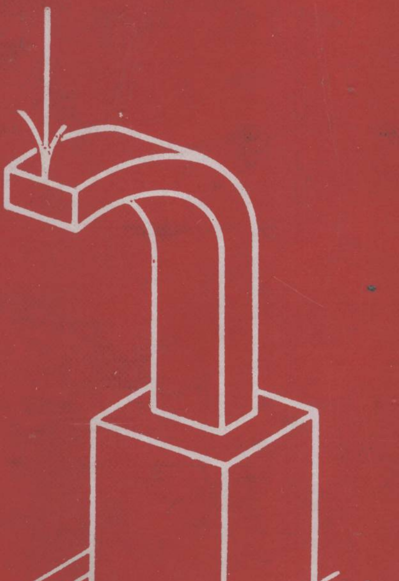
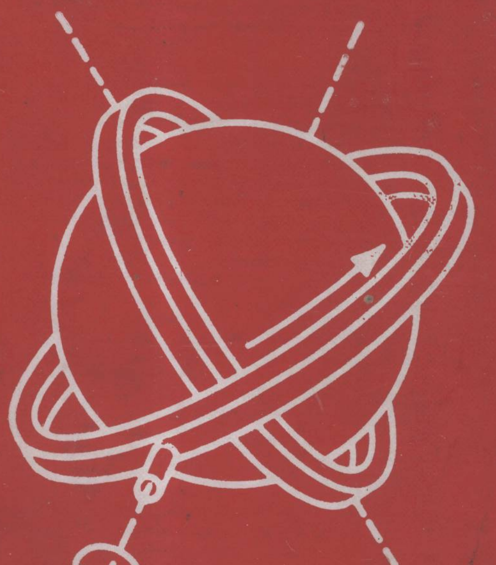
ENGINEERING MECHANICS

STATICS AND DYNAMICS

J.L. MERIAM





SI VERSION

ENGINEERING MECHANICS STATICS AND DYNAMICS

J. L. MERIAM

Professor of Mechanical Engineering
California Polytechnic State University

SI VERSION

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CONVERSION FACTORS
U.S. Customary Units to SI Units

To convert from	To	Multiply by
(Acceleration)		
foot/second² (ft/sec²)	meter/second² (m/s²)	3.048×10^{-1}*
inch/second² (in./sec²)	meter/second² (m/s²)	2.54×10^{-2}*
(Area)		
foot² (ft²)	meter² (m²)	9.2903×10^{-2}
inch² (in.²)	meter² (m²)	6.4516×10^{-4}*
(Density)		
pound mass/inch³ (lbm/in.³)	kilogram/meter³ (kg/m³)	2.7680×10^{4}
pound mass/foot³ (lbm/ft³)	kilogram/meter³ (kg/m³)	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-sec²/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·m)	1.3558
pound-inch (lb-in.)	newton-meter (N·m)	0.1129 8
(Moment of inertia, area)		
inch⁴	meter⁴ (m⁴)	41.623×10^{-8}
(Moment of inertia, mass)		
pound-foot-second² (lb-ft-sec²)	kilogram-meter² (kg·m²)	1.3558
(Momentum, linear)		
pound-second (lb-sec)	kilogram-meter/second (kg·m/s)	4.4482
(Momentum, angular)		
pound-foot-second (lb-ft-sec)	newton-meter-second (kg·m²/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/meter² (N/m² or Pa)	1.0133×10^{5}
pound/foot² (lb/ft²)	newton/meter² (N/m² or Pa)	4.7880×10
pound/inch² (lb/in.² or psi)	newton/meter² (N/m² 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)		
foot³ (ft³)	meter³ (m³)	2.8317×10^{-2}
inch³ (in.³)	meter³ (m³)	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}	terra	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, decka, deci, and centi should be generally avoided except for certain areas or volumes where the numbers would be otherwise awkward.
   (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)

FOREWORD

The innovations and contributions of Dr. James L. Meriam to the field of engineering mechanics cannot be overstated. He has undoubtedly had more influence on instruction in mechanics during the last quarter century than any other individual.

No one who commenced the study of engineering mechanics after 1950 can fully appreciate the apprehension and lack of understanding that the average engineer once experienced when facing a problem in mechanics. Professor Meriam did much to bring clarity and comprehension to this subject. His first book on mechanics in 1951 literally reconstructed undergraduate mechanics and became the definitive textbooks for the next decade. His texts were logically organized, easy to read, directed to the average engineering undergraduate and were packed with exciting examples of real-life engineering problems superbly illustrated. These books became the model for other engineering mechanics texts in the 1950s and 1960s.

