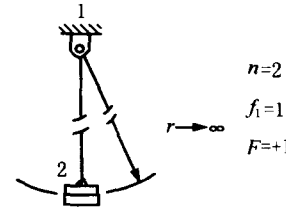
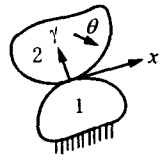
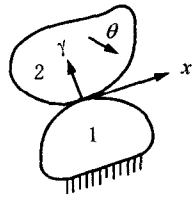
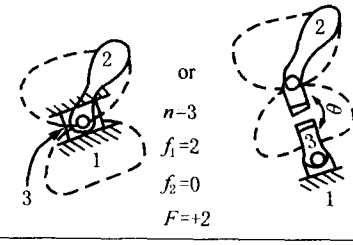
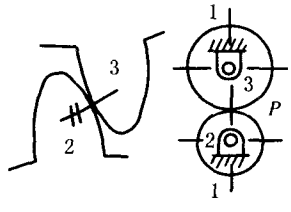
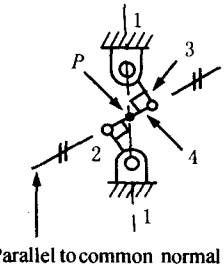
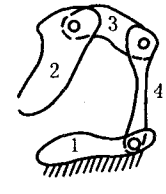
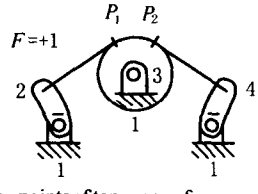
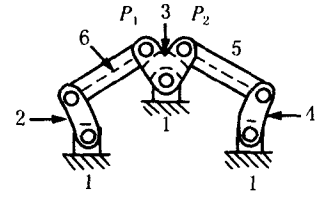
Link types	Typical form	Skeleton diagram(s)
Binary		
Ternary		
Quaternary		

Table 1 – 2 Planar kinematic pairs—link joint

Joint name	Diagram	Lower pair with equivalent instantaneous velocity
Pin (revolute)	 $n=2$ $f_1=1$ $F=+1$ F=degrees of freedom	

Continue

Joint name	Diagram	Lower pair with equivalent instantaneous velocity
Slider(prismatic)	 $n=2$ $f_1=1$ $F=+1$	 $n=2$ $f_1=1$ $F=+1$
Rolling contact (no sliding)	 $n=2$ $F=+1$	 $n=2$ $f_1=1$ $F=+1$
Roll – slide contact	 $n=2$ $f_1=0$ $f_2=1$ $F=+2$	 or $n=3$ $f_1=2$ $f_2=0$ $F=+2$
Gear contact (includes roll – slide contact between gear teeth and rolling contact between pitch circles)	 $n=3$ $f_1=2$ $f_2=1$ $F=1$	 $n=4$ $f_1=4$ $f_2=0$ $F=+1$ Parallel to common normal of contacting tooth flanks; P pitch point
Spring	 $n=2$ $f_1=0$ $f_2=0$ $F=+3$	 $n=4$ $f_1=3$ $f_2=0$ $F=+3$
Belt and pulley (no sliding) or chain and sprocket	 P_1,P_2: points of tangency of approaching and receding belt(chain)leads	 $n=6$ $f_1=7$ $f_2=0$ $F=+1$

