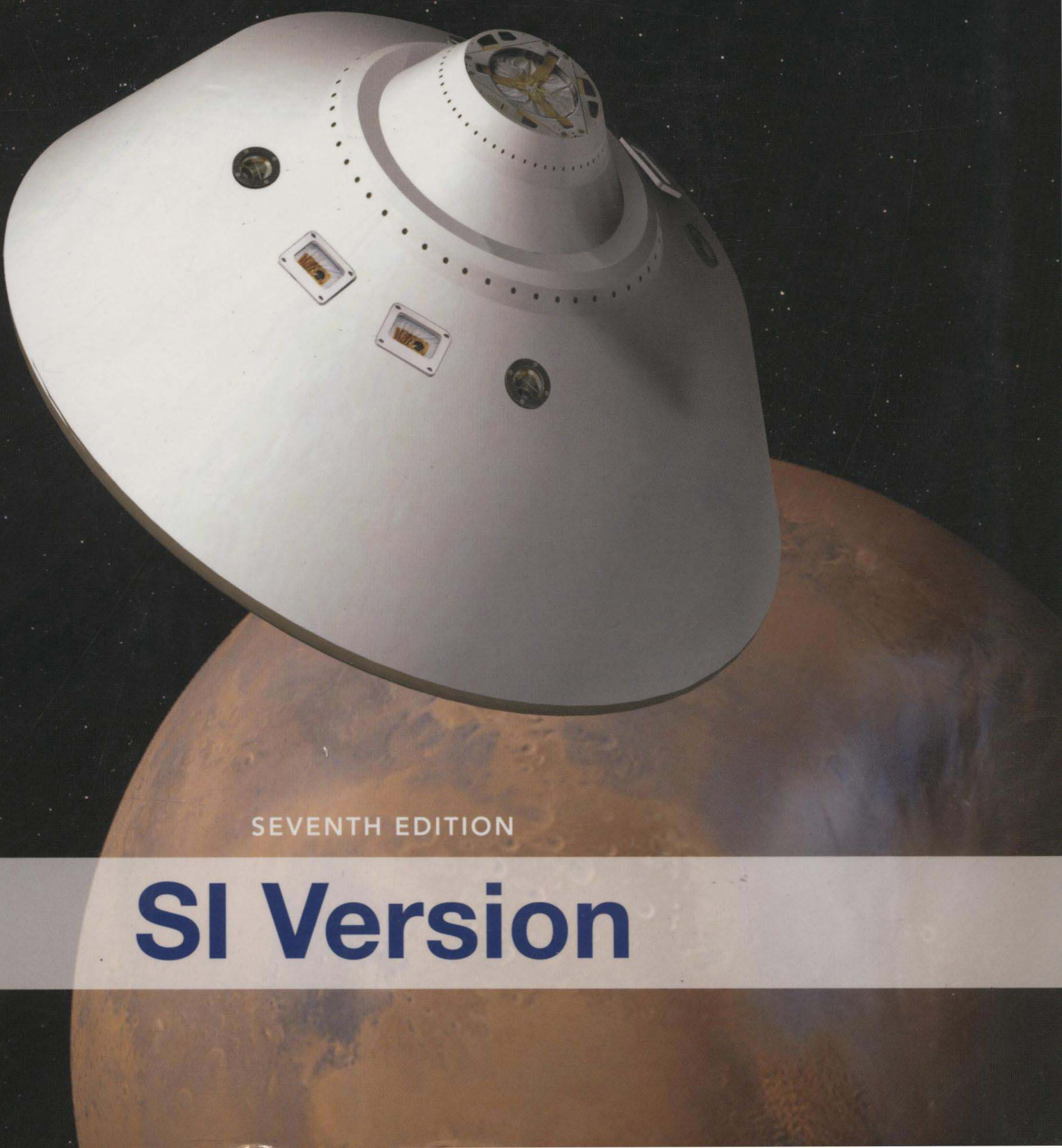
ENGINEERING MECHANICS

DYNAMICS

J.L. MERIAM | L.G. KRAIGE



SEVENTH EDITION

SI Version

Engineering Mechanics

Volume 2

Dynamics

Seventh Edition

SI VERSION

J. L. Meriam

L. G. Kraige
Virginia Polytechnic Institute and State University

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On the Cover: NASA and the European Space Agency are collaborating on the design of future missions which will gather samples of Martian surface material and return them to the earth. This artist's view shows a spacecraft carrying a sample-retrieving rover and an ascent vehicle as it approaches Mars. The rover would collect previously gathered materials and deliver them to the ascent vehicle, which would then rendezvous with another spacecraft already in orbit about Mars. This orbiting spacecraft would then travel to the earth. Such missions are planned for the 2020s.

