教育部高等教育面向21世纪课程教材

普通高等学校机械工程类专业双语系列教材

MECHANISMS AND MACHINE THEORY

机械原理

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WUHAN UNIVERSITY OF TECHNOLOGY PRESS

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(机械原理)

Li Can
Zhang Xianmin

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ABSTRACT

According to the basic teaching requirements for the course Mechanisms and Machine Theory, and the requirement of bilingual teaching, this textbook is written for students and teachers of mechanical engineering major in universities and colleges in China.

There are 12 chapters in this textbook: Introduction, Structure Analysis of Mechanisms, Kinematic Analysis of Mechanisms, Friction and Efficiency of Machineries, Planar Linkage Mechanisms, Cams and Their Design, Gears and Their Design, Gear Trains, The Design of Combined Mechanism and Other Common Mechanisms, Machinery Operation and Adjustment of Velocity Fluctuation in Machineries and Balancing. There are some problems and notes at the end of each chapter for students to grasp and practice.

This book can be used as textbook for course Mechanisms and Machine Theory, taught as bilingual teaching material, or be used as textbook for course English in Mechanical Engineering, for students of mechanical engineering major in universities and colleges. It can also be used as reference book for teachers, students and engineers of mechanical engineering major and other relevant majors.

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出版说明

随着经济全球化的发展，中国的经济必然要与世界接轨。由于近年来中国经济的快速增长，各发达国家的装备制造业纷纷向中国转移，中国将会成为世界制造业的中心。大力发展装备制造业是我国经济发展的一个重要方向，机电产品将是出口创汇的主要来源之一。中国的企业和产品必须面向世界市场，参与国际竞争。与此相适应，高等学校培养出来的人才，不管是到国外的企业（包括合资企业）工作，还是在国内的企业就业，用外语进行交流的机会将逐渐增多。因此，能熟练使用外语的学生在人才市场的竞争中将会具有更大的优势。

为了提高我国高等教育的国际竞争能力，教育部于2001年8月印发了《关于加强高等学校本科教学工作提高教学质量的若干意见》的通知（教高[2001]4号），文件强调，“按照‘教育面向现代化、面向世界、面向未来’的要求，为适应经济全球化和科技革命的挑战，本科教育要创造条件使用英语等外语进行公共课和专业课教学。……力争三年内，外语教学课程达到所开课程的5%～10%。暂不具备直接用外语讲授条件的学校、专业，可以对部分课程先实行外语教材，中文授课，分步到位。”该文件还大力提倡编写、引进和使用先进教材。高等学校要结合学科的调整，加快教材的更新换代，鼓励有条件的高等学校编写具有特色的高水平教材。

双语教学（使用母语和英语等外语进行教学）对于提高学生的外语水平非常有利。因此，有计划地逐步推进双语教学，扩大双语教学的课程门数，提高双语教学的质量，是今后一个时期内高等学校必须重视的工作之一。机械工程类专业招生人数最多、就业面最广，而且随着我国装备制造业的发展，今后对能够熟练使用外语（主要是英语）的机械工程类人才的需求会越来越大。因此，在机械工程类专业中实施双语教学，具有更加现实的意义。

教材是教学的基础，对于双语教学来说尤其如此。要搞好机械工程类专业的双语教学工作，必须要有相应的英文教材，而机械工业类专业的原版英文教材与我国的教学大纲及教学体系差异较大，不太适合我国高校阶段的教学状况。此外，我国大学生现阶段的英语水平参差不齐，大多数学生的英语水平还不足以很好地理解英文原版教材的体系和内容，故英文原版教材现在还不可能在我国一般的高等院校大面积地推广。

许多高等学校的机械工业类专业，在开展双语教学的试点工作中，除了采用少量英文原版教材之外，还编写了部分英文讲义，经过试用后有的已经出版。但迄

今为止，各校出版的零星英文教材，还没有形成系列，还远远不能满足日益发展的双语教学的需要。为此，武汉理工大学出版社经过广泛、深入的调研，组织编写了这套面向全国普通高等学校机械工程类专业双语教学的系列教材。

