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Vector Mechanics for Engineers

Dynamics

(Third SI Metric Edition)

工程师的矢量力学

动力学（国际单位制第3版）

Ferdinand P. Beer　　E. Russell Johnston Jr.

McGraw-Hill

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DYNAMICS

THIRD SI METRIC EDITION

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[1] IE=International Edition

Vector Mechanics for Engineers　Dynamics

(Third SI Metric Edition)

影 印 版 序

本书是美国采用得最多的“工程力学”著名教材之一，由里海大学的 F. P. Beer 教授和康奈狄克大学的 E. R. Johnston 教授合著。自 1962 年首版以来已经出版了 6 版。世界上已有超过 350 万的大学生通过本书学习力学的基本概念和基本原理。

牛顿于 17 世纪末创立的力学基本原理已经成为当今工程科学的基石。作为高等理工院校多数专业的大学生都要学习力学基础课。美国的“工程力学”课程分为静力学和动力学两部分，基本上相当于我国的“理论力学”课程，只是作为选讲内容在静力学中增加了有关梁的内力分析的内容，这在我国是由“材料力学”课程讲授的。

本册是该教材的第 2 部分——动力学。第 11 章是质点运动学，包括直角坐标系和曲线坐标系中的运动。第 12 章讲质点动力学：牛顿第二定律。第 13 章结合质点动力学介绍能量方法和动量方法。第 14 章讲质点系。第 15 章论述刚体运动学。第 16 和 17 章分别从力与加速度的关系和能量与动量方法讨论刚体平面运动问题。第 18 章讲三维刚体动力学。第 19 章研究机械振动问题。其中供教师自由选讲的章节在目录中加有*号，第 18 章被整章列为选讲内容。附录 A 综述了矢量代数的定义和性质。附录 B 是第 1 册第 9 章中有关质量惯性矩部分的内容。附录 C 给出了与动力学相关的国际单位和美国常用单位间的转换关系。

牛顿力学研究的主要物理量都是矢量，例如矢径、位移、速度和角速度、加速度和角加速度、力和力矩等，所以又称为“矢量力学”。有些教材回避矢量运算来讲牛顿力学就很难讲明三维问题和一般规律。本书的重要特点是基于矢量运算和矢量分析来讲述牛顿力学，因而推导过程简明清晰，所得结论具有一般性，实现了严密的逻辑演绎和清晰的物理概念的紧密结合。作者强调指出，矢量运算是一个数学工具，重点要抓住对力学基本概念和基本原理的正确理解，并学会将力学原理应用于求解工程实际问题的技巧。

本书另一个特点是阐述由浅入深、循序渐进。例如先通过较为简单的“质点力学”讲解基本概念和基本原理，然后再深入讲授较难的“刚体力学”问题；先用矢量运算讲明平面问题，然后再引入矢量运算讲授三维一般情况。

本书第三个特点是基于作者丰富的教学经验对教材内容和讲解顺序作了精心的安排。每章分为若干单元，每个单元相当于一堂课，先讲理论，再讲应用例题，然后有供学生复习用的思考题，最后给出大量习题，习题还按由易到难的顺序排列。每章末给出简短的评论和小结，最后有适合用微机编程求解的作业（编号中都带字母 C）。本书共计有 1400 余道习题，其中 70%附有答案。没有答案的习题的编号用斜体印刷。

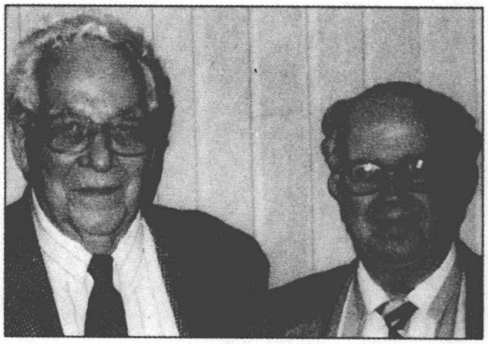
本书对数学基础的要求是：代数、三角、初等微积分和矢量代数，对二年级大学生来说这要求并不高。

本书附有基于 Windows 的交互式软件，内容包括使用动画讲述基本概念以及给出更多的例题和检测题。

本书内容介于我国理论力学多学时和中学时的教学要求之间，概念清晰、推理严谨、论述简明易懂、应用灵活多样、习题丰富，是一本优秀的工程力学教材，可作为我国高等理工院校理论力学和工程力学课程的英文教材或主要参考书。

陆明万
清华大学工程力学系

About the Authors



"How did you happen to write your books together, with one of you at Lehigh and the other at UConn, and how do you manage to keep collaborating on their successive revisions?" These are the two questions most often asked of our two authors.