Cover Photo Courtesy of NASA/JPL-Caltech

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Conversion Factors

U.S. Customary Units to SI Units

To convert from	To	Multiply by
(Acceleration)		
foot/second^2 (ft/sec^2)	meter/second^2 (m/s^2)	3.048×10^{-1}*
inch/second^2 (in./sec^2)	meter/second^2 (m/s^2)	2.54×10^{-2}*
(Area)		
foot^2 (ft^2)	meter^2 (m^2)	9.2903×10^{-2}
inch^2 (in.^{2})	meter^2 (m^2)	6.4516×10^{-4}*
(Density)		
pound mass/inch^3 (lbm/in.^{3})	kilogram/meter^3 (kg/m^3)	2.7680×10^{4}
pound mass/foot^3 (lbm/ft^3)	kilogram/meter^3 (kg/m^3)	1.6018×10
(Force)		
kip (1000 lb)	newton (N)	4.4482×10^{3}
pound force (lb)	newton (N)	4.4482
(Length)		
foot (ft)	meter (m)	3.048×10^{-1}*
inch (in.)	meter (m)	2.54×10^{-2}*
mile (mi), (U.S. statute)	meter (m)	1.6093×10^{3}
mile (mi), (international nautical)	meter (m)	1.852×10^{3}*
(Mass)		
pound mass (lbm)	kilogram (kg)	4.5359×10^{-1}
slug (lb-sec^2/ft)	kilogram (kg)	1.4594×10
ton (2000 lbm)	kilogram (kg)	9.0718×10^{2}
(Moment of force)		
pound-foot (lb-ft)	newton-meter ($N \cdot m$)	1.3558
pound-inch (lb-in.)	newton-meter ($N \cdot m$)	0.1129 8
(Moment of inertia, area)		
inch^4	meter^4 (m^4)	41.623×10^{-8}
(Moment of inertia, mass)		
pound-foot-second^2 (lb-ft-sec^2)	kilogram-meter^2 ($kg \cdot m^2$)	1.3558
(Momentum, linear)		
pound-second (lb-sec)	kilogram-meter/second ($kg \cdot m/s$)	4.4482
(Momentum, angular)		
pound-foot-second (lb-ft-sec)	newton-meter-second ($kg \cdot m^2/s$)	1.3558
(Power)		
foot-pound/minute (ft-lb/min)	watt (W)	2.2597×10^{-2}
horsepower (550 ft-lb/sec)	watt (W)	7.4570×10^{2}
(Pressure, stress)		
atmosphere (std)(14.7 lb/in.^{2})	newton/meter^2 (N/m^2 or Pa)	1.0133×10^{5}
pound/foot^2 (lb/ft^2)	newton/meter^2 (N/m^2 or Pa)	4.7880×10
pound/inch^2 (lb/in.^{2} or psi)	newton/meter^2 (N/m^2 or Pa)	6.8948×10^{3}
(Spring constant)		
pound/inch (lb/in.)	newton/meter (N/m)	1.7513×10^{2}
(Velocity)		
foot/second (ft/sec)	meter/second (m/s)	3.048×10^{-1}*
knot (nautical mi/hr)	meter/second (m/s)	5.1444×10^{-1}
mile/hour (mi/hr)	meter/second (m/s)	4.4704×10^{-1}*
mile/hour (mi/hr)	kilometer/hour (km/h)	1.6093
(Volume)		
foot^3 (ft^3)	meter^3 (m^3)	2.8317×10^{-2}
inch^3 (in.^{3})	meter^3 (m^3)	1.6387×10^{-5}
(Work, Energy)		
British thermal unit (BTU)	joule (J)	1.0551×10^{3}
foot-pound force (ft-lb)	joule (J)	1.3558
kilowatt-hour (kw-h)	joule (J)	3.60×10^{6}*