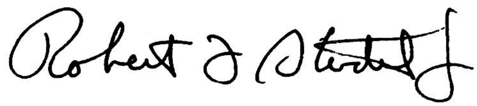
Dr. Meriam began his work in mechanical engineering at Yale University where he earned his B.E., M. Eng., and Ph.D. degrees. He had early industrial experience with Pratt and Whitney Aircraft and the General Electric Company, which stimulated his first contributions to mechanics in mathematical and experimental stress analysis. In the Second World War he served in the U.S. Coast Guard. These early experiences influenced Professor Meriam in two ways. First, he discovered his profound interest in the practical applications of mechanics and, second, he developed a lifelong interest in ships and the sea.

Dr. Meriam was a member of the faculty of the University of California, Berkeley, for twenty-one years where he served as Professor of Engineering Mechanics, Assistant Dean of Graduate Studies, and Chairman of the Division of Mechanics and Design. In 1963 he became Dean of Engineering at Duke University where he devoted his full energies to the development of its School of Engineering. In 1972 Professor Meriam followed his desire to return to full-time teaching and accepted appointment as Professor of Mechanical Engineering at the California Polytechnic State University. Dr. Meriam has always placed great emphasis on teaching, and this trait has been recognized by his students wherever he has taught. For example, at Berkeley in 1963 he was the first recipient of the Outstanding Faculty Award of Tau Beta Pi, given primarily for excellence in teaching.

More recently, in 1978 Dr. Meriam received the Distinguished Educator Award for Outstanding Service to Engineering Mechanics Education from the American Society for Engineering Education.

The free-body diagram is the foundation for mechanics. This was not a new concept with Dr. Meriam, but the emphasis and rigor with which he developed the free body in mechanics were new and highly successful. They permeate his writing and teaching. He was the first author to show clearly how the method of virtual work in statics can be employed to solve a class of problems largely neglected by previous authors. In dynamics, plane motion became understandable, and in his later editions, three-dimensional kinematics and kinetics received the same treatment. He is credited with original developments in the theory of variable-mass dynamics, which are contained in his *Dynamics, 2nd Edition.* More recently, Professor Meriam has been a leader in promoting the use of SI units, and his *SI Versions of Statics* and *Dynamics* published in 1975 were the first mechanics textbooks in SI units in this country.

Professor Meriam's new book promises to meet and even to exceed the high standards that he has set in the past. Without question it contains one of the most outstanding collections of problems yet assembled. This new text is especially designed to assist students in the preliminary stages of each new topic, and then to lead them to more challenging engineering applications as well. The new book will appeal to a wide audience of students, teachers, and engineers and will further extend the author's contributions to mechanics.



Robert F. Steidel
Professor of Mechanical Engineering
University of California, Berkeley

PREFACE
To the Student

As you undertake the study of engineering mechanics, first statics and then dynamics, you will be building a foundation of analytical capability for the solution of a great variety of engineering problems. Modern engineering practice demands a high level of analytical capability, and you will find that your study of mechanics will help you immensely in developing this capacity.

In engineering mechanics we learn to construct and solve mathematical models which describe the effects of force and motion on a variety of structures and machines that are of concern to engineers. In applying our principles of mechanics we formulate these models by incorporating appropriate physical assumptions and mathematical approximations. Both in the formulation and solution of mechanics problems you will have frequent occasion to use your background in plane and solid geometry, scalar and vector algebra, trigonometry, analytic geometry, and calculus. Indeed, you are likely to discover new significance to these mathematical tools as you make them work for you in mechanics.

Your success in mechanics (and throughout engineering) will be highly contingent upon developing a well-disciplined method of attack from hypothesis to conclusion in which the applicable principles are applied rigorously. From many years of experience as a teacher and an engineer I know the importance of developing the ability to represent one's work in a clear, logical, and concise manner. Mechanics is an excellent place in which to develop these habits of logical thinking and effective communication.

ENGINEERING MECHANICS contains a large number of sample problems in which the solutions are presented in detail. Also included in these examples are helpful observations with mention made of common errors and pitfalls to be avoided. In addition, the book contains a large selection of simple, introductory problems and problems of intermediate difficulty to help you gain initial confidence and understanding of each new topic. Also included are many problems which illustrate significant and contemporary engineering situations to stimulate your interest and help develop your appreciation for the many applications of mechanics in engineering.