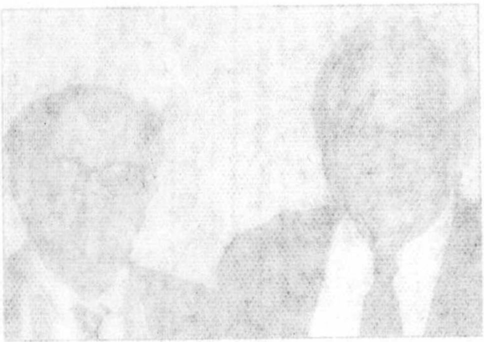
The answer to the first question is simple. Russ Johnston's first teaching appointment was in the Department of Civil Engineering and Mechanics at Lehigh University. There he met Ferd Beer, who had joined that department two years earlier and was in charge of the courses in mechanics. Born in France and educated in France and Switzerland (he holds an M.S. degree from the Sorbonne and an Sc.D. degree in the field of theoretical mechanics from the University of Geneva), Ferd had come to the United States after serving in the French army during the early part of World War II and had taught for four years at Williams College in The Williams-MIT joint arts and engineering program. Born in Philadelphia, Russ had obtained a B.S. degree in civil engineering from the University of Delaware and an Sc.D. degree in the field of structural engineering from MIT.

Ferd was delighted to discover that the young man who had been hired chiefly to teach graduate structural engineering courses was not only willing but eager to help him reorganize the mechanics courses. Both believed that these courses should be taught from a few basic principles and that the various concepts involved would be best understood and remembered by the students if they were presented to them in a graphic way. Together they wrote lecture notes in statics and dynamics, to which they later added problems they felt would appeal to future engineers, and soon they produced the manuscript of the first edition of *Mechanics for Engineers*.

The second edition of *Mechanics for Engineers* and the first edition of *Vector Mechanics for Engineers* found Russ Johnston at Worcester Polytechnic Institute and the next editions at the University of Connecticut. In the meantime, both Ferd and Russ had assumed administrative responsibilities in their departments, and both were involved in research, consulting, and supervising graduate students—Ferd in the area of stochastic processes and random vibrations, and Russ in the area of elastic stability and structural analysis and design. However, their interest in improving the teaching of the basic mechanics courses had not subsided, and they both taught sections of these courses as they kept revising their texts and began writing the manuscript of the first edition of *Mechanics of Materials*.

This brings us to the second question: How did the authors manage to work together so effectively after Russ Johnston had left Lehigh? Part of the answer is provided by their phone bills and the money they have spent on postage. As the publication date of a new edition approaches, they call each other daily and rush to the post office with express-mail packages. There are also visits between the two families. At one time there were even joint camping trips, with both families pitching their tents next to each other. Now, with the advent of the fax machine, they do not need to meet so frequently.

Their collaboration has spanned the years of the revolution in computing. The first editions of *Mechanics for Engineers* and of *Vector Mechanics for Engineers* included notes on the proper use of the slide rule. To guarantee the accuracy of the answers given in the back of the book, the authors themselves used oversize 20-inch slide rules, then mechanical desk calculators complemented by tables of trigonometric functions, and later four-function electronic calculators. With the advent of the pocket multifunction calculators, all these were relegated to their respective attics, and the notes in the text on the use of the slide rule were replaced by notes on the use of calculators. Now problems requiring the use of a computer are included in each chapter of their texts, and Ferd and Russ program on their own computers the solutions of most of the problems they create.