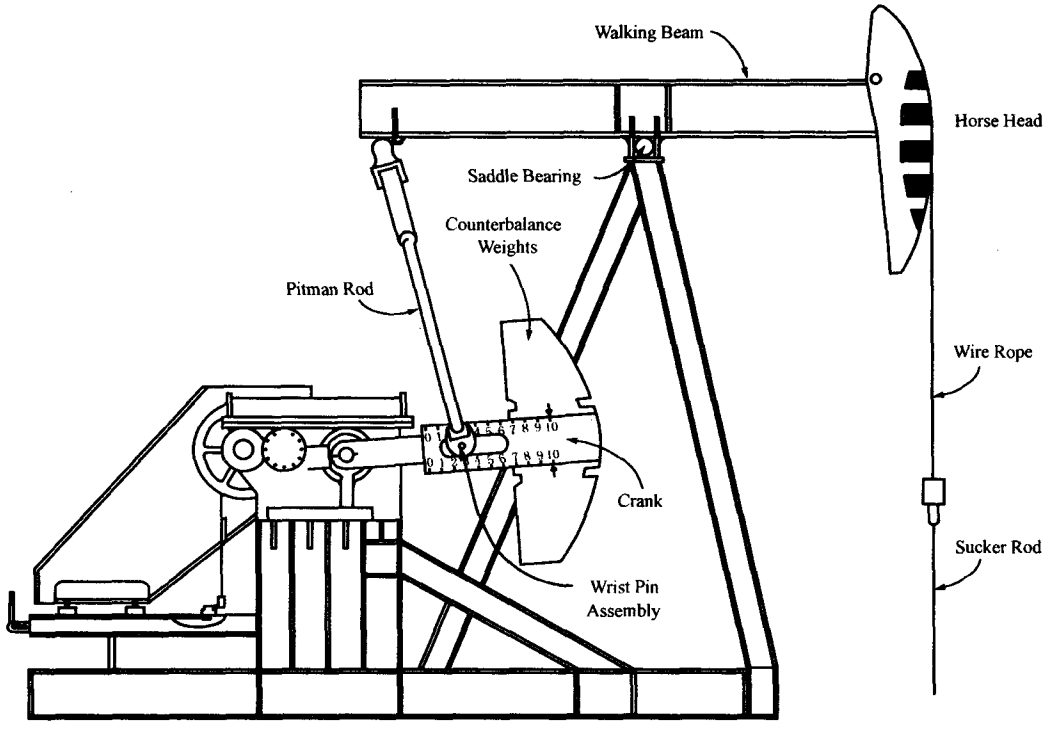


Fig. 1 – 1 Mechanical linkages are employed to pump oil from wells

1.1.2 Kinematic Chains

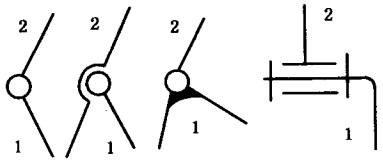
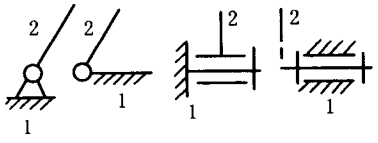
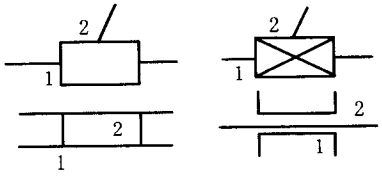
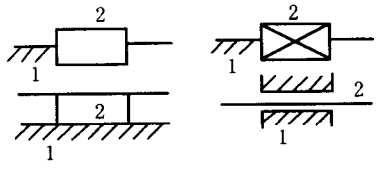
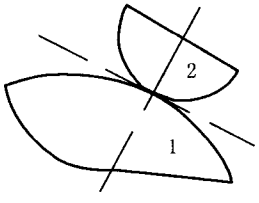
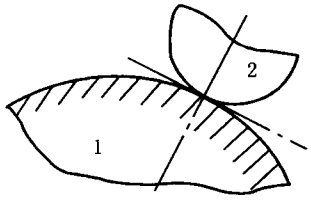
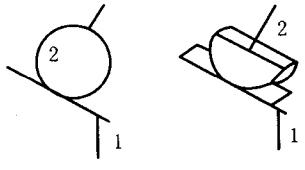
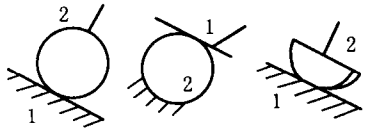
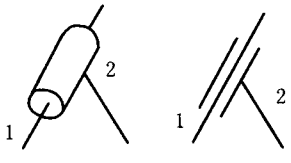
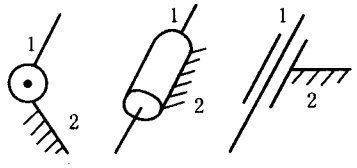
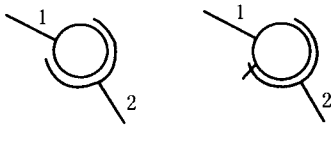
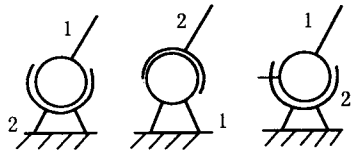
The open or closed loops formed by linkages is called kinematic chains. In the kinematic chains two connected links that permit relative motion between its "rigid" links are called kinematic pairs.