*Exact value

SI Units Used in Mechanics

Quantity	Unit	SI Symbol
(Base Units)		
Length	meter*	m
Mass	kilogram	kg
Time	second	s
(Derived Units)		
Acceleration, linear	meter/second^2	m/s^2
Acceleration, angular	radian/second^2	rad/s^2
Area	meter^2	m^2
Density	kilogram/meter^3	kg/m^3
Force	newton	N (= kg · m/s^2)
Frequency	hertz	Hz (= 1/s)
Impulse, linear	newton-second	N · s
Impulse, angular	newton-meter-second	N · m · s
Moment of force	newton-meter	N · m
Moment of inertia, area	meter^4	m^4
Moment of inertia, mass	kilogram-meter^2	kg · m^2
Momentum, linear	kilogram-meter/second	kg · m/s (= N · s)
Momentum, angular	kilogram-meter^2/second	kg · m^2/s (= N · m · s)
Power	watt	W (= J/s = N · m/s)
Pressure, stress	pascal	Pa (= N/m^2)
Product of inertia, area	meter^4	m^4
Product of inertia, mass	kilogram-meter^2	kg · m^2
Spring constant	newton/meter	N/m
Velocity, linear	meter/second	m/s
Velocity, angular	radian/second	rad/s
Volume	meter^3	m^3
Work, energy	joule	J (= N · m)
(Supplementary and Other Acceptable Units)		
Distance (navigation)	nautical mile	(= 1.852 km)
Mass	ton (metric)	t (= 1000 kg)
Plane angle	degrees (decimal)	°
Plane angle	radian	—
Speed	knot	(1.852 km/h)
Time	day	d
Time	hour	h
Time	minute	min

*Also spelled *metre*.

SI Unit Prefixes

Multiplication Factor	Prefix	Symbol
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^9	giga	G
1 000 000 = 10^6	mega	M
1 000 = 10^3	kilo	k
100 = 10^2	hecto	h
10 = 10	deka	da
0.1 = 10^{-1}	deci	d
0.01 = 10^{-2}	centi	c
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	μ
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p

Selected Rules for Writing Metric Quantities

1. (a) Use prefixes to keep numerical values generally between 0.1 and 1000.
   (b) Use of the prefixes hecto, deka, deci, and centi should generally be avoided except for certain areas or volumes where the numbers would be awkward otherwise.
   (c) Use prefixes only in the numerator of unit combinations. The one exception is the base unit kilogram. (*Example:* write kN/m not N/mm; J/kg not mJ/g)
   (d) Avoid double prefixes. (*Example:* write GN not kMN)
2. Unit designations
   (a) Use a dot for multiplication of units. (*Example:* write N · m not Nm)
   (b) Avoid ambiguous double solidus. (*Example:* write N/m^2 not N/m/m)
   (c) Exponents refer to entire unit. (*Example:* mm^2 means (mm)^2)
3. Number grouping
   Use a space rather than a comma to separate numbers in groups of three, counting from the decimal point in both directions. (*Example:* 4 607 321.048 72) Space may be omitted for numbers of four digits. (*Example:* 4296 or 0.0476)

Engineering Mechanics

Dynamics

SI VERSION

Foreword

This series of textbooks was begun in 1951 by the late Dr. James L. Meriam. At that time, the books represented a revolutionary transformation in undergraduate mechanics education. They became the definitive textbooks for the decades that followed as well as models for other engineering mechanics texts that have subsequently appeared. Published under slightly different titles prior to the 1978 First Editions, this textbook series has always been characterized by logical organization, clear and rigorous presentation of the theory, instructive sample problems, and a rich collection of real-life problems, all with a high standard of illustration. In addition to the U.S. versions, the books have appeared in SI versions and have been translated into many foreign languages. These texts collectively represent an international standard for undergraduate texts in mechanics.