Ferd and Russ's contributions to engineering education have earned them a number of honors and awards. They were presented with the Western Electric Fund Award for excellence in the instruction of engineering students by their respective regional sections of the American Society for Engineering Education, and they both received the Distinguished Educator Award from the Mechanics Division of the same society. In 1991 Russ received the Outstanding Civil Engineer Award from the Connecticut Section of the American Society of Civil Engineers, and in 1995 Ferd was awarded an honorary Doctor of Engineering degree by Lehigh University.

Two new collaborators, Elliot Eisenberg, Professor of Engineering at the Pennsylvania State University, and Robert Sarubbi, Professor of Mechanical Engineering and Mechanics at Lehigh University, have joined the Beer and Johnston team for this new edition. Elliot holds a B.S. degree in engineering and an M.E. degree, both from Cornell University. He has focused his scholarly activities on professional service and teaching, and he was recognized for this work in 1992 when the American Society of Mechanical Engineers awarded him the Ben C. Sparks Medal for his contributions to mechanical engineering and mechanical engineering technology education and for service to that society and to the American Society for Engineering Education. Bob holds a B.S. degree in Civil Engineering from the Cooper Union, and an M.S. in Civil Engineering and Ph.D. in Applied Mechanics, both from Lehigh University. After working for five years at Bell Telephone Laboratories on missile systems and design, Bob joined in 1968 the faculty of Lehigh University, where he has specialized in the teaching of system dynamics and design. His research involvement has been in structural mechanics, thermo-fluid systems, and stochastic processes and random vibrations.

Preface

The main objective of a first course in mechanics should be to develop in the engineering student the ability to analyze any problem in a simple and logical manner and to apply to its solution a few well-understood, basic principles. It is hoped that this text, as well as the preceding volume, *Vector Mechanics for Engineers: Statics*, will help the instructor achieve this goal.†

Vector algebra was introduced at the beginning of the first volume and used in the presentation of the basic principles of statics, as well as in the solution of many problems, particularly three-dimensional problems. Similarly, the concept of vector differentiation will be introduced early in this volume, and vector analysis will be used throughout the presentation of dynamics. This approach results in a more concise derivation of the fundamental principles. It also makes it possible to analyze many problems in kinematics and kinetics which could not be solved by scalar methods. The emphasis in this text, however, remains on the correct understanding of the principles of mechanics and on their application to the solution of engineering problems, and vector analysis is presented chiefly as a convenient tool.‡

One of the characteristics of the approach used in these volumes is that the mechanics of *particles* has been clearly separated from the mechanics of *rigid bodies*. This approach makes it possible to consider simple practical applications at an early stage and to postpone the introduction of more difficult concepts. In the volume on statics, the statics of particles was treated first, and the principle of equilibrium was immediately applied to practical situations involving only concurrent forces. The statics of rigid bodies was considered later, at which time the vector and scalar products of two vectors were introduced and used to define the moment of a force about a point and about an axis. In this volume, the

†Both texts are also available in a single volume, *Vector Mechanics for Engineers: Statics and Dynamics*, sixth edition.

‡In a parallel text, *Mechanics for Engineers: Dynamics*, fourth edition, the use of vector algebra is limited to the addition and subtraction of vectors, and vector differentiation is omitted.

same division is observed. The basic concepts of force, mass, and acceleration, of work and energy, and of impulse and momentum are introduced and first applied to problems involving only particles. Thus students may familiarize themselves with the three basic methods used in dynamics and learn their respective advantages before facing the difficulties associated with the motion of rigid bodies.

Since this text is designed for a first course in dynamics, new concepts have been presented in simple terms and every step explained in detail. On the other hand, by discussing the broader aspects of the problems considered and by stressing methods of general applicability, a definite maturity of approach has been achieved. For example, the concept of potential energy is discussed in the general case of a conservative force. Also, the study of the plane motion of rigid bodies has been designed to lead naturally to the study of their general motion in space. This is true in kinematics as well as in kinetics, where the principle of equivalence of external and effective forces is applied directly to the analysis of plane motion, thus facilitating the transition to the study of three-dimensional motion.