本套教材集中了国内十多所大学从事过双语教学的专家、教授和有过留学经历的中青年骨干教师，承担教材编写和审校的任务；并且组织了以全国高校机械工程类专业教学指导委员会主任杨叔子院士为首的编审委员会，负责整套教材的策划和指导工作。

本套教材以机械工程类专业的学科基础课为主要对象，选择相应的优秀中文教材作为蓝本，同时广泛收集国外优秀的同类英文教材作为参考。各门课程都按照我国通用教学大纲的要求，用英文编写，并附有适当的中文注释和说明，在文字上力求规范、通俗易懂、繁简得当。本套教材分两批编写、出版，并逐步配齐相应的电子课件，以满足双语教学的需要。我们衷心希望广大读者多提宝贵意见，共同将这套教材建设成为机械工程类专业双语教学的精品。

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PREFACE

Mechanisms and Machine Theory is the study of kinematics and dynamics of mechanisms, and the basic principles of machines. It is one of the important fundamental courses for mechanical engineering students. It also serves practical purpose in production, as it involves the first considerations of the designer in machine design.

In order to meet the challenge of economic globalization and technical and scientific revolution, according to the requirement of "facing modernization, facing the world, facing the future", English should be used in some courses in undergraduate education in China.

Because of historic reasons, there are significant differences in contents between Chinese textbook and English textbook for the course Mechanisms and Machine Theory. In this field we cannot find a suitable English textbook, which can appropriately cover the whole contents currently taught in China's universities and colleges. Thus to write and compile an English textbook which appropriately covers whole necessary contents and is suitable for China's mechanical education is a meaningful work and an urgent task.

This book is intended for undergraduate students of most mechanical engineering major and some other relevant majors, and contains sufficient material for a full semester's work. The usual prerequisites are advanced mathematics, kinematics statics, dynamics, and engineering graphics.

This textbook is a result of collective effort of many experienced teachers from several universities and colleges. They bring their plentiful experiences from their teaching and practical work in machine design to this textbok, and each is responsible for his own work. They are: Li Can from Wuhan University of Technology (chapter 1), Xiao Pei from Wuhan University of Technology (chapter 2), Wang Zhong from Southwest University of Science and Technology (chapter 3), Li Shuiping from Wuhan University of Technology (chapter 4), Mao Ya from Wuhan University of Technology (chapter 5), Li Gangyan from Wuhan University of Technology (chapter 6), Zhang Tie from South China University of Technology and Zhang Xueliang from Taiyuan Heavy Machinery Institute (chapter 7), Han Bin from North China Institute of Water Conservancy and Hydroelectric Power (chapter 8), Zhang Zhihong from Taiyuan Heavy Machinery Institute (chapter 9), Feng Xuemei from Wuhan University of Technology (chapter 10), Zhang Xianmin from South China University of Technology (chapter 11).

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Wuhan University of Technology
March 10,2004

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 ABOUT THIS COURSE

This course is called "Mechanisms and Machine Theory[1]". Obviously, the objects of this course are mechanisms[2] and machines, and the contents of this course are about the basic theoretical problems of design of mechanism and machine.

This course is intended for college students of mechanical engineering and is based on some foregoing courses, such as advanced mathematics, physics, chemistry, mechanics, and mechanical drawing. It is also the foundation of some other subsequent courses, such as machinery design, machine tools, mechanical manufacture, etc.

1.2 MECHANISMS AND MACHINES

What are mechanisms and machines?

A mechanism is a device, which transforms motion into some desirable pattern and typically involves very low forces and transmits very little power. Some examples of common mechanisms are a camera shuttle, a mechanical toy car, a mechanical clock, a folding chair, an adjustable desk lamp, and an automatic umbrella.

A machine is a device for transforming or transferring energy. It is sometimes defined as consisting of a number of fixed and moving bodies interposed between the source of power and work to be done for the purpose of adapting one to the other.

