工业和信息化部“十二五”规划教材

国家级双语教学示范课程建设项目

Theoretical Mechanics

理论力学（双语）

WANG Kaifu
王开福 编著

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Synopsis
内容简介

This book consists of statics, kinematics, and kinetics. The main contents of the book include: statics of particle, reduction of force system, statics of rigid body, friction, kinematics of particle, kinematics of rigid body in plane motion, resultant motion of particle, kinetics of particle, kinetics of rigid body in plane motion, mechanical vibration, principle of virtual work, Lagrange's equations, and impact.

The book can be used as an English, Chinese, or bilingual textbook of theoretical mechanics for the student majoring in aeronautical, mechanical, civil, and hydraulic engineering.

本书由静力学、运动学和动力学组成。主要内容包括:质点静力学、力系简化、刚体静力学、摩擦、质点运动学、刚体平面运动学、质点合成运动、质点动力学、刚体平面动力学、机械振动、虚功原理、拉格朗日方程和碰撞。

本书可作为高等院校航空、机械、土木和水利等专业学生的英文、中文或双语理论力学教材。

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Preface

Theoretical mechanics is a required subject for the student majoring in aeronautical, mechanical, civil, and hydraulic engineering and usually taught during the sophomore year. This book intends to provide the student with the theory and application of theoretical mechanics.

The book is written in English and Chinese, respectively; the English part of the book can be used as an English textbook of theoretical mechanics, while the Chinese part can be used as a Chinese textbook of theoretical mechanics.

Theoretical mechanics consists of statics, kinematics, and kinetics. Statics is the study of bodies at rest or in equilibrium, kinematics deals with the geometry of the motion without regard to the forces acting on bodies, and kinetics is with the relation between the motion of bodies and the forces acting on bodies.

The book is organized into fourteen chapters and two appendixes. Chapter 1 is an introduction to the fundamental concepts and general principles of theoretical mechanics. Chapter 2 discusses the resultant and equilibrium of concurrent forces acting on a particle. In Chapter 3 the reduction and equivalence of a force system acting on a rigid body are discussed, and in Chapter 4 the equilibrium of a rigid body, as well the internal force of a planar truss, is considered. The concepts of both sliding friction and rolling resistance are introduced in Chapter 5. The velocity and acceleration of a particle are analyzed in Chapter 6. Chapter 7 deals with the velocity and acceleration of a rigid body in translation, rotation, and general plane motion. The resultant motion of a particle is studied in Chapter 8. Chapter 9 and Chapter 10 are on the kinetics of a particle and of a rigid body in plane motion. Chapter 11 describes the mechanical vibrations of bodies. The principle of virtual work, and Lagrange's equations in analytical mechanics are, respectively, dealt with in Chapter 12, and 13. The impact is briefly introduced in Chapter 14.

The book can be used as an English, Chinese, or bilingual textbook of theoretical mechanics for the student majoring in aeronautical, mechanical, civil, and hydraulic engineering.

Kaifu Wang

Nanjing, December 2014

前　言

理论力学是航空、机械、土木和水利工程等专业学生的必修课，通常在大二学年讲授。本书旨在向学生传授理论力学的理论及其应用。

本书用英文和中文分别撰写：英文部分可作为理论力学的英文教材，中文部分可作为理论力学的中文教材。

理论力学由静力学、运动学和动力学组成。静力学研究物体的静止与平衡；运动学在不涉及作用力的情况下研究物体的运动；动力学研究物体的运动与作用力之间的关系。

全书由 14 章正文和 2 个附录组成。第 1 章介绍理论力学的基本概念与普遍原理。第 2 章讨论作用于质点上的汇交力系的合成与平衡。第 3 章讨论作用于刚体上的力系的简化与等效。第 4 章考虑刚体的平衡以及平面桁架的内力。第 5 章介绍滑动摩擦与滚动摩阻的概念。第 6 章分析质点的速度与加速度。第 7 章涉及平移、转动和一般平面运动刚体的速度与加速度。第 8 章研究质点合成运动。第 9 章和第 10 章分别研究质点动力学和刚体平面动力学。第 11 章描述物体的机械振动。第 12 章和第 13 章分别涉及分析力学的虚功原理和拉格朗日方程。第 14 章简要介绍碰撞。

本书可作为高等院校航空、机械、土木和水利工程等专业学生的英文、中文或双语理论力学教材。

王开福

2014 年 12 月于南京

Contents

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Chapter 1 Basic Concepts and General Principles

Theoretical mechanics is the study of equilibrium or motion of bodies subjected to the action of forces, and consists of statics, kinematics and kinetics. Statics is the study of bodies at rest or in equilibrium; kinematics treats the geometry of the motion without regard to the forces acting on bodies; and kinetics deals with the relation between the motion of bodies and the forces acting on bodies.