The innovations and contributions of Dr. Meriam (1917–2000) to the field of engineering mechanics cannot be overstated. He was one of the premier engineering educators of the second half of the twentieth century. Dr. Meriam earned his B.E., M. Eng., and Ph.D. degrees from Yale University. He had early industrial experience with Pratt and Whitney Aircraft and the General Electric Company. During the Second World War he served in the U.S. Coast Guard. He was a member of the faculty of the University of California–Berkeley, Dean of Engineering at Duke University, a faculty member at the California Polytechnic State University–San Luis Obispo, and visiting professor at the University of California–Santa Barbara, finally retiring in 1990. Professor Meriam always placed great emphasis on teaching, and this trait was recognized by his students wherever he taught. At Berkeley in 1963, he was the first recipient of the Outstanding Faculty Award of Tau Beta Pi, given primarily for excellence in teaching. In 1978, he received the Distinguished Educator Award for Outstanding Service to Engineering Mechanics Education from the American Society for Engineering Education, and in 1992 was the Society's recipient of the Benjamin Garver Lamme Award, which is ASEE's highest annual national award.

Dr. L. Glenn Kraige, coauthor of the *Engineering Mechanics* series since the early 1980s, has also made significant contributions to mechanics education. Dr. Kraige earned his B.S., M.S., and Ph.D. degrees at the University of Virginia, principally in aerospace engineering, and he currently serves as Professor of Engineering Science and Mechanics at Virginia Polytechnic Institute and State University. During the mid 1970s, I had the singular pleasure of chairing Professor Kraige's graduate committee and take particular pride in the fact that he was the first of my forty-five Ph.D. graduates. Professor Kraige was invited by Professor Meriam to team with him and thereby ensure that the Meriam legacy of textbook authorship excellence was carried forward to future generations. For the past three decades, this highly successful team of authors has made an enormous and global impact on the education of several generations of engineers.

In addition to his widely recognized research and publications in the field of spacecraft dynamics, Professor Kraige has devoted his attention to the teaching of mechanics at both introductory and advanced levels. His outstanding teaching has been widely recognized and has earned him teaching awards at the departmental, college, university, state, regional, and national levels. These include the Francis J. Maher Award for excellence in education in the Department of Engineering Science and Mechanics, the Wine Award for excellence in university teaching, and the Outstanding Educator Award from the State Council of Higher Education for the Commonwealth of Virginia. In 1996, the Mechanics Division of ASEE bestowed upon him the Archie Higdon Distinguished Educator Award. The Carnegie Foundation for the Advancement of Teaching and the Council for Advancement and Support of Education awarded him the distinction of Virginia Professor of the Year for 1997. During 2004–2006, he held the W. S. "Pete" White Chair for Innovation in Engineering Education, and in 2006 he teamed with Professors Scott L. Hendricks and Don H. Morris as recipients of the XCaliber Award for Teaching with Technology. In his teaching, Professor Kraige stresses the development of analytical capabilities along with the strengthening of physical insight and engineering judgment. Since the early 1980s, he has worked on personal-computer software designed to enhance the teaching/learning process in statics, dynamics, strength of materials, and higher-level areas of dynamics and vibrations.

The Seventh Edition of *Engineering Mechanics* continues the same high standards set by previous editions and adds new features of help and interest to students. It contains a vast collection of interesting and instructive problems. The faculty and students privileged to teach or study from Professors Meriam and Kraige's *Engineering Mechanics* will benefit from the several decades of investment by two highly accomplished educators. Following the pattern of the previous editions, this textbook stresses the application of theory to actual engineering situations, and at this important task it remains the best.

John L. Junkins
Distinguished Professor of Aerospace Engineering
Holder of the George J. Eppright Chair Professorship in Engineering
Texas A&M University
College Station, Texas

Preface

Engineering mechanics is both a foundation and a framework for most of the branches of engineering. Many of the topics in such areas as civil, mechanical, aerospace, and agricultural engineering, and of course engineering mechanics itself, are based upon the subjects of statics and dynamics. Even in a discipline such as electrical engineering, practitioners, in the course of considering the electrical components of a robotic device or a manufacturing process, may find themselves first having to deal with the mechanics involved.

