MECHANISMS AND MACHINE THEORY

（机械原理）

Ye Zhonghe
Lan Zhaohui
M.R. Smith

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Textbook for University

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Ye Zhonghe（叶仲和）
Lan Zhaohui（蓝兆辉）
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Abstract

This textbook is written according to "The Basic Teaching Requirements for the Course of Mechanisms and Machine Theory in Advanced Industrial Colleges" drawn up by the National Ministry of Education. It contains the authors' results on teaching and scientific research during recent years. It aims at cultivating students' basic design ability and creative ability in design. Analytical methods and synthesis of mechanisms are emphasized. This textbook reflects new achievements and developments current in mechanism study. Altogether there are twelve chapters: Introduction, Structural Analysis of Planar Mechanisms, Kinematic Analysis of Mechanisms, Planar Linkage Mechanisms, Cam Mechanisms, Gear Mechanisms, Gear Trains, Other Mechanisms in Common Use, Combined Mechanisms, Balancing of Machinery, Motion of Mechanical Systems and Its Regulation, Creative Design of Mechanism Systems. At the end of most chapters, many thinking problems and exercises are enclosed. To help Chinese students to read the text, an English-Chinese vocabulary is appended.

This book can be used as a textbook for the course of Mechanisms and Machine Theory or that of speciality English for undergraduates specializing in machinery in advanced engineering universities. It can also be used as a reference book for related teachers, students and engineering technicians.

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Preface

"Mechanisms and Machine Theory" is one of the important technical foundation courses for mechanical students in universities. It covers the basic knowledge needed in analysis and synthesis of commonly-used mechanisms and the dynamics of mechanism systems. This course gives students an elementary ability to design or improve mechanical devices. This course plays an important part in cultivating their creative ability and great attention has been paid to this course in engineering universities. Although many Chinese textbooks have been published, English textbooks written by Chinese teachers have not yet appeared.

Faced with the globalisation of the economy, technology and education, Chinese students should be able to study and work in English. They have, in fact, learnt English for six years in middle school. After entering university, they learn more English courses but, because almost all other courses use Chinese textbooks and are taught in Chinese, they have few opportunities to learn other courses in English directly. In order to change this status, more and more attention has been paid to English or bilingual teaching. Of course, English textbooks are in stock in English-speaking countries. However, at the initial stage, Chinese teachers and students could accept textbooks written by Chinese teachers more easily. It is for this reason that we have produced this textbook.

Mainly Ye Zhonghe and Lan Zhaohui of Fuzhou University wrote the contents of this book. The contents fulfil the fundamental teaching requirements in China. Dr. M.R.Smith, of the University of Newcastle upon Tyne in Great Britain, has had over thirty years' experience of teaching this subject and has checked and embellished the whole book to ensure the fluency of the language. This textbook is therefore a result of international cooperation.

We would like to express our thanks here to Professor Zou Huijun of Shanghai Jiao Tong University and Professor Zhang Ce of Tianjin University for their encouragement and support for this textbook. We are also grateful to Fuzhou University for the support for its publication. We hope that the publication of this textbook will promote the teaching in English of technical courses in universities throughout China. We hope also that people outside China will find this textbook helpful, not least in coming to know something about the teaching of "Mechanisms and Machine Theory" in China.

This book can be used as a textbook for the course of Mechanisms and Machine Theory or that of speciality English for undergraduates specializing in machinery in advanced engineering universities. It can also be used as a reference book for related teachers, students and engineering technicians.