I am pleased to extend my encouragement to you as a student of mechanics. I hope this book will provide both help and stimulation as you develop your background in engineering.

J. L. Meriam

Santa Barbara, California
January 1978

PREFACE
To the Instructor

The primary purpose of the study of engineering mechanics is to develop capacity to predict the effects of force and motion in the course of carrying out the creative design function of engineering. Successful prediction 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 practical limitations which govern the behavior of machines and structures. One of our primary objectives in teaching mechanics should be 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.

Courses in mechanics are often regarded by students as a difficult requirement and frequently as an uninteresting academic hurdle as well. The difficulty stems from the extent to which reasoning from fundamentals, as distinguished from rote learning, is required. The disinterest which is frequently felt is due primarily to the extent to which mechanics is presented as an academic discipline largely lacking in engineering purpose and challenge. This attitude is traceable to the 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 much of the 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 of interest and purpose in providing the strongest possible motive for learning cannot be overemphasized. Further, we should stress the view 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.

During the past twenty years there has been a strong trend in engineering education to increase the extent and level of theory in the engineering-science courses. Nowhere has this trend been felt more than in mechanics courses. To the extent that students are prepared to handle the accelerated treatment, the trend is beneficial. There is evidence and justifiable concern, however, that a significant disparity has more recently appeared between coverage and comprehension. Among the contributing factors there are three trends which we should note. 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 served to enhance 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.

One of our responsibilities as teachers of mechanics is to use the mathematics which is most appropriate for the problem at hand. The use of vector notation for one-dimensional problems is usually trivial; for two-dimensional problems it is often optional; but for three-dimensional problems it is quite essential. As we introduce vector operations in two-dimensional problems, it is especially important that their geometric meaning be emphasized. A vector equation is brought to life by a sketch of the corresponding vector polygon, which often discloses through its geometry the shortest solution. There are, of course, many mechanics problems where the complexity of variable interdependence is beyond normal powers of visualization and physical perception, and reliance on analysis is essential. This fact notwithstanding, our students become better engineers when their abilities to perceive, visualize, and represent are developed to the fullest.

As teachers of engineering mechanics we have the strongest obligation to the engineering profession to set reasonable standards of performance and to uphold them. In addition, we have a serious responsibility to encourage our students to think for themselves. Too much help with details that the student should be reasonably able to handle from prerequisite subjects can be as bad as too little help and can easily condition him to becoming overly dependent on others rather than to exercise his own initiative and ability. Also, when mechanics is subdivided into an excessive number of small compartments, each with detailed and repetitious instructions, the student can have difficulty seeing the 'forest' for the 'trees' and, consequently, fail to perceive the unity of mechanics and the far-reaching applicability of its few basic principles and methods.

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. The book omits a number of the more advanced topics contained in the author's more extensive treatments, *Statics* and *Dynamics, 2nd Edition* and *SI Version*, and is designed especially to facilitate self-study. To this end a major feature of the book is a greatly expanded treatment of sample problems which are presented in a single-page format for more convenient study. In addition to presenting the solution in detail, each sample problem also contains comments and cautions keyed to salient points in the solution and printed in colored type. These comments alert students to common pitfalls and should provide a valuable aid to their self-study efforts.

ENGINEERING MECHANICS contains 168 sample problems and 1820 unsolved problems from which a wide choice of assignments can be made. Of these "problems over 50 percent are totally new and the balance selected from the author's *Statics* and *Dynamics, 2nd Edition* and *SI Version*. All problems are presented in SI units. Each problem set begins with relatively simple, uncomplicated problems to help the student gain confidence with the new topic. Many practical problems and examples of interesting engineering situations drawn from a wide range of applications are represented in the problem collection. Simple numerical values have been used throughout, however, so as not to complicate the solutions and divert attention from the principles. The problems are arranged generally in order of increasing difficulty, and the answers to a majority of them are given. The more difficult problems are identified by a ▶ mark or the mark ▶ and may often be used to provide a comprehensive classroom experience when solved by the instructor. All numerical solutions have been carried out and checked with an electronic computer without rounding intermediate values. Consequently, the final answers should be correct to within the number of significant figures cited. The author is confident that the book is exceptionally free from error.

ENGINEERING MECHANICS is written in a style which is both concise and friendly. The major emphasis is focused 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.