Thus, the engineering mechanics sequence is critical to the engineering curriculum. Not only is this sequence needed in itself, but courses in engineering mechanics also serve to solidify the student's understanding of other important subjects, including applied mathematics, physics, and graphics. In addition, these courses serve as excellent settings in which to strengthen problem-solving abilities.

Philosophy

The primary purpose of the study of engineering mechanics is to develop the capacity to predict the effects of force and motion while carrying out the creative design functions of engineering. This capacity requires more than a mere knowledge of the physical and mathematical principles of mechanics; also required is the ability to visualize physical configurations in terms of real materials, actual constraints, and the practical limitations which govern the behavior of machines and structures. One of the primary objectives in a mechanics course is to help the student develop this ability to visualize, which is so vital to problem formulation. Indeed, the construction of a meaningful mathematical model is often a more important experience than its solution. Maximum progress is made when the principles and their limitations are learned together within the context of engineering application.

There is a frequent tendency in the presentation of mechanics to use problems mainly as a vehicle to illustrate theory rather than to develop theory for the purpose of solving problems. When the first view is allowed to predominate, problems tend to become overly idealized and unrelated to engineering with the result that the exercise becomes dull, academic, and uninteresting. This approach deprives the student of valuable experience in formulating problems and thus of discovering the need for and meaning of theory. The second view provides by far the stronger motive for learning theory and leads to a better balance between theory and application. The crucial role played by interest and purpose in providing the strongest possible motive for learning cannot be overemphasized.

Furthermore, as mechanics educators, we should stress the understanding that, at best, theory can only approximate the real world of mechanics rather than the view that the real world approximates the theory. This difference in philosophy is indeed basic and distinguishes the *engineering* of mechanics from the *science* of mechanics.

Over the past several decades, several unfortunate tendencies have occurred in engineering education. First, emphasis on the geometric and physical meanings of prerequisite mathematics appears to have diminished. Second, there has been a significant reduction and even elimination of instruction in graphics, which in the past enhanced the visualization and representation of mechanics problems. Third, in advancing the mathematical level of our treatment of mechanics, there has been a tendency to allow the notational manipulation of vector operations to mask or replace geometric visualization. Mechanics is inherently a subject which depends on geometric and physical perception, and we should increase our efforts to develop this ability.

A special note on the use of computers is in order. The experience of formulating problems, where reason and judgment are developed, is vastly more important for the student than is the manipulative exercise in carrying out the solution. For this reason, computer usage must be carefully controlled. At present, constructing free-body diagrams and formulating governing equations are best done with pencil and paper. On the other hand, there are instances in which the *solution* to the governing equations can best be carried out and displayed using the computer. Computer-oriented problems should be genuine in the sense that there is a condition of design or criticality to be found, rather than "makework" problems in which some parameter is varied for no apparent reason other than to force artificial use of the computer. These thoughts have been kept in mind during the design of the computer-oriented problems in the Seventh Edition. To conserve adequate time for problem formulation, it is suggested that the student be assigned only a limited number of the computer-oriented problems.

As with previous editions, this Seventh Edition of *Engineering Mechanics* is written with the foregoing philosophy in mind. It is intended primarily for the first engineering course in mechanics, generally taught in the second year of study. *Engineering Mechanics* is written in a style which is both concise and friendly. The major emphasis is on basic principles and methods rather than on a multitude of special cases. Strong effort has been made to show both the cohesiveness of the relatively few fundamental ideas and the great variety of problems which these few ideas will solve.

Pedagogical Features

The basic structure of this textbook consists of an article which rigorously treats the particular subject matter at hand, followed by one or more Sample Problems, followed by a group of Problems. There is a Chapter Review at the end of each chapter which summarizes the main points in that chapter, followed by a Review Problem set.

Problems

The 124 sample problems appear on specially colored pages by themselves. The solutions to typical dynamics problems are presented in detail. In addition, explanatory and cautionary notes (Helpful Hints) in blue type are number-keyed to the main presentation.

There are 1541 homework exercises, of which approximately 45 percent are new to the Seventh Edition. The problem sets are divided into *Introductory Problems* and *Representative Problems*. The first section consists of simple, uncomplicated problems designed to help students gain confidence with the new topic, while most of the problems in the second section are of average difficulty and length. The problems are generally arranged in order of increasing difficulty. More difficult exercises appear near the end of the *Representative Problems* and are marked with the symbol ▶. *Computer-Oriented Problems*, marked with an asterisk, appear in a special section at the conclusion of the *Review Problems* at the end of each chapter. The answers to all problems have been provided in a special section at the end of the textbook.