According to the different contact between two links, there are many different types of kinematic pairs(see Fig. 1 – 2). The pair in which links are connected through point or line contact is called high – pair(see Fig. 1 – 2(a),(b),(c)),because its degrees of freedom are high.

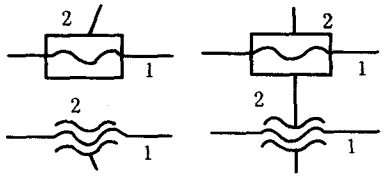
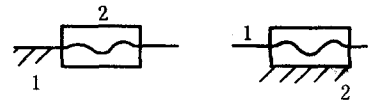
Otherwise, the pair in which two links are connected through surface is called a lower kinematic pair, owning to its degrees of freedom are low(see Fig. 1 – 2(d),(e)), In general, if the relative motion between two connected links is planar motion, the kinematic pair formed by these two connected links is called planar.

Kinematic pair(see Table 1 – 2). In other words, the relative motion between two connected links of a kinematic pair is space motion; the pair is called a space kinematic pair. Table 1 – 3 shows the symbols of different kinematic pairs according to notional standards of PRC(GB 460—1984).

Table 1-3 Symbol of kinematic pairs(PRC Standard)

Kinematic pair		Symbol of kinematic pair	
		Kinematic pair of two movement links	Kinematic pair of one of the two fixed links
Planar kinematic pair	Rotation pair	 (grade V)	 (grade V)
	Translation pair	 (grade V)	 (grade V)
	Plan high pair	 (grade IV)	 (grade IV)
Space kinematic pair	Point contact high pair and line contact high pair	 (grade I) (grade II)	 (grade I) (grade II)
	Cylinder pair	 (grade I) (grade II)	 (grade I) (grade II)
	Sphere plan pair and sphere pin pair	 (grade III) (grade IV)	 (grade III) (grade IV)

Continue

Kinematic pair		Symbol of kinematic pair	
		Kinematic pair of two movement links	Kinematic pair of one of the two fixed links
Space kinematic pair	Screw pair	 (grade V)	 (grade V)

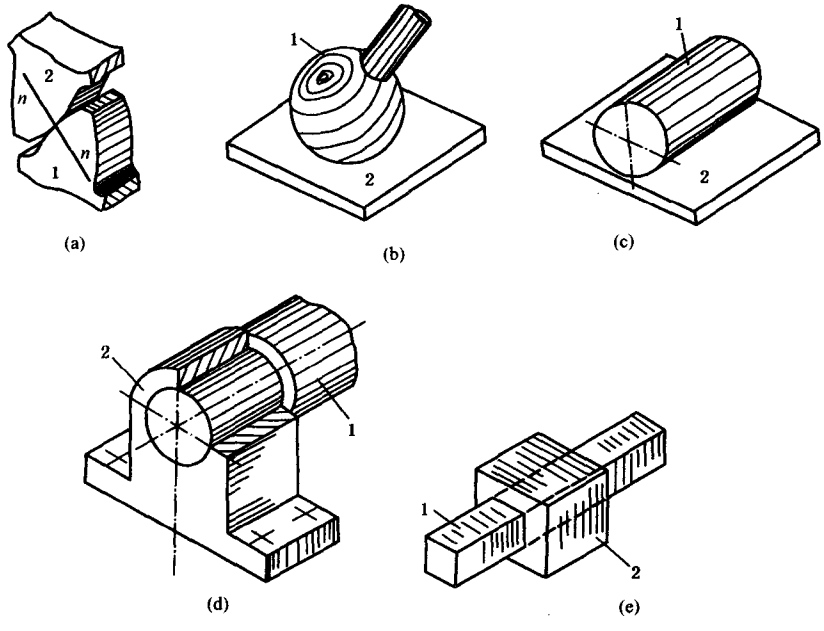


Fig. 1 – 2 Different types of kinematic pairs

1.1.3 Mechanism

A mechanism is a mechanical device that has the purpose of transferring motion and /or force from a source to an output.