Ye Zhonghe
Lan Zhaohui
M.R.Smith

CONTENTS

Chapter 1 Introduction

1.1 Study Object

There are vast numbers of different kinds of machines in the world, all with a wide variety of constructions, characteristics and uses. The single-cylinder four-stroke internal combustion engine shown in Fig. 1-1 is a typical and very familiar machine and works as follows. The power from the combusting gases pushes on the piston *2* causing it to translate downwards. Through connecting-rod (or coupler) *3*, the reciprocation of piston *2* is transformed into the rotation of crank *4* and flywheel $4''$. (The inertia of the flywheel $4''$ drives the piston *2* to move upwards on the return stroke.) The crank *4*, the flywheel $4''$, and the pinion $4'$ are fixed together by keys, so their motions are the same. Also, the camshaft (with its two cams $5'$ and $5''$) is keyed to gear *5*. Therefore, gear *5*, cam $5'$ and cam $5''$ rotate together as one body. The number of teeth on the gear *5* is twice that of the pinion $4'$ so that the pinion $4'$ rotates twice for every revolution of the gear *5*. This is to coordinate the motions of piston *2*, inlet valve *6* and outlet valve *7*. Through the contact between the cam $5'$ and follower *6*, the cam rotation is transformed into a regular reciprocation of the inlet valve *6* so that the valve opens and closes at a precise time. Similarly, the cam $5''$ controls the regular reciprocation of outlet valve *7*. In this way, the internal combustion engine transforms the heat energy from the fuel and air mixture into mechanical energy of the crank rotation.

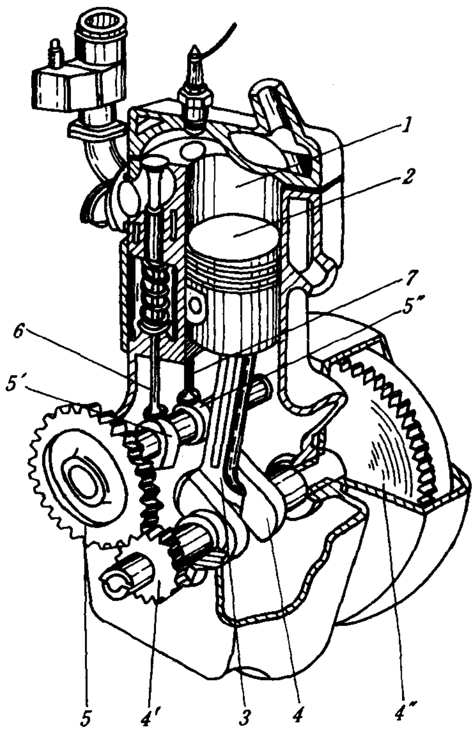


Fig. 1-1

The connecting-rod *3* is formed by the rigid assembly of the coupler body, big-end cover, nuts, bolts etc. They are the basic elements of manufacture, which are called *machine elements*. After assembly, the body, the big-end cover, the nuts and the bolts form a rigid structure and move together. The rigid structure is a basic element in kinematics analysis, which is called a *link*. Similarly, the crank *4*, the pinion *4′*, the flywheel *4″*, and the keys, form another link. The gear *5* and the two cams form a third link. In the study of kinematics, we are concerned only with the motion of links, not of individual machine elements.

As described above, the function of the cylinder *1* (or the engine body or frame), the piston *2*, the coupler *3* and the crank *4* is to transform the reciprocation of the piston *2* into the rotation of the crank *4*. They constitute a *slider-crank mechanism*. The function of the engine frame *1*, the pinion *4′* and the gear *5* is to change the direction and speed of rotation. They constitute a *gear mechanism*. The function of the frame *1*, the cam *5′* and the follower *6* is to transform the continuous rotation of the cam into a regular reciprocation of the follower. They constitute a *cam mechanism*. (The same applies to the frame *1*, the cam *5″* and the follower 7.) We see, therefore, that a *mechanism* is a system of links which can transform or transmit force and motion. The internal combustion engine shown in Fig. 1-1 is thus a system consisting of three kinds of mechanism. Its structural block diagram is shown in Fig. 1-2.

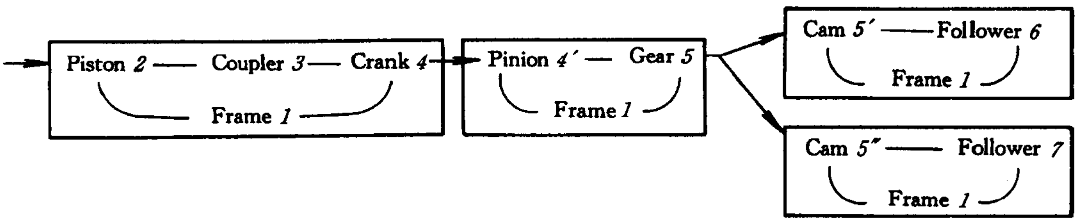


Fig. 1-2

Machine is a mechanical system that can transmit or transform energy, materials or information. As we shall see, many practical machines contain more than one mechanism while many simple machines are composed of only one basic mechanism. The term "*machinery*" is used to cover both mechanisms and machines. The study object of this book is machinery.