In theoretical mechanics, bodies are assumed to be perfectly rigid. Though actual bodies are never absolutely rigid and deform under the action of forces, these deformations are usually small and do not affect the state of equilibrium or motion of bodies under consideration.

1.1 Basic Concepts

1. Length

Length is used to locate the position of a point in space. The position of a point can be defined by three lengths measured from a certain reference point in three given directions.

2. Time

Time is used to represent a nonspatial continuum in which events occur in irreversible succession from the past through the present to the future. To define an event, it is not sufficient to indicate its position in space. The time of the event should be given.

3. Mass

Mass is used to characterize the quantity of matter that a body contains. The mass of a body is not dependent on gravity and therefore is different from but proportional to its weight. Two bodies of the same mass, for example, will be attracted by the earth in the same manner; they will also offer the same resistance to a change in velocity.

4. Force

Force is used to represent the action of one body on another. A force tends to produce an acceleration of a body in the direction of its application. The effect of a force is completely characterized by its magnitude, direction, and point of application.

5. Particle

If the size and shape of a body do not affect the solution of the specific problem under consideration, then this body can be idealized as a particle, i.e., a particle has a mass, but its size and shape can be neglected. For example, the size and shape of the earth is insignificant compared to the size and shape of its orbit, and therefore the earth can be modeled as a particle when studying the orbital motion of the earth.

6. Rigid Body

A rigid body can be considered as a combination of a large number of particles in which all the particles occupy fixed positions with respect to each other within the body both before and after the action of forces, i.e., a rigid body is defined as one which does not deform when it is subjected to the action of forces.

7. Scalars

Scalars possess only magnitude, e. g. , length, time, mass, work, energy. Scalars are added by algebraic methods.

8. Vectors

Vectors possess both magnitude and direction (direction is understood to include both the inclination angle that the line of action makes with a given reference line and the sense of the vector along the line of action), e.g., force, displacement, impulse, momentum. Vectors are added by the parallelogram law.

9. Free Vectors

A free vector can be moved anywhere in space provided it remains the same magnitude and direction.

10. Sliding or Slip Vectors

A sliding or slip vector can be moved to any point along its line of action.

11. Fixed or Bound Vectors

A fixed or bound vector must remain at the same point of application.

1.2 General Principles

1. Parallelogram Law

This law states that two forces acting on a particle can be replaced by a single resultant force obtained by drawing the diagonal of the parallelogram which has sides equal to the given forces.

For example, two forces $\boldsymbol{F}_1$ and $\boldsymbol{F}_2$ acting on a particle O, as shown in Fig. 1.1(a), can be replaced by a single force $\boldsymbol{R}$, as shown in Fig. 1.1(b), which has the same effect on the particle O and is called the resultant force of the forces $\boldsymbol{F}_1$ and $\boldsymbol{F}_2$. The resultant force $\boldsymbol{R}$ can be obtained by drawing a parallelogram using $\boldsymbol{F}_1$ and $\boldsymbol{F}_2$ as two adjacent sides of the parallelogram. The diagonal that passes through O represents the resultant force $\boldsymbol{R}$, i.e., $\boldsymbol{R}=\boldsymbol{F}_1+\boldsymbol{F}_2$. This method for finding the resultant force of two forces is known as the parallelogram law.

From the parallelogram law, an alternative method for determining the resultant force of two forces, as shown in Fig. 1.2(a), by drawing a triangle, as shown in Fig. 1.2(b), can

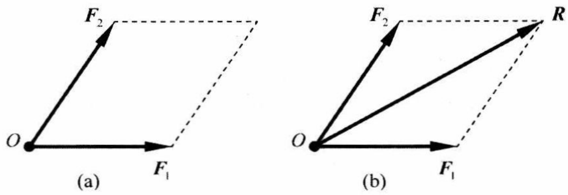

Fig. 1.1

be obtained. The resultant force $\boldsymbol{R}$ of the forces $\boldsymbol{F}_1$ and $\boldsymbol{F}_2$ can be found by arranging $\boldsymbol{F}_1$ and $\boldsymbol{F}_2$ in tip-to-tail fashion and then connecting the tail of $\boldsymbol{F}_1$ with the tip of $\boldsymbol{F}_2$, i.e., $\boldsymbol{R}=\boldsymbol{F}_1+\boldsymbol{F}_2$. This is known as the triangle rule.

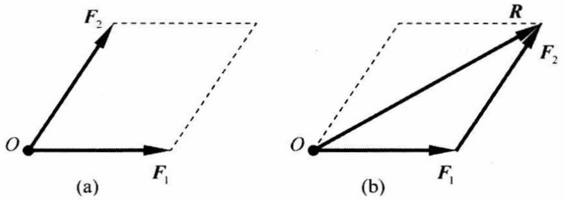

Fig. 1.2

2. Principle of Transmissibility

This principle states that the state of equilibrium or motion of a rigid body will remain unchanged if one force acting at a given point of the rigid body is replaced by another force of the same magnitude and same direction, but acting at a different point, provided that the two forces have the same line of action.