The kinematic chains, with at least one link fixed, become

1) Mechanisms: if at least two other links retain mobility, or

2) Structures: if no mobility remains.

In other words, a mechanism permits relative motion between its "rigid" links; a structure does not.

Since linkages make simple mechanisms and can be designed to perform complex tasks, such as nonlinear motion and force transmission, they will receive much attention in this book.

According to the relative motion between connected links the mechanism may be divided into planar mechanism(planar motion) and space mechanism(space motion)(see Table 1-3).

1.1.4 Machine

A machine is a mechanical system consisting of various mechanisms that has the purpose of transferring energy and/or performing useful mechanical work, while the mechanism has only the purpose of transferring motion and/or force.

This is the main difference between the mechanism and machine. In general, a machine consists of the following four systems:

1) Motive power system: Such as internal combustion engine, hydraulic motor, pneumatic cylinder, electric motor and so on;

2) Executive mechanisms: Performing the given purpose of a machine;

3) Transmission system: Between the motive power system and executive mechanics to transfer power and/or motion;

4) Control system: Starting or stopping the given function of the machine at any time by operator; mechanical control system and electronic control system are very important in the modern machine design.

Fig. 1-1 shows the components of oil pumping jack.

Based upon the above descriptions of machine the contents for designing a machine can be divided into the following three aspects:

1) Kinematic design of mechanism: To select a proper mechanism and analyzing its kinematics in order to satisfy a given motion;

2) Dynamic design of machinery: Such as to decrease the velocity fluctuation, avoid harmful vibration, balance out inertial force, increase mechanical efficiency and so on;

3) Scheme design of mechanical system of a machine: It consists of selecting proper motive power engine, making the mechanical transmission system design, providing the executive mechanics and describing the control system.

1.2 Kinematic Diagrams

1.2.1 Relative Motion

All motion observed in nature is relative motion; That is, the motion of the observed body is relative to the observer.

In the study of motion, kinematics has been referred to as the science of relation motion. Design and analysis of machinery and mechanisms relies on the designer's ability to visualize relative motion of machinery components.

The first step in the motion analysis of more complicated mechanisms is to sketch the equivalent kinematic or skeleton diagram.

1.2.2 Skeleton (Kinematic) Diagram

The skeleton diagram serves a purpose similar to that of the electrical schematic or circuit diagram in that it displays only the essential skeleton of the mechanism, which, however, embodies the key dimensions that affect its motion. This requires a "stripped – down" stick diagram, such as that shown in Fig. 1 – 3. It is an equivalent kinematic diagram (sketch) of Fig. 1 – 1 (oil pumping jack). Here link 3 is the roller at A that is attached to link 2.

Fig. 1 – 3 shows the kinematic diagram (sketch) for the casement window linkage. Notice that there are six links, five pin joints, one slider joint, and one roller in this sketch. Note also that one loop of the mechanism contains a slider – crank linkage (1,5,4,6). Connected to the slider crank is a bar and a roller (2,3) which provide the input for opening and closing the window. The kinematic diagram simplifies the mechanism for visual inspection and, if drawn to scale, provides the means for further analysis.