1.2 Study Content

The internal combustion engine is only one example of the many different kinds of machines in the world. Many machines, at first sight, appear to have very different constructions, transmission characteristics and applications. Fortunately, after examination of more examples in detail, we find that most machines, even very complicated ones, are built up from only a few types of commonly used mechanisms, such as linkage mechanisms (the slider-crank mechanism is one of these), gear mechanisms, cam mechanisms etc. The functions and profiles of machines may be quite different, but the mechanisms used in them are often the same. This situation is similar to the combinations of the seven-piece puzzle. With only seven plates, many different patterns can be constructed. The most content of this book is for "analysis" and "synthesis" of some commonly used mechanisms.

Although there are many kinds of machine, it is not possible or necessary to study all kinds in this book. We will examine the necessary basic topics in "machinery theory" and study the analysis and synthesis of some commonly used mechanisms. Dimensions affecting the motion of the mechanisms are called ***kinematics dimensions***. For example, the radii of the holes and the shape of the cross-section of the coupler *3* have no effect on its motion. They are not kinematics dimensions. In the coupler *3*, the distance between the centres of the two holes is the only kinematics dimension. *Synthesis* is the process of determining only the kinematics dimensions of a mechanism required to produce a particular motion. The term "synthesis" differs from "*design*" which is the process of prescribing the sizes, shapes, material compositions, arrangements of parts, calculations of strength, methods of production, etc. For example, the radii of the holes and the shape of the cross-section of the coupler *3* are not considered in the synthesis of the mechanism, but must be considered during the design of the machine when forces and stresses are to be calculated.

1.3 Purpose

This textbook "Mechanisms and Machine Theory" is an aid to the study of machines and mechanisms. It is hoped that, after studying this textbook, the students will grasp the basic theory and obtain the basic knowledge and skills needed in mechanisms synthesis and kinematic and dynamic analysis of machinery. This should lead to the ability to choose machinery motion patterns, analyze and synthesize mechanisms and develop designs for practical working machinery. The knowledge to be obtained from this textbook is therefore a fundamental in analyzing existing machines and designing new ones.

Chapter 2
Structural Analysis of Planar Mechanisms

2.1 Planar Kinematic Pairs and Planar Mechanisms

2.1.1 Kinematic Pairs

As mentioned in Chapter 1, a mechanism is a combination of links which can transform or transmit a determined motion. In order to transmit and transform motion, every link must be kept permanently in contact with other links by some kind of connection and have motion relative to them. Such a mobile connection is called a *kinematic pair*. For example, the connections between two links in Fig. 2-1 to Fig. 2-6 are kinematic pairs. A pair that permits only relative rotation is called a *revolute pair*, as shown in Fig. 2-1. A pair that allows only relative rectilinear translation is called a *sliding pair* or *prismatic pair*, as shown in Fig. 2-2. The kinematic pairs in Fig. 2-3 to Fig. 2-6 are called *gear pair*, *cam pair*, *screw pair*, *and spherical pair*, respectively. One kinematic pair can connect only two links.

The part of the link surface which makes contact with another link and forms a kinematic pair is called a *pair element*. The combination of two such elements on the connected links constitutes a kinematic pair. For example, the cylindrical surfaces of the hole and the shaft in a revolute pair (Fig. 2-1) are two pair-elements. Those connections that join two machine elements firmly and do not allow the connected machine elements to move relative to each other, such as welds, rivets, or nuts and bolts, are not kinematic pairs.

If two links connected by a kinematic pair can move relative to each other only on a plane, the kinematic pair is called a *planar kinematic pair*, otherwise, a *spatial kinematic pair*. For example, the revolute pair in Fig. 2-1, the sliding pair in Fig. 2-2, the gear pair in Fig. 2-3, and the cam pair in Fig. 2-4 are planar pairs, while the screw pair in Fig. 2-5 and the spherical pair in Fig. 2-6 are spatial pairs.