The fact that mechanics is essentially a *deductive* science based on a few fundamental principles has been stressed. Derivations have been presented in their logical sequence and with all the rigor warranted at this level. However, the learning process being largely *inductive*, simple applications have been considered first. Thus the dynamics of particles precedes the dynamics of rigid bodies; and, in the latter, the fundamental principles of kinetics are first applied to the solution of two-dimensional problems, which can be more easily visualized by the student (Chaps. 16 and 17), while three-dimensional problems are postponed until Chap. 18.

This entirely metric version of the sixth edition of *Vector Mechanics for Engineers* retains the unified presentation of the principles of kinetics which characterized the previous four editions. The concepts of linear and angular momentum are introduced in Chap. 12 so that Newton's second law of motion may be presented not only in its conventional form $\mathbf{F} = m\mathbf{a}$, but also as a law relating, respectively, the sum of the forces acting on a particle and the sum of their moments to the rates of change of the linear and angular momentum of the particle. This makes possible an earlier introduction of the principle of conservation of angular momentum and a more meaningful discussion of the motion of a particle under a central force (Sec. 12.9). More importantly, this approach may be readily extended to the study of the motion of a system of particles (Chap. 14) and leads to a more concise and unified treatment of the kinetics of rigid bodies in two and three dimensions (Chaps. 16 through 18).

Free-body diagrams were introduced early in statics. They were used not only to solve equilibrium problems but also to express the equivalence of two systems of forces or, more generally, of two systems of vectors. The advantage of this approach becomes apparent in the study of the dynamics of rigid bodies, where it is used to solve three-dimensional as well as two-dimensional problems. By placing the emphasis on "free-body-diagram equations" rather than on the standard algebraic equations of motion, a more intuitive and more complete understanding of the fundamental principles of dynamics can be achieved. This approach, which was first introduced in 1962 in the first edition of *Vector Mechanics for Engineers*, has now gained wide acceptance among mechanics teachers in this country. It is, therefore, used in preference to the method of dynamic equilibrium and to the equations of motion in the solution of all sample problems in this edition.

Color has been used, not only to enhance the quality of the illustrations, but also to help students distinguish among the various types of vectors used in dynamics. In any given chapter, the same color has been used to represent vectors of the same type. For example, in Chap. 11, which introduces the students to kinematics, blue, green, and red are associated, respectively, with position, velocity, and acceleration. In Chap. 12, where students begin the study of kinetics, green is still used for velocities, but red is now used exclusively to represent forces—applied forces as well as effective forces.

The text material and problems are all expressed in terms of the International System of Units (SI). This is in response to the almost universal use of the SI throughout the world. However, the interactive software program, which accompanies the textbook and is provided in the form of three disks, offers problems expressed in both the SI and the U.S. customary system of units. The reason is that many American engineers and American publications still use the U.S. customary system. Appendix C gives an overview of the relationship between the two systems of units, together with the conversion factors between the relevant units. The authors believe that this approach will best serve the needs of the students, who, as engineers, may have to be conversant with both systems of units.

A number of optional sections have been included. These sections are indicated by asterisks and may thus easily be distinguished from those which form the core of the basic dynamics course. They may be omitted without prejudice to the understanding of the rest of the text. The topics covered in these additional sections include graphical methods for the solution of rectilinear-motion problems, the trajectory of a particle under a central force, the deflection of fluid streams, problems involving jet and rocket propulsion, the kinematics and kinetics of rigid bodies in three dimensions, damped mechanical vibrations, and electrical analogues. These topics will be found of particular interest when dynamics is taught in the junior year.

The material presented in this volume and most of the problems require no previous mathematical knowledge beyond algebra, trigonometry, elementary calculus, and the elements of vector algebra presented in Chaps. 2 and 3 of the volume on statics.† However, special problems have been included, which make use of a more advanced knowledge of calculus, and certain sections, such as Secs. 19.8 and 19.9 on damped vibrations, should be assigned only if the students possess the proper mathematical background.