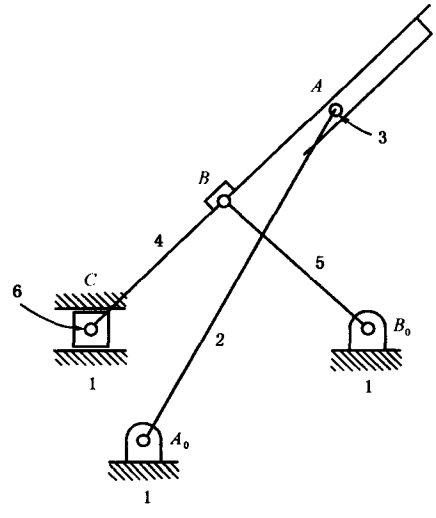


Fig. 1 – 3 Equivalent kinematic diagram (sketch) of oil pumping jack (see Fig. 1 – 1)

1.2.3 Two Forms of Kinematic Diagram

The kinematic diagram takes one of two forms:

1) a sketch (proportional but not exactly to scale);

2) the scaled kinematic diagram (usually used for further analysis: position, displacement, velocity, acceleration, force, and torque transmission etc.).

We have already used an unscaled kinematic diagram to help understand the oil pump mechanisms in Fig. 1 – 1 and Fig. 1 – 3, Fig. 1 – 4 is also a scale model of the oil – pumping jack.

For convenient reference, in the kinematic diagram the links are numbered (starting with ground link as number 1), while the joints are lettered. The input and output links are also labeled. Table 1 – 1 shows typical skeleton diagram of planar links.

1.2.4 Universal Symbol for Drawing Kinematic Diagram

In order to transfer motion from a source to an output various transmission mechanisms are often used. Table 1 – 4 shows the universal symbol for drawing various transmission mechanisms and electric motor in the kinematic diagram according to the national standard GB 4460—1984 of PRC.

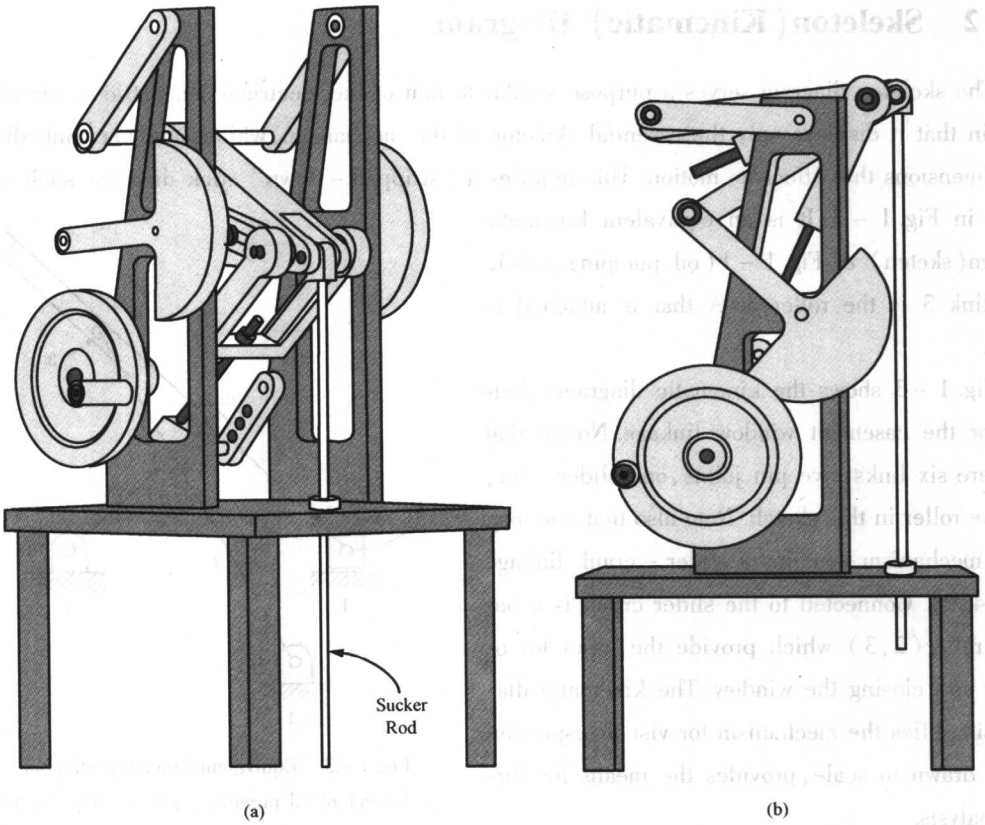
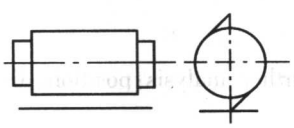
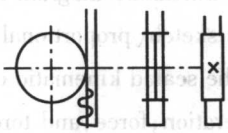
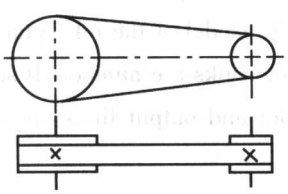
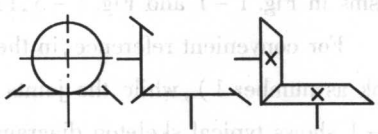
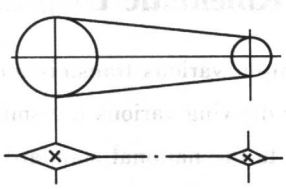
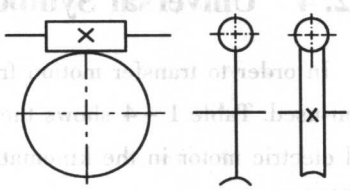
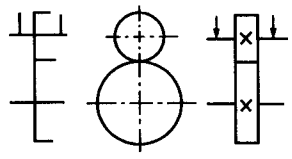
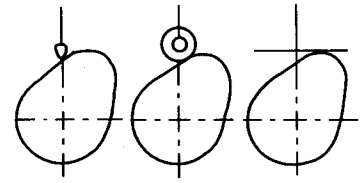
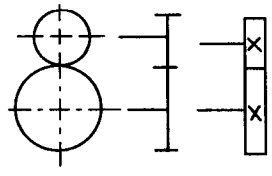
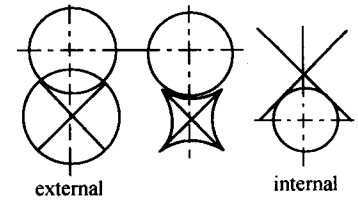
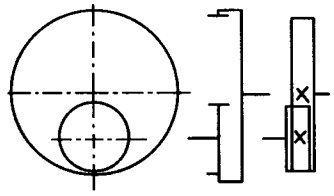
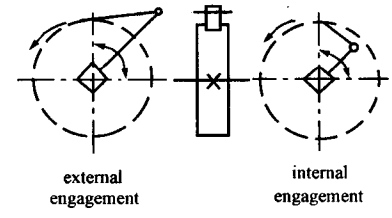