If two pair-elements of a kinematic pair have surface contact or its equivalent, the kinematic pair is known as a *lower pair*. The revolute pair in Fig. 2-1 and the sliding pair in Fig. 2-2 are planar lower pairs, while the screw pair in Fig. 2-5 and the spherical pair in Fig. 2-6 are spatial lower pairs. Since the two links of a lower pair are connected by a surface, the pressure between the two links is lower. This is a simple way of remembering why it is called a

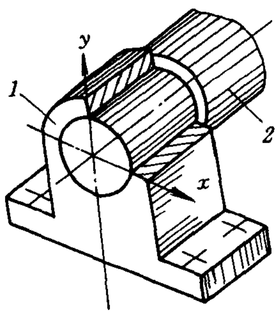


Fig. 2-1

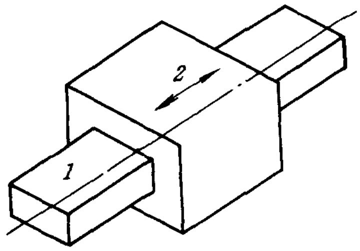


Fig. 2-2

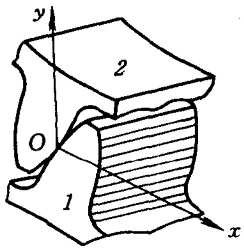


Fig. 2-3

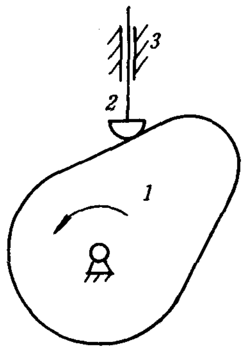


Fig. 2-4

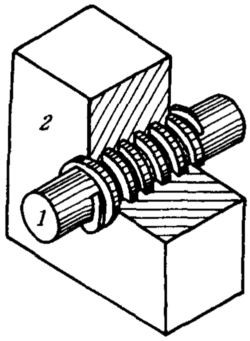


Fig. 2-5

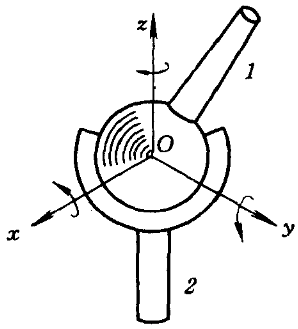


Fig. 2-6

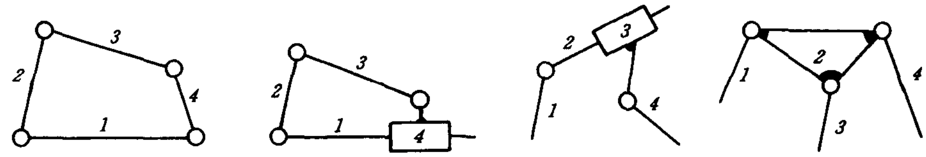
lower pair.

If the connection takes place only at a point or along a line (assuming the materials to be rigid), it is known as a *higher pair*. The gear pair in Fig. 2-3 and the cam pair in Fig. 2-4 are planar higher pairs. The connection between a ball and a plane is a spatial higher pair. Since the two links of a higher pair are connected by a point or a line, the pressure between the two links is higher. That is why it is called a higher pair.

2.1.2 Kinematic Chain and Mechanism

When a number of links are connected by means of kinematic pairs, the resulting mobile system is a *kinematic chain*. If every link in a kinematic chain has at least two pair-elements, all links form a *closed chain*, as shown in Fig. 2-7a and b. If one or more links in a kinematic chain have only one pair-element, then the kinematic chain will be an *open chain*, as shown in Fig. 2-7c and d. Most machines use closed chains, while open chains are often used in robots and manipulators.

In order to transmit motion, one of the links in the kinematic chain must be fixed to the base of the machine. The fixed link is also called the *frame* and there is only one frame for each mechanism. The frames of most machines are fixed to the ground, while the frames of



a) b) c) d)

Fig. 2-7

some machines, e.g.cars, aeroplanes, etc., can move relative to the ground. The relative reference system is often fixed to the frame when the motion of links is studied.