Volume 1, Statics. In Chapter 2 the properties of forces, moments, couples, and resultants are developed so that the student may proceed directly to the equilibrium of noncurrent force systems in Chapter 3 without belaboring unnecessarily the relatively trivial problem of the equilibrium of concurrent forces acting on a particle. In both Chapters 2 and 3 analysis of two-dimensional problems is presented before three-dimensional problems are treated. The vast majority of students acquire a greater physical insight and understanding of mechanics by first gaining confidence in two-dimensional analysis before coping with the third dimension.

Application of equilibrium principles to simple trusses and to frames and machines is presented in Chapter 4 with primary attention given to two-dimensional systems. A sufficient number of three-dimensional examples are included, however, to enable the student to exercise his more general vector tools of analysis.

The concepts and categories of distributed forces are introduced at the beginning of Chapter 5 with the balance of the chapter divided into two main sections. Section A treats centroids and mass centers where detailed examples are presented to help the student master his early applications of calculus to physical and geometrical problems. Section B includes the special topics of beams, flexible cables, and fluid forces which may be omitted without loss of continuity of basic concepts.

Chapter 6 on friction is divided into Section A on the phenomenon of dry friction, and Section B on selected machine applications. Although Section B may be omitted if time is limited, this material does provide a valuable experience for the student in dealing with distributed forces.

Chapter 7 presents a consolidated introduction to virtual work with application limited to single-degree-of-freedom systems. Special emphasis is placed on the advantage of the virtual-work and energy method for interconnected systems and stability determination. Virtual work provides an excellent opportunity to convince the student of the power of mathematical analysis in mechanics.

Volume 2, Dynamics. The logical division between particle dynamics and rigid-body dynamics, with each part treating the kinematics prior to the kinetics, has been followed in Chapters 2 and 3. This arrangement greatly facilitates a more thorough and rapid excursion in rigid-body dynamics with the prior benefit of a comprehensive introduction to particle dynamics.

Chapter 3 on particle kinetics focuses on the three basic methods, force-mass-acceleration, work-energy, and impulse-momentum. The special topics of central-force motion, impact, relative motion, and vibrations are grouped together in Chapter 4 on special applications 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 which are developed in the single chapter. Vibrations, once treated as a major topic in dynamics, is now more frequently covered in other courses. Consequently, the treatment of vibrations has been limited to a single article which, however, is sufficient to introduce the formulation and solution of the equation for free and forced linear oscillation.

Chapter 5 on systems of particles is a generalization of the principles of motion for a single particle. The chapter also includes the topics of steady mass flow and variable mass which may be considered as optional material depending on the time available.

In Chapter 6 on the kinematics of rigid bodies in plane motion, emphasis is placed jointly on the geometry and algebra of vector solutions to relative-velocity and relative-acceleration equations. Again, this dual approach serves the purpose of re-enforcing the meaning of vector mathematics.

In Chapter 7 on the kinetics of rigid bodies in plane motion each basic motion is separately identified and solved. Strong dependence is placed on forming the direct equivalence between the actual forces and their $m\bar{\mathbf{a}}$ 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 8, 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 8 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 handle most of the engineering problems on gyros without a detailed study of three-dimensional dynamics. The second approach makes use of the more general momentum equations for three-dimensional rotation where all components of momentum are accounted for.

Moments and products of inertia of areas are presented in Appendix A (Statics). This topic helps to bridge the subjects of statics and solid mechanics. Moments and products of inertia of mass are included in Appendix A (Dynamics). Appendix B contains a summary review of selected topics of elementary mathematics that the student should be prepared to use in mechanics.

It is a pleasure for me to recognize again the continuing contribution of Dr. A. L. Hale of the Bell Telephone Laboratories for his invaluable suggestions and careful checking of the manuscript. The critical reviews of Professor Andrew Pytel of The Pennsylvania State University and Professors Kenneth Schneider and John Biddle of the California State Polytechnic University have also been of great assistance and are acknowledged with gratitude. In addition, appreciation is expressed to Professor J. M. Henderson of the University of California, Davis, for helpful comments and suggestions of selected problems. Contribution by the staff of John Wiley & Sons during the planning and production of the book reflects a high degree of professional competence and is duly recognized. The support of the California Polytechnic State University in granting me a leave of absence in which to prepare this book is likewise acknowledged. Finally, I acknowledge the patience and forebearance of my wife, Julia, during the many hours required to prepare this manuscript.

J. L. Meriam

Santa Barbara, California
January 1978

ENGINEERING MECHANICS
VOLUME 1
STATICS
SI VERSION

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