SI units are used throughout the book, except in a limited number of introductory areas in which U.S. units are mentioned for purposes of completeness and contrast with SI units.

A notable feature of the Seventh Edition, as with all previous editions, is the wealth of interesting and important problems which apply to engineering design. Whether directly identified as such or not, virtually all of the problems deal with principles and procedures inherent in the design and analysis of engineering structures and mechanical systems.

Illustrations

In order to bring the greatest possible degree of realism and clarity to the illustrations, this textbook series continues to be produced in full color. It is important to note that color is used consistently for the identification of certain quantities:

- *red* for forces and moments
- *green* for velocity and acceleration arrows
- *orange dashes* for selected trajectories of moving points

Subdued colors are used for those parts of an illustration which are not central to the problem at hand. Whenever possible, mechanisms or objects which commonly have a certain color will be portrayed in that color. All of the fundamental elements of technical illustration which have been an essential part of this *Engineering Mechanics* series of textbooks have been retained. The author wishes to restate the conviction that a high standard of illustration is critical to any written work in the field of mechanics.

Special Features

While retaining the hallmark features of all previous editions, we have incorporated these improvements:

- The main emphasis on the work-energy and impulse-momentum equations is now on the time-order form, both for particles in Chapter 3 and rigid bodies in Chapter 6.
- New emphasis has been placed on three-part impulse-momentum diagrams, both for particles and rigid bodies. These diagrams are well integrated with the time-order form of the impulse-momentum equations.
- Within-the-chapter photographs have been added in order to provide additional connection to actual situations in which dynamics has played a major role.
- Approximately 45 percent of the homework problems are new to this Seventh Edition. All new problems have been independently solved in order to ensure a high degree of accuracy.

- New Sample Problems have been added, including ones with computer-oriented solutions.
- All Sample Problems are printed on specially colored pages for quick identification.
- All theory portions have been reexamined in order to maximize rigor, clarity, readability, and level of friendliness.
- Key Concepts areas within the theory presentation have been specially marked and highlighted.
- The Chapter Reviews are highlighted and feature itemized summaries.

Organization

The logical division between particle dynamics (Part I) and rigid-body dynamics (Part II) has been preserved, with each part treating the kinematics prior to the kinetics. This arrangement promotes thorough and rapid progress in rigid-body dynamics with the prior benefit of a comprehensive introduction to particle dynamics.

In Chapter 1, the fundamental concepts necessary for the study of dynamics are established.

Chapter 2 treats the kinematics of particle motion in various coordinate systems, as well as the subjects of relative and constrained motion.

Chapter 3 on particle kinetics focuses on the three basic methods: force-mass-acceleration (Section A), work-energy (Section B), and impulse-momentum (Section C). The special topics of impact, central-force motion, and relative motion are grouped together in a special applications section (Section D) and serve as optional material to be assigned according to instructor preference and available time. With this arrangement, the attention of the student is focused more strongly on the three basic approaches to kinetics.

Chapter 4 on systems of particles is an extension of the principles of motion for a single particle and develops the general relationships which are so basic to the modern comprehension of dynamics. This chapter also includes the topics of steady mass flow and variable mass, which may be considered as optional material.

In Chapter 5 on the kinematics of rigid bodies in plane motion, where the equations of relative velocity and relative acceleration are encountered, emphasis is placed jointly on solution by vector geometry and solution by vector algebra. This dual approach serves to reinforce the meaning of vector mathematics.

In Chapter 6 on the kinetics of rigid bodies, we place great emphasis on the basic equations which govern all categories of plane motion. Special emphasis is also placed on forming the direct equivalence between the actual applied forces and couples and their $m\bar{a}$ and $\bar{I}\alpha$ resultants. In this way the versatility of the moment principle is emphasized, and the student is encouraged to think directly in terms of resultant dynamics effects.