Some moving links have their own independent motion characteristics. They are called *driving links*. The other moving links are called *driven links*. Among all the driven links, one or more are used to generate the expected output motion. Such driven links are called *output links*. For example, in the internal combustion engine in Fig. 1-1, the piston *2* is the driving link, the coupler *3* and the crank *4* are the driven links. The crank *4* is also an output link.

If all links of a mechanism move in planes that remain parallel to each other, we say that the mechanism is a *planar mechanism*. Otherwise, it is a *spatial mechanism*. For example, in the internal combustion engine shown in Fig. 1-1, all planes on which links move are parallel, so it is a planar mechanism. Gear mechanism in Fig. 6-6 to Fig. 6-8 are spatial mechanisms. All kinematic pairs in a planar mechanism must be planar kinematic pairs, while the mechanism containing only planar kinematic pairs may be a spatial mechanism. For example, the universal joint shown in Fig. 8-20, which contains only revolutes, is a spatial mechanism.

If all kinematic pairs in a mechanism are lower pairs, the mechanism is called a *lower pair mechanism*, or more often, a *linkage mechanism*. All mechanisms in Chapter 4 are planar linkage mechanisms. The universal joint in Fig. 8-20 is a spatial lower pair mechanism. If a mechanism has one or more higher pairs, it is called a *higher pair mechanism*. The internal combustion engine in Fig. 1-1 is a planar higher pair mechanisms. The gear mechanism in Fig. 6-6 to Fig. 6-8 are spatial higher pair mechanisms.

2.2 The Kinematic Diagram of a Mechanism

2.2.1 Definition and Purpose

In order to analyze an existing mechanism or design a new mechanism, it is helpful to draw a simple diagram to indicate the kinematic relationship between links. Since this diagram is used *only* to express the relationship between the *motions* of links, it should be simple but provide all necessary (not redundant) information determining the relative motion of all links. Such a diagram is called the *kinematic diagram* of the mechanism. Those detailed structures irrelevant to the motion transmission should be omitted or simplified. For example, the profile and section shape of a link, the radius of a revolute, the shape of the cross section of a sliding pair, the number of machine elements in a link and their manner of connection are irrelevant to the motion transmission. They should not be crowed into a kinematic diagram. In the kinematic diagram, links and kinematic pairs should be represented by simple and specified symbols. In this way, the kinematic diagram can reflect the kinematic characteristics of the mechanism more clearly and more simply. The ability to draw the kinematic diagrams of mechanisms from examination of real machines or the assembly drawing of a machine is a basic technical skill for engineers engaged in designing, manufacturing or maintaining machines.

Since a mechanism is built of links and kinematic pairs, we study first the representations of links and kinematic pairs in the kinematic diagram before we start to draw the whole kinematic diagram of a mechanism.

2.2.2 Representation of a Kinematic Pair

The kinematic function of a kinematic pair is only to constrain the two links it connects in order to maintain a special relative motion. For example, the kinematic function of a revolute (referring to Fig. 2-1) is to constrain the two links connected to rotate about the centre of the revolute relative to each other. A revolute is conveniently represented by a small circle placed at the centre of the revolute no matter how large its radius is, as shown in Fig. 2-8. If a link is connected to the frame by a revolute; the revolute is called a *fixed pivot*. The frame is often indicated by shading, as shown in Fig. 2-8d. A fixed pivot can also be represented by a small circle with triangle support and shading, as shown in Fig. 2-8e.

The kinematic function of a sliding pair (Fig. 2-2) is to constrain the two connected links to translate in the direction of the pathway relative to each other. Therefore, the actual shape of the cross section of the sliding pair has no influence on the kinematics of the mechanism. Shown in Fig. 2-9 are some typical kinematic representations of sliding pairs. The shaded links represent the frame.

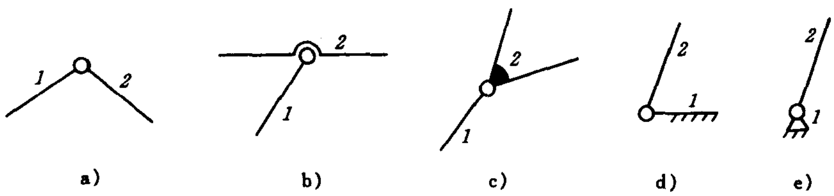


Fig. 2-8

For the two links in a sliding pair, the motion characteristics of the sliding pair will not change no matter which link is drawn as the sliding block or the guide bar. Furthermore, the kinematic relationship between two links in a sliding pair does not change so long as the centerline of the sliding pair in the kinematic diagram is parallel to the pathway in the mechanism.