Machines are designed to provide significant forces, transform and/or transmit significant power and energy. Some examples of machines are a food blender, an automobile transmission system, a bulldozer, a mechanical manipulator and a robot. The electric motor transforms electrical energy into mechanical energy, while its counterpart, the electrical generator, transforms mechanical energy into electrical energy. A gasoline engine acts as a machine for transforming chemical energy into mechanical energy. The input energy is released

by gasoline's burning. This energy is transferred to the crankshaft, where it appears as output mechanical energy and is the product of the torque and the angle of crankshaft rotation. Of course, they are also machines.

All machines are composed of mechanism or mechanisms, which, in turn, are composed of kinematical elements[3] such as links[4], cams[5], gears[6], belts[7], chains[8], etc. For example, a typical internal-combustion engine[9] contains at least one slider-crank mechanism[10] composed of machine frame, piston[11], connecting rod[12] and crankshaft[13]; some gear mechanisms composed of frame, pinions and gears[14], and at least two cam mechanisms[15] composed of frame, cams and followers. Your bicycle is a simple example of kinematical system that contains a chain drive mechanism to provide torque multiplication and a linkage[16] for braking. An automobile contains many more examples of mechanisms. Its steering system, wheel suspension, and engine, all contains linkages. The engine valves are operated by cam and follower mechanisms and the transmission is mainly gear mechanisms, even the windshield wipers are driven by a linkage mechanism.

Construction equipment such as tractors, cranes, and backhoes all use linkages extensively in their design.

Though all machines are mechanisms, not all mechanisms are machines. Many instruments are mechanisms but not machines because they do not do useful work, nor do they transform energy. For example, a clock does not work in excess of what required to overcome its own friction.

To better explain the difference between the mechanisms and machines, the mechanisms can also be defined as a system of elements arranged to transmit motion in a predetermined fashion. Correspondingly, the machines can be defined as a system of elements arranged to transmit or transform power and energy.

There is no clear-cut dividing line between mechanisms and machines. They differ in degree rather than in kind. If the force or energy levels within the device are significant, it is considered a machine; if not, it is considered a mechanism.

One of the tasks in solving any machine design problem is to determine the kinematical configuration, that is, the mechanism need to provide desired motions. Forces and stress analysis cannot be done until the kinematical issues have been solved.

Mechanisms, if lightly loaded and run at low speeds, can be treated as kinematical devices; that is, they can be analyzed kinematically without regard to forces, because the actually involved dynamic force is small and can be neglected. On the other hand, machines must first be treated as mechanisms, a kinematical analysis of their positions, velocities and accelerations must be done, and then they must be subsequently analyzed as dynamic systems in which their static and dynamic forces due to those accelerations are analyzed, because the actually involved dynamic force is large and cannot be neglected.

1.3 CONTENT OF THIS COURSE

The main content of this course includes following four aspects:

1.3.1 Fundamental Knowledge for Mechanism Structure Analysis

In this aspect we will first study the compositions of mechanisms, the effects of these compositions on the mechanisms movements, and the conditions for the mechanisms to have constrained motions. In addition, in order to facilitate our study on mechanisms we will also learn how to express the mechanism structures through simple and explicit drawing, that is, kinematical diagram.

1.3.2 Movement Analysis of Mechanisms

Kinematics of machine is the study of the relative motion of machine parts without regard to forces, and is one of the first considerations of the designer in the design of a machine. A kinematical study is necessary to insure that the designed machines have optimum mechanisms and have required displacement, velocity, and acceleration. In addition, the kinematical analysis of an existing machine will enable us to understand and use the machine better.

1.3.3 Dynamics of Machines

Dynamics treats with forces acting on the parts of a machine and the motions resulting from these forces. A dynamic analysis is necessary to insure that balance is provided for rotating and reciprocating parts and that all members are strong enough to withstand static and dynamic forces.

But in real design practice, these two aspects are really not physically separable. We separate them mainly for instructional reason in engineering education. One cannot design a good mechanical system without taking both aspects into thorough consideration.