Chapter 7, which may be treated as optional, provides a basic introduction to three-dimensional dynamics which is sufficient to solve many of the more common space-motion problems. For students who later pursue more advanced work in dynamics, Chapter 7 will provide a solid foundation. Gyroscopic motion with steady precession is treated in two ways. The first approach makes use of the analogy between the relation of force and linear-momentum vectors and the relation of moment and angular-momentum vectors. With this treatment, the student can understand the gyroscopic phenomenon of steady precession and can handle most of the engineering problems on gyroscopes without a detailed study of three-dimensional dynamics. The second approach employs the more general momentum equations for three-dimensional rotation where all components of momentum are accounted for.

Chapter 8 is devoted to the topic of vibrations. This full-chapter coverage will be especially useful for engineering students whose only exposure to vibrations is acquired in the basic dynamics course.

Moments and products of inertia of mass are presented in Appendix B. Appendix C contains a summary review of selected topics of elementary mathematics as well as several numerical techniques which the student should be prepared to use in computer-solved problems. Useful tables of physical constants, centroids, and moments of inertia are contained in Appendix D.

Supplements

The following items have been prepared to complement this textbook:

Instructor's Manual

Prepared by the authors and independently checked, fully worked solutions to all odd-numbered problems in the text are available to faculty by contacting their local Wiley representative.

Instructor Lecture Resources

The following resources are available online at www.wiley.com/college/meriam. There may be additional resources not listed.

WileyPLUS: A complete online learning system to help prepare and present lectures, assign and manage homework, keep track of student progress, and customize your course content and delivery. See the description in front of the book for more information, and the website for a demonstration. Talk to your Wiley representative for details on setting up your *WileyPLUS* course.

Lecture software specifically designed to aid the lecturer, especially in larger classrooms. Written by the author and incorporating figures from the textbooks, this software is based on the Macromedia Flash® platform. Major use of animation, concise review of the theory, and numerous sample problems make this tool extremely useful for student self-review of the material.

All ***figures*** in the text are available in electronic format for use in creating lecture presentations.

All ***Sample Problems*** are available as electronic files for display and discussion in the classroom.

Acknowledgments

Special recognition is due Dr. A. L. Hale, formerly of Bell Telephone Laboratories, for his continuing contribution in the form of invaluable suggestions and accurate checking of the manuscript. Dr. Hale has rendered similar service for all previous versions of this entire series of mechanics books, dating back to the 1950s. He reviews all aspects of the books, including all old and new text and figures. Dr. Hale carries out an independent solution to each new homework exercise and provides the author with suggestions and needed corrections to the solutions which appear in the *Instructor's Manual*. Dr. Hale is well known for being extremely accurate in his work, and his fine knowledge of the English language is a great asset which aids every user of this textbook.

I would like to thank the faculty members of the Department of Engineering Science and Mechanics at VPI&SU who regularly offer constructive suggestions. These include Scott L. Hendricks, Saad A. Ragab, Norman E. Dowling, Michael W. Hyer, Michael L. Madigan, and J. Wallace Grant. Jeffrey N. Bolton of Bluefield State College is recognized for his significant contributions to this textbook series.

The following individuals (listed in alphabetical order) provided feedback on recent editions, reviewed samples of the Seventh Edition, or otherwise contributed to the Seventh Edition:

Michael Ales, *U.S. Merchant Marine Academy*
Joseph Arumala, *University of Maryland Eastern Shore*
Eric Austin, *Clemson University*
Stephen Bechtel, *Ohio State University*
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Achala Chatterjee, *San Bernardino Valley College*
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Finally, I wish to state the extremely significant contribution of my family. In addition to providing patience and support for this project, my wife Dale has managed the preparation of the manuscript for the Seventh Edition and has been a key individual in checking all stages of the proof. In addition, both my daughter Stephanie Kokan and my son David Kraige have contributed problem ideas, illustrations, and solutions to a number of the problems over the past several editions.

I am extremely pleased to participate in extending the time duration of this textbook series well past the sixty-year mark. In the interest of providing you with the best possible educational materials over future years, I encourage and welcome all comments and suggestions. Please address your comments to kraige@vt.edu.

L. Glenn Kraige

Blacksburg, Virginia

Contents