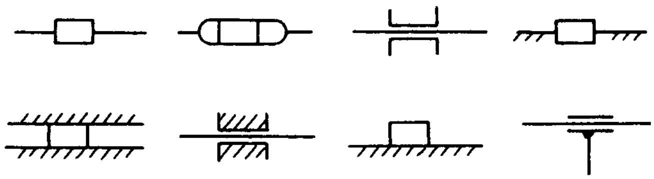
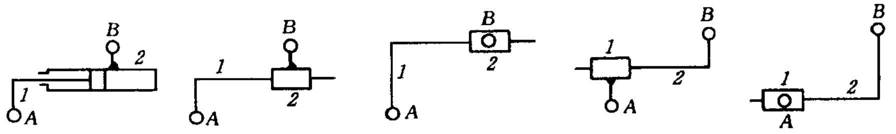


Fig. 2-9

Therefore, the two links of a hydraulic cylinder shown in Fig. 2-10a can be represented in the kinematic diagram as shown in Fig. 2-10b to e.



a) b) c) d) e)

Fig. 2-10

The gear pair is represented by two chain dotted circles tangent to each other (two tooth profiles may be added), as shown in Fig. 2-11, since two gears are equivalent kinematically to two friction wheels rolling without slipping.

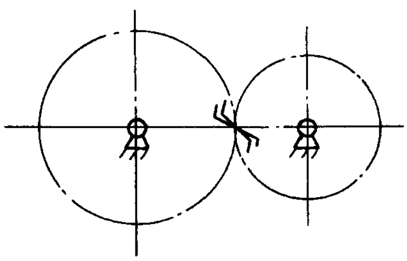
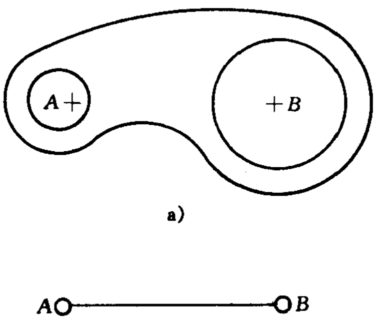


Fig. 2-11

In a cam mechanism, the cam contour and the end profile of the follower have an effect on the motion characteristics between the cam and the follower. Hence it is necessary to draw the actual cam contour and the end profile of the follower in the kinematic diagram, as shown in Fig. 2-4.

2.2.3 The representation of a Link in the Kinematic Diagram

The kinematic function of a link is to hold the relative position of all pair elements on the link unchanged during the motion of the mechanism. For example, for a two-revolute link in Fig. 2-12a, the kinematic function of the link is to keep the distance l_{AB} between the centers of the revolutes A and B unchanged. l_{AB} is the only kinematic dimension in this link. Therefore, a link with only two revolutes is illustrated merely by a straight line joining two small circles centered at the centers of the revolutes, as shown in Fig. 2-12b. A link with more than two pair elements can be represented by a hatched or welded polygon with pair elements at corners, as shown in Fig. 2-13.



b)

Fig. 2-12

Note the difference between two diagrams in Fig. 2-14.