Each chapter begins with an introductory section setting the purpose and goals of the chapter and describing in simple terms the material to

†Some useful definitions and properties of vector algebra have been summarized in Appendix A at the end of this volume for the convenience of the reader. Also, Secs. 9.11 through 9.18 of the volume on statics, which deal with the moments of inertia of masses, have been reproduced in Appendix B.

be covered and its application to the solution of engineering problems. The body of the text has been divided into units, each consisting of one or several theory sections, one or several sample problems, and a large number of homework problems. Each unit corresponds to a well-defined topic and generally may be covered in one lesson. In a number of cases, however, the instructor will find it desirable to devote more than one lesson to a given topic. Each chapter ends with a review and summary of the material covered in that chapter. Marginal notes are used to help the students organize their review work, and cross-references have been included to help them find the portions of material requiring their special attention.

The sample problems have been set up in much the same form that students will use in solving the assigned problems. They thus serve the double purpose of amplifying the text and demonstrating the type of neat and orderly work that students should cultivate in their own solutions. A section entitled *Solving Problems on Your Own* has been added to each lesson, between the sample problems and the problems to be assigned. The purpose of these new sections is to help students organize in their own minds the preceding theory of the text and the solution methods of the sample problems so that they may more successfully solve the homework problems. Also included in these sections are specific suggestions and strategies which will enable the students to more efficiently attack any assigned problems.

Most of the problems are of a practical nature and should appeal to engineering students. They are primarily designed, however, to illustrate the material presented in the text and to help students understand the basic principles of mechanics. The problems have been grouped according to the portions of material they illustrate and have been arranged in order of increasing difficulty. Problems requiring special attention have been indicated by asterisks. Answers to 70 percent of the problems are given at the end of the book. Problems for which no answer is given are indicated by a number set in italic.

The inclusion in the engineering curriculum of instruction in computer programming and the increasing availability of personal computers or mainframe terminals on most campuses make it now possible for engineering students to solve a number of challenging dynamics problems. At one time these problems would have been considered inappropriate for an undergraduate course because of the large number of computations their solutions require. In this new edition of *Vector Mechanics for Engineers: Dynamics*, a group of problems designed to be solved with a computer has been added to the review problems at the end of each chapter. These problems may involve the determination of the motion of a particle under various initial conditions, the kinematic or kinetic analysis of mechanisms in successive positions, or the numerical integration of various equations of motion. Developing the algorithm required to solve a given dynamics problem will benefit the students in two different ways: (1) it will help them gain a better understanding of the mechanics principles involved; (2) it will provide them with an opportunity to apply the skills acquired in their computer programming course to the solution of a meaningful engineering problem.

The authors wish to acknowledge the collaboration of Professors Elliot Eisenberg and Robert Sarubbi to this sixth edition of *Vector*

Mechanics for Engineers and thank them especially for contributing many new and challenging problems. The authors also wish to acknowledge gratefully the many helpful comments and suggestions offered by the users of the previous editions of *Mechanics for Engineers* and of *Vector Mechanics for Engineers*.

Ferdinand P. Beer
E. Russell Johnston, Jr.

List of Symbols

$\mathbf{a}$, a	Acceleration
a	Constant; radius; distance; semimajor axis of ellipse
$\bar{\mathbf{a}}$, $\bar{a}$	Acceleration of mass center
$\mathbf{a}_{B/A}$	Acceleration of B relative to frame in translation with A
$\mathbf{a}_{P/\mathcal{F}}$	Acceleration of P relative to rotating frame $\mathcal{F}$
$\mathbf{a}_c$	Coriolis acceleration
$\mathbf{A}, \mathbf{B}, \mathbf{C}, \ldots$	Reactions at supports and connections
$A, B, C, \ldots$	Points
A	Area
b	Width; distance; semiminor axis of ellipse
c	Constant; coefficient of viscous damping
C	Centroid; instantaneous center of rotation; capacitance
d	Distance
$\mathbf{e}_n$, $\mathbf{e}_t$	Unit vectors along normal and tangent
$\mathbf{e}_r$, $\mathbf{e}_\theta$	Unit vectors in radial and transverse directions
e	Coefficient of restitution; base of natural logarithms
E	Total mechanical energy; voltage
f	Scalar function
f_f	Frequency of forced vibration
f_n	Natural frequency
$\mathbf{F}$	Force; friction force
g	Acceleration of gravity
G	Center of gravity; mass center; constant of gravitation
h	Angular momentum per unit mass
$\mathbf{H}_O$	Angular momentum about point O
$\dot{\mathbf{H}}_G$	Rate of change of angular momentum $\mathbf{H}_G$ with respect to frame of fixed orientation
$(\dot{\mathbf{H}}_G)_{Gxyz}$	Rate of change of angular momentum $\mathbf{H}_G$ with respect to rotating frame $Gxyz$