In machinery, the largest forces encountered are often those due to the dynamics of the machine itself. These dynamic forces are proportional to accelerations, which bring us back to kinematics, the foundation of mechanical design. Very early and basic decisions in the design process involving kinematical principles can be crucial to the success of any mechanical design. A design, which has poor kinematics, will prove troublesome and perform badly.

From Newton's law, $F=ma$, one typically needs to know the accelerations in order to compute the dynamic forces. There are also many situations in which the applied forces are known and the resultant accelerations are to be found. It results in two types of problems in dynamic study of machines: one is to analyze the forces exerted on each member of the machines and the work done by these forces, the other is to analyze the movement conditions of the machines acted by known eternal forces.

There are also other two types of problems. In most cases, the running velocities of machines are unstable. The speed fluctuations may be harmful to the machine operations and have to be adjusted properly. This is the speed adjustment problem. In addition, the inertia

forces caused by accelerations could make great dynamic pressure on corresponding joints and parts, damage the machines and harm the machine operations and therefore must be balanced. This is the machine balance problem.

1.3.4 Study of Commonly Used Mechanisms

In our daily life we see a great variety of machines such as sewing machines, washing machines, automobiles, tractors, etc. All different machines have different appearances, different structures and are used for different purposes. A simple machine may contain only a few parts, while a complicated machine may contain numerous and jumbled parts. But, through careful analysis we can find that all these different machines, from the most sophisticated to the simplest, are composed of some common and basic mechanisms, such as four-bar linkages, gear trains, cam mechanisms. Thus, we cannot study all machines, but we need to analyze all these basic mechanisms, study their characteristics and learn the design methods to meet some specified requirements.

1.4 DESIGN PROCESS AND THIS BOOK

Machine design is a creative, multidisciplinary activity. It has been defined as "… the process of applying various techniques and scientific principles for the purpose of defining a device, or a mechanical system in sufficient detail to permit its realization… Design may be simple or enormously complex, easy or difficult, mathematical or nonmathematical; it may involve a trivial problem or one of great importance."

Much of mechanical engineering education deals with topics of analysis, which means to decompose, to take part, to resolve into its constituent parts. The engineer must know how to analyze systems of various types, mechanical, electrical, thermal, or fluid. Analysis requires a thorough understanding of both the appropriate mathematical techniques and the fundamental physics of the system's function. But, before any system can be analyzed, it must exist, and a blank sheet of paper provides little substance for analysis. Thus the first step in any engineering design exercise is that of synthesis[17], which means putting together.

In this course, we will pay great attention on kinematical analysis and synthesis. In kinematical analysis, a particular given mechanism is investigated based on the mechanism geometry plus possibly other known characteristics (such as input angular velocity, angular acceleration, etc). Kinematical synthesis, on the other hand, is the process of designing a mechanism to accomplish a desired task. Here, choosing the type as well as the dimensions of the new mechanism can be part of kinematical synthesis.

On the other hand, in general we will not involve strength and process consideration of machine parts and thus not involve detailed dimension design of machine parts. These aspects of design will be considered in another course——mechanical design.

Notes

1 美国的大学课程设置与我国不完全一致，美国国内各大学的课程内容与课程名称也不统一，美国一些大学开设的课程 Mechanisms and Machine Theory 与我国的机械原理课程的内容大致相当。

2 mechanism 机构

3 kinematical element 运动学元件

4 link 构件

5 cam 凸轮

6 gear 齿轮

7 belt 带

8 chain 链

9 internal-combustion engine 内燃机

10 slider-crank mechanism 曲柄滑块机构

11 piston 活塞

12 connecting rod 连杆

13 crankshaft 曲轴

14 frame, pinion and gear 机架、小齿轮和大齿轮

15 cam mechanism 凸轮机构

16 linkage 连杆机构

17 synthesis 综合

CHAPTER 2

STRUCTURE ANALYSIS OF MECHANISMS

2.1 INTRODUCTION

The processes of drawing kinematical diagrams and determining degrees of freedom of mechanisms are the first steps in both the kinematical analysis and the synthesis process. The fundamentals described in this chapter are most important in the initial stages of either analysis or synthesis.