Fig. 1 – 4 A scale model of the "Minnesota" oil pumping jack

Table 1 – 4 Universal symbol for drawing kinematic diagram

Electric motor on frame		Gear and rack transmission	
Belt transmission		Bevel – gear transmission	
Chain transmission		Cylindrical worm transmission	

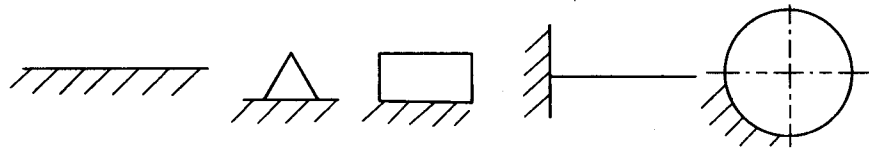
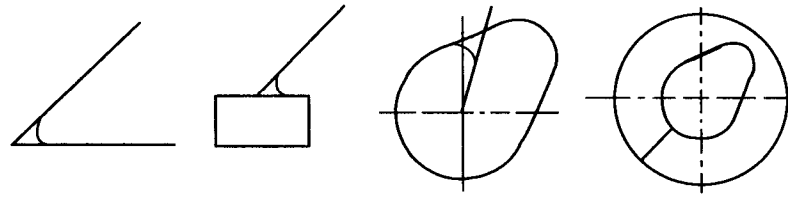
Continue

Friction – wheel transmission		Cam transmission	
External cylindrical gear transmission		Geneva wheel mechanism	
Internal cylindrical gear transmission		Ratchet mechanism	

While in Table 1 – 5 the expression methods of various linkages are given.