$\mathbf{i}, \mathbf{j}, \mathbf{k}$	Unit vectors along coordinate axes
i	Current
$I, I_x, \ldots$	Moment of inertia
$\bar{I}$	Centroidal moment of inertia
$I_{xy}, \ldots$	Product of inertia
J	Polar moment of inertia
k	Spring constant
k_x, k_y, k_O	Radius of gyration
$\bar{k}$	Centroidal radius of gyration
l	Length
$\mathbf{L}$	Linear momentum
L	Length; inductance
m	Mass
m'	Mass per unit length
$\mathbf{M}$	Couple; moment
$\mathbf{M}_O$	Moment about point O
$\mathbf{M}_O^R$	Moment resultant about point O
M	Magnitude of couple or moment; mass of earth
M_{OL}	Moment about axis OL
n	Normal direction
$\mathbf{N}$	Normal component of reaction
O	Origin of coordinates
$\mathbf{P}$	Force; vector
$\dot{\mathbf{P}}$	Rate of change of vector $\mathbf{P}$ with respect to frame of fixed orientation
q	Mass rate of flow; electric charge
$\mathbf{Q}$	Force; vector
$\dot{\mathbf{Q}}$	Rate of change of vector $\mathbf{Q}$ with respect to frame of fixed orientation
$(\dot{\mathbf{Q}})_{Oxyz}$	Rate of change of vector $\mathbf{Q}$ with respect to frame $Oxyz$
$\mathbf{r}$	Position vector
$\mathbf{r}_{B/A}$	Position vector of B relative to A
r	Radius; distance; polar coordinate
$\mathbf{R}$	Resultant force; resultant vector; reaction
R	Radius of earth; resistance
$\mathbf{s}$	Position vector
s	Length of arc
t	Time; thickness; tangential direction
$\mathbf{T}$	Force
T	Tension; kinetic energy
$\mathbf{u}$	Velocity
u	Variable
U	Work
$\mathbf{v}, v$	Velocity
v	Speed
$\bar{\mathbf{v}}, \bar{v}$	Velocity of mass center
$\mathbf{v}_{B/A}$	Velocity of B relative to frame in translation with A
$\mathbf{v}_{P/\mathcal{F}}$	Velocity of P relative to rotating frame $\mathcal{F}$
$\mathbf{V}$	Vector product
V	Volume; potential energy
w	Load per unit length

$\mathbf{W}$, W	Weight; load
x, y, z	Rectangular coordinates; distances
$\dot{x}$, $\dot{y}$, $\dot{z}$	Time derivatives of coordinates x, y, z
$\bar{x}$, $\bar{y}$, $\bar{z}$	Rectangular coordinates of centroid, center of gravity, or mass center
$\boldsymbol{\alpha}$, α	Angular acceleration
α, β, γ	Angles
γ	Specific weight
δ	Elongation
ε	Eccentricity of conic section or of orbit
$\boldsymbol{\lambda}$	Unit vector along a line
η	Efficiency
θ	Angular coordinate; Eulerian angle; angle; polar coordinate
μ	Coefficient of friction
ρ	Density; radius of curvature
τ	Periodic time
τ_n	Period of free vibration
ϕ	Angle of friction; Eulerian angle; phase angle; angle
φ	Phase difference
ψ	Eulerian angle
$\boldsymbol{\omega}$, ω	Angular velocity
ω_f	Circular frequency of forced vibration
ω_n	Natural circular frequency
$\boldsymbol{\Omega}$	Angular velocity of frame of reference

Contents