
FUNDAMENTALS OF MECHANICAL COMPONENT DESIGN

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McGraw-Hill, Inc.

New York St. Louis San Francisco Auckland Bogotá Caracas
Hamburg Lisbon London Madrid Mexico Milan Montreal New Delhi
Paris San Juan São Paulo Singapore Sydney Tokyo Toronto

This book was set in Times Roman.
The editors were John J. Corrigan and Scott Amerman;
the production supervisor was Denise L. Puryear.
The cover was designed by Rafael Hernandez.
R. R. Donnelley & Sons Company was printer and binder.

FUNDAMENTALS OF MECHANICAL COMPONENT DESIGN

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1 2 3 4 5 6 7 8 9 0 DOC DOC 9 5 4 3 2 1 0

ISBN 0-07-019102-6

Library of Congress Cataloging-in-Publication Data

Edwards, Kenneth S. (Kenneth Scott)

Fundamentals of mechanical component design / Kenneth S. Edwards.

Jr., Robert B. McKee.

p. cm.

ISBN 0-07-019102-6

1. Machine parts--Design and construction. I. McKee, Robert B.

II. Title.

TJ243.E38 1991

621.8'15--dc20

90-5771

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PREFACE

This book is intended primarily for component design and selection courses in the design sequence of mechanical engineering curricula. While the principal objective has been a text that is easy to read for students, the depth of the topic coverage makes the book a useful professional reference.

Much of the challenge and opportunity in mechanical engineering consists of devising load-bearing elements which combine superior function with minimum cost. Such design requires mastery of both engineering fundamentals and practical optimization techniques. Thus the text aims at giving the reader useful training and insight in optimal design within the context of the design of basic mechanical components.

The book begins with a review of fundamentals. Students are usually astonished to find that they will be expected, as engineers, to define the problem which they will later solve. Thus the first chapter deals with the process of creating designs to answer particular needs. Uncertainty being a fact of engineering life, probability theory is presented in the next chapter. Tolerancing and computer-aided design and manufacture are discussed. A review of the principles of static equilibrium is followed by a detailed presentation of the Mohr's-circle method of analyzing commonly encountered stress situations. A discussion of factors of safety includes factors based on statistics. Materials testing is discussed to give the student an understanding of the meaning of published material properties. Next is an examination of current theories of failure for metals under static loads, including linear elastic fracture mechanics. Methods for designing against fatigue failure include the state-of-the-art local-strain model. The background material concludes with a chapter on practical optimization techniques.

The remainder of the text examines the design of various types of mechanical elements, with necessary theory reviewed in the context of the problem. Optimal proportions are chosen for tension members with the aid of the computer. Column theory, including the powerful energy method, is used to design members loaded in compression. The chapter on torsion includes calculation of the stiffness of members of nonsymmetric cross sections. A beam acting as a vibration isolator is examined, and proportions are chosen for best performance. Several practical methods of obtaining beam deflections and their resonant vibration frequency are presented. Practical ways

to handle triaxial stress situations are discussed. An up-to-date review of bolted joints accompanies the principles of design of such elements. Similarly, review of theory is combined with design technique and component selection for composite materials, helical springs, weldments, rolling bearings, and drive belts.

The authors will be grateful for comments and suggestions.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to several individuals for review and suggestions in their areas of expertise: John H. Bickford, Raymond Engineering; Dr. Michael J. Manjoine, Westinghouse Research and Development Center; Dr. Paul W. Wallace, SPS Technologies; and George F. Leon, General Dynamics, Electric Boat Division—all experts in bolted-joint design. John C. Ekvall, Lockheed-California; Drs. Harold S. Reemsnyder, Bethlehem Steel Co.; and Ronald G. Lambert, General Electric Co.—authorities in fatigue theory. Dr. Po-Wen Hu, University of Texas at El Paso, an expert in probability theory. Dr. David K. Felbeck, the University of Michigan, an expert in fracture mechanics. Stephen Landsman, Associated Spring, the Barnes Group, an expert in spring design. And Ted Howe of the Fafnir Bearings Division, the Torrington Co., an expert in rolling-component bearings.

Thanks also are due to numerous persons for contributions to examples and figures and for permission to use them, acknowledged where they occur.

McGraw-Hill and the authors would like to thank the following reviewers for their valuable comments and suggestions: Charles Beadle, University of California, Davis; Gary Gabrielle, Rensselaer Polytechnic Institute and State University; Ed Haug, University of Iowa; Jerald Henderson, University of California, Davis; Jack Holman, Southern Methodist University; Harold Johnson, Georgia Institute of Technology; Robert Lucas, Lehigh University; Robert Pangborn, Pennsylvania State University; Gerhard Reethof, Pennsylvania State University; Charles Reinholtz, Virginia Polytechnic Institute and State University; Joseph Shigley, University of Michigan; Karel Silovsky, South Dakota School of Mines and Technology; Darrell Socie, University of Illinois, Urbana-Champaign; and Ralph Stephens, University of Iowa.

Teaching assistants William Morton and Jenq-Tzong Chern at the University of Texas at El Paso and Frank Stanko at the University of Nevada, Reno, gave invaluable help in editing, trying out problems, and programming solutions. Our thanks also go to Kim H. Pries, systems manager of the engineering computer at UTEP, for the individual attention projects like this require. We are particularly grateful to the mechanical engineering department secretaries at UTEP and UNR for their patience with manuscript revisions: Mary Jean Acosta, Sandra Tipton, and Peggy Hart. To the several others whom we have no doubt overlooked, our apologies and thanks.

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THE INTERNATIONAL SYSTEM OF UNITS, SI (SYSTÈME INTERNATIONAL d'UNITÉS)

Humans understandably turned first to parts of the body and their natural surroundings for measuring instruments. Early Babylonian and Egyptian records and the Bible indicate that length was first measured with the forearm, hand, or finger and that time was measured by the periods of the sun, moon, and other heavenly bodies. When it was necessary to compare the capacities of containers such as gourds or clay or metal vessels, they were filled with plant seeds which were then counted to measure the volumes. When means for weighing were invented, seeds and stones served as standards. For instance, the "