For example, a force $\boldsymbol{F}$, as shown in Fig. 1.3(a), acting at a given point O of a rigid body can be replaced by a force $\boldsymbol{F}'$, as shown in Fig. 1.3(b), of the same magnitude and same direction, but acting at a different point O' on the same line of action. The two forces $\boldsymbol{F}$ and $\boldsymbol{F}'$ have the same effect on the rigid body and are said to be equivalent. This principle shows that the effect of a force on a rigid body remains unchanged provided the force acting on the rigid body is moved along its line of action. Thus forces acting on a rigid body are sliding vectors.

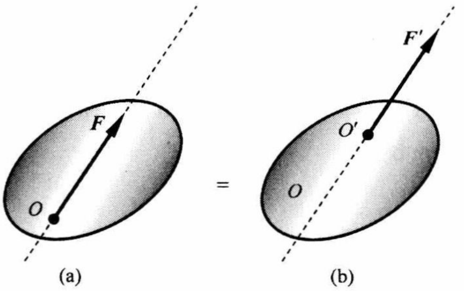

Fig. 1.3

3. Newton's First Law

This law states that if the resultant force acting on a particle is zero, then the particle will remain at rest (if originally at rest) or will move with constant velocity in a straight line (if originally in motion).

4. Newton's Second Law

This law states that if the resultant force acting on a particle is not zero, then the particle will have an acceleration proportional to the magnitude of the resultant force and in the direction of this resultant force. This law can be expressed mathematically as

$$\boldsymbol{F} = m\boldsymbol{a} \tag{1.1}$$

where $\boldsymbol{F}$, m, and $\boldsymbol{a}$ are, respectively, the resultant force acting on the particle, the mass of the particle, and the acceleration of the particle.

5. Newton's Third Law

This law states that the forces of action and reaction between two bodies in contact have the same magnitude (equal), same line of action (collinear), and opposite sense (direction).

6. Newton's Law of Gravitation

This law states that two particles are mutually attracted by equal and opposite forces. The magnitude of the two forces can be given by

$$F = G\frac{m_1 m_2}{r^2} \tag{1.2}$$

where F is the force of gravitation between the two particles, G is the universal constant of gravitation, m_1 and m_2 are, respectively, the mass of each of the two particles, and r is the distance between the two particles.

When a particle is located on or near the surface of the earth, the force exerted by the earth on the particle is defined as the weight of the particle. Taking m_1 equal to the mass M of the earth, m_2 equal to the mass m of the particle, and r equal to the radius R of the earth, and letting

$$g = G\frac{M}{R^2} \tag{1.3}$$

where g is the acceleration of gravity, then the magnitude of the weight of the particle can be given by

$$W = mg \tag{1.4}$$

The value of g is approximately equal to 9.81 m/s^2 in SI units, as long as the particle is located on or near the surface of the earth.

Chapter 2 Statics of Particle

A body under consideration can be idealized as a particle if its size and shape are able to be neglected. All the forces acting on this particle can be assumed to be applied at the same point and will thus form a system of concurrent forces.

2.1 Resultant of Coplanar Concurrent Forces

A coplanar system of concurrent forces consists of concurrent forces that lie in one plane.

1. Graphical Method for Resultant of Forces

The resultant force of a coplanar system of concurrent forces acting on a particle can be obtained by using the graphical method. If a particle is acted upon by three or more coplanar concurrent forces, the resultant force can be obtained by the repeated applications of the triangle rule.

Considering that a particle O is acted upon by coplanar concurrent forces $\boldsymbol{F}_1$, $\boldsymbol{F}_2$, and $\boldsymbol{F}_3$, as shown in Fig. 2.1(a), the resultant force $\boldsymbol{R}$ of these forces can be obtained graphically by arranging all the given forces in tip-to-tail fashion and connecting the tail of the first force with the tip of the last one, as shown in Fig. 2.1(b). This method is known as the polygon rule.