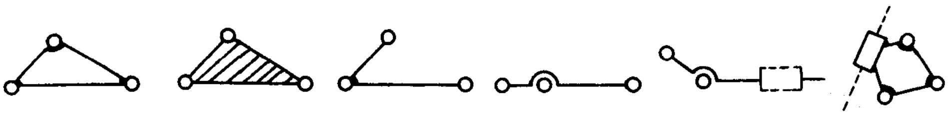


Fig. 2-13

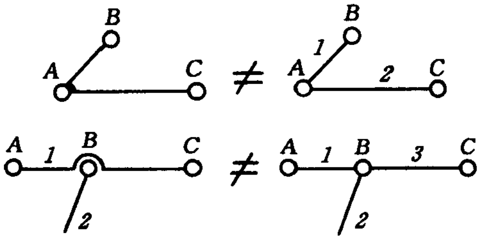
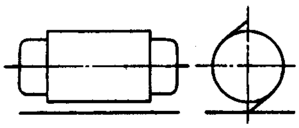
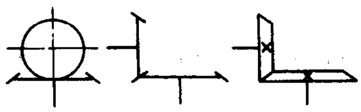
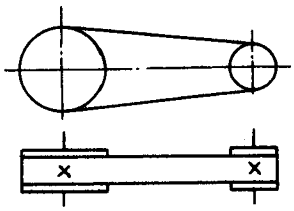
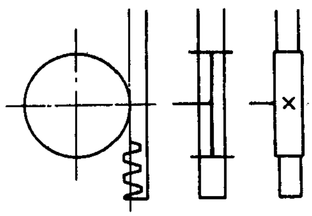
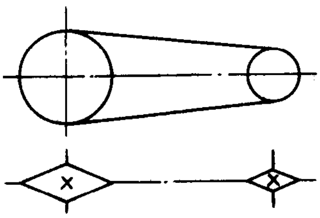
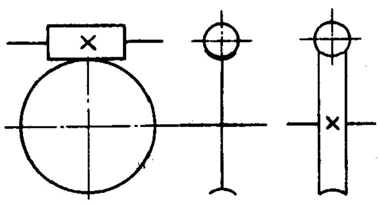


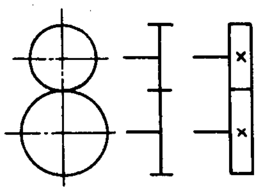
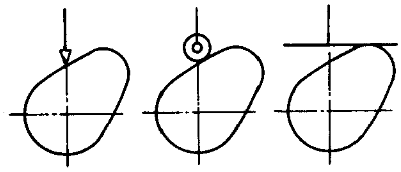
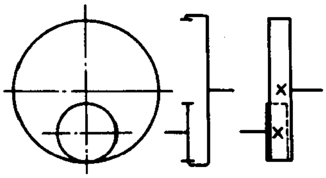
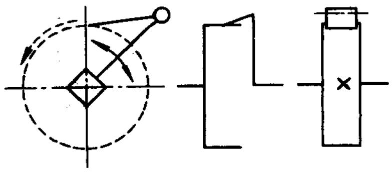
Fig. 2-14

The special representative symbols used in a kinematic diagram for some common mechanisms are listed in Table 2-1.

Table 2-1 Special Symbols for Some Commonly Used Mechanisms

Electric Motor 	Cone Gear Drive 
Belt Drive 	Rack and Pinion 
Chain drive 	Worm and Worm Gear Drive 

Continue

Outer-meshed Cylindrical Gear Drive	Cam Drive
	
Inner-meshed Cylindrical Gear Drive	Ratchet Mechanism
	

The kinematic diagram should be drawn to scale so that the diagram has the same kinematic characteristics as those of the original mechanism. It can be used in graphical kinematic and dynamic analysis. If we want to emphasize only the structural characteristics and illustrate the motion transmission, then the diagram does not have to be drawn exactly to scale. Such a diagram is called the *schematic diagram* of the mechanism.

2.2.4 Procedures for Drawing the Kinematic Diagram of a Mechanism

(1) Run the mechanism slowly, study carefully the structure of the mechanism. Determine the types of all kinematic pairs. Analyze the transmission route from the driving link to the output link. Then stop the mechanism at a suitable position for drawing.

(2) For a planar mechanism, all moving links move in parallel planes. Thus, a plane parallel to these planes is chosen as a drawing plane. Sometimes, a local view may be drawn to clarify the structure.

(3) Draw the schematic diagram of the mechanism. Firstly, draw all fixed pair elements or the pair elements on the frame. Be careful about the relative positions between these fixed pair elements. This is an important step. Then begin to draw the moving links. Draw the drivers first and then draw the driven links according to the route of motion transmission. Before drawing a link, determine the types of all kinematic pairs on it and its kinematic dimensions.

(4) For convenient reference, the links are numbered while the kinematic pairs are lettered. The input link is marked with an arrow in the direction of motion. Each link, no matter how many machine elements it has, can have only one serial number. An apostrophe to the right of the serial number may be used to distinguish the different machine elements of the same link. All machine elements belonging to the same link in the kinematic diagram must be con-