It is known that one purpose of the skeleton diagram is to provide a kinematic schematic of the relative motions in the mechanisms. For example, a pin joint depicts relative rotation, a slider depicts relative straight – line translation, and so on.

Table 1 – 5 Ewpression method for drawing some linkages

Link of bar and shaft	
Fixed links	
A same link	

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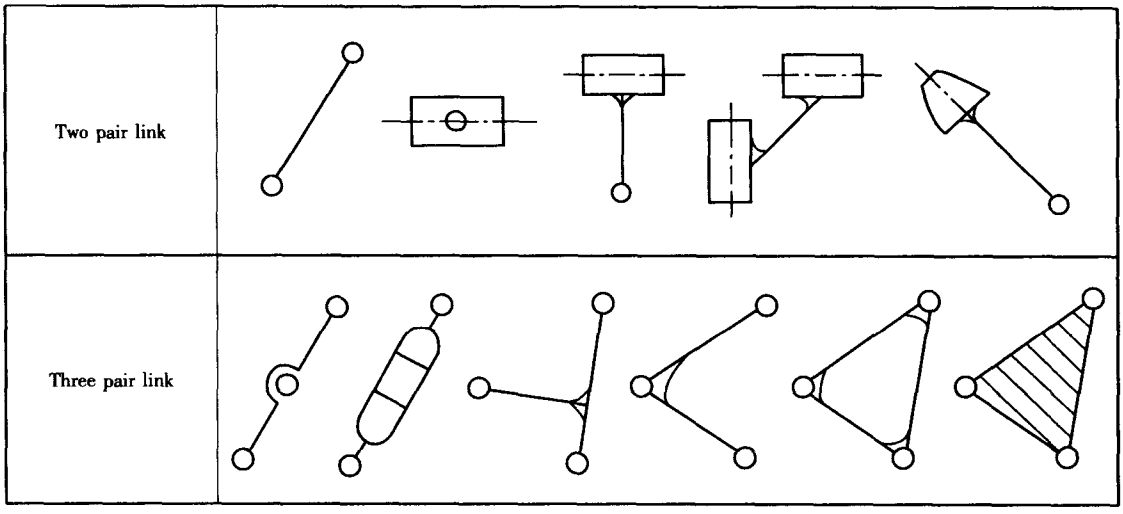

1.3 Degrees of Freedom

The next step in the kinematic analysis of mechanisms, following the drawing of the schematic is to determine the number of degrees of freedom of mechanism. There are hundreds of thousands of different linkage types that one could invent Envision a bag containing a large variety of linkage components from Table 1 – 1 and Table 1 – 2: binary, ternary, quaternary, links and so on; pin joints, slider joints; cams and cam followers; gears, chains, sprocket belts, pulleys and so on (Spherical and helical as well as other connections that allow three – dimensional relative motion are not included here, as only planar motion in parallel planes is discussed in this portion of the book).

Furthermore, imagine the possibility of forming all sorts of linkage types by putting a number of these components together. For example, several binary links might be connected by pin joints. Are there any rules that help govern how these mechanisms are formed. For instance is the linkage in Fig. 1 – 5 usable as a function generator, where we wish to specify the angular relationship between ϕ, the independent variable and φ, the dependent variable? Obviously, in order to answer these questions and to find the rules, the means of degrees of freedom must be known.

1.3.1 Conditions for Mechanism Having Determined Motion

Suppose that the exact position of a rigid link K is required in coordinate system XY as depicted in Fig. 1 – 6. How many independent variables will completely specify the position of this link? The location of point A can be reached, say, from the origin by first moving along the X axis by x_A and y_A in the direction of the Y axis. Thus, these two coordinates, representing two translations, locate point A. More information is required, however, to define completely the position of link K. If the angle of the line of points A and B with respect to the X axis is known, the position of link K is specified in the plane XY. Thus there are three independent variables: x_A, y_A, and (two translations and one rotation, or three independent coordinates) associated with the position of a link in the plane. In other