Content and objective of structure analysis of mechanisms are:

(1) Study of the composition of mechanism and method of drawing kinematical diagram

Since mechanisms will be studied in this text, we must first understand the composition of these mechanisms. On the other hand, the first step in the motion analysis of complicated mechanisms is to draw the kinematical or skeleton diagram.

(2) Understanding of rules concerning the motion certainty of mechanisms

Since a mechanism is a mechanical device that can transfer motion and/or force from a source to an output, its motion must be predetermined and predictable. We should understand the rules concerning this aspect.

2.2 COMPOSITION OF MECHANISMS

Within any mechanism there must be bodies that can move and are interconnected. In the kinematical analysis and synthesis of machines, the bodies are referred to as components, and connections are referred to as joints.

2.2.1 Component

Component[1] is also called as link. All machines are composed of parts. An internal-combustion engine is composed of several parts, some parts can move independently as one unit, e. g. crank shaft, and some parts are joined together tightly and move as only one

independent unit. For example, the connecting rod is united by the rod body, rod cover, shaft tile, bolts, nuts and washers. Every unit that has independent motion in mechanism is called a component. From the view point of motion, all machines are composed of components.

2.2.2 Joint

Joint is also called as kinematical pair[2]. The machines that we will be interested in will all consist of more than one component. In these components, one component must be at least connected to another component, and the connection between these components will allow some relative motions. These connections are called joints. Figure 2-1 shows four types of joints that may be used to connect two components together but allow some relative motions between them.

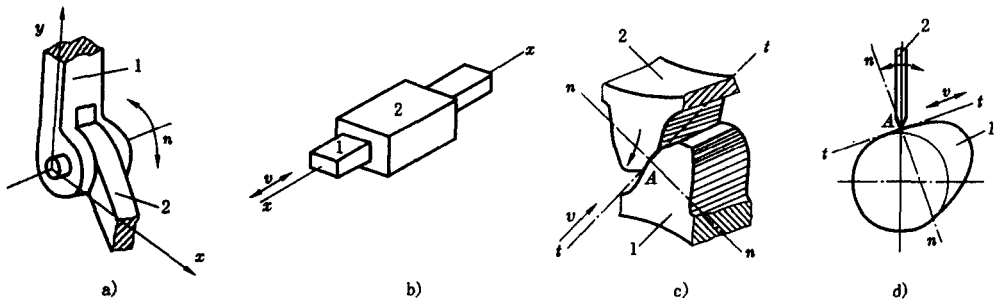

Figure 2-1

Figure 2-2 shows a rigid body lying on a flat piece of paper with an x, y coordinate system added. If we constrain this rigid body to always remain in the plane of the paper, three parameters (DOF) are required to completely define the position of the rigid body on the paper, two linear coordinates (x, y) to define the position of any one point on the rigid body and one angular coordinate to define the angle of the rigid body with respect to the axes. The minimum number of measurements needed to define its position are shown in the figure as x, y and θ (two translations and one rotation, or three independent coordinates). In other words, an unconstrained rigid body in plane motion has three DOF. Note that DOF is defined with respect to a selected frame of reference.

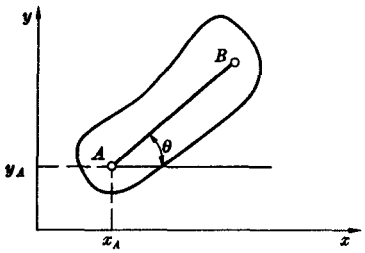

Figure 2-2

The connections between the components serve to constrain the motions of the components so that they are not free to move with what would otherwise be three degrees of freedom for each body. For example, if the body 1 were to be attached to reference frame xy in Fig. 2-1a by a revolute joint or pivot centered at point A and with its axis perpendicular to the page, the body 2 would then be free to move relative to the reference frame in such a manner as to vary the parameters α but not such as to vary x_A or y_A. Use of the revolute joint would