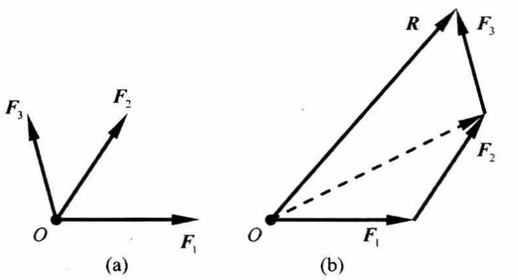

Fig. 2.1

We thus conclude that a coplanar system of concurrent forces acting on a particle can be replaced by a resultant force through the concurrence, and that the resultant force is equal to the vector sum of the given coplanar concurrent forces, i.e.,

$$\boldsymbol{R} = \boldsymbol{F}_1 + \boldsymbol{F}_2 + \boldsymbol{F}_3 + \cdots = \sum \boldsymbol{F} \tag{2.1}$$

Example 2.1

Two rods, AC and AD, are attached at A to column AB, as shown in Fig. E2.1(a). Knowing that the force in the left-hand rod is $F_1 = 150$ N, and that the inclination angles of the rods are $\theta_1 = 30^\circ$ and $\theta_2 = 15^\circ$, using the graphical method determine (a) the force F_2 in the right-hand rod if the resultant of the forces exerted by the rods on the column is to be vertical, (b) the corresponding magnitude of the resultant.

Solution

The forces $\boldsymbol{F}_1$ and $\boldsymbol{F}_2$ acting at A can be replaced by a resultant force $\boldsymbol{R}$ from the

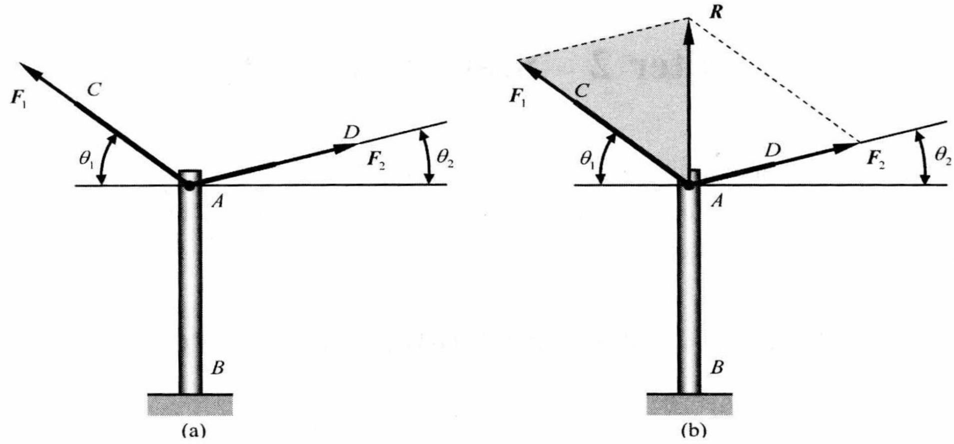

Fig. E2.1

parallelogram law, as shown in Fig. E2.1(b). Considering the shaded triangle shown in Fig. E2.1(b) and using the law of sines, we have

$$\frac{F_1}{\sin(90^\circ - \theta_2)} = \frac{F_2}{\sin(90^\circ - \theta_1)} = \frac{R}{\sin(\theta_1 + \theta_2)}$$

Using $F_1 = 150$ N, $\theta_1 = 30^\circ$, and $\theta_2 = 15^\circ$, we obtain

$$F_2 = \frac{\sin(90^\circ - \theta_1)}{\sin(90^\circ - \theta_2)} F_1 = 134.49 \text{ N}, \; R = \frac{\sin(\theta_1 + \theta_2)}{\sin(90^\circ - \theta_2)} F_1 = 109.81 \text{ N}$$

Example 2.2

Two rods, AC and AD, are attached at A to column AB, as shown in Fig. E2.2(a). Knowing that the forces in the rods are $F_1 = 120$ N and $F_2 = 100$ N, and that the inclination angles of the rods are $\theta_1 = 35^\circ$ and $\theta_2 = 20^\circ$, using the graphical method determine the resultant force.

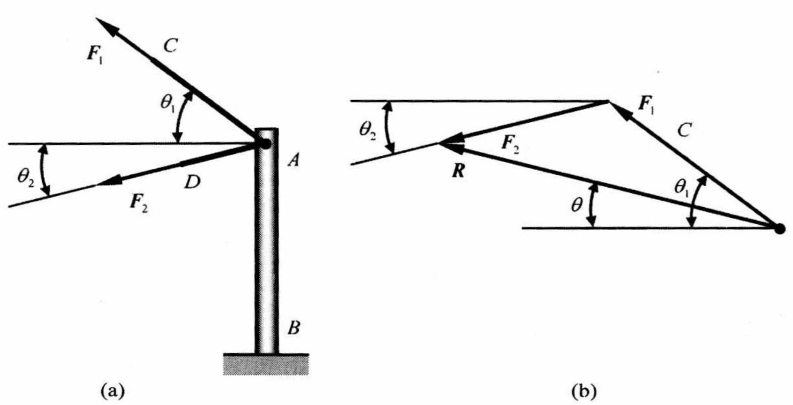

Fig. E2.2

Solution

The force triangle drawn based on the triangle rule is shown in Fig. E2.2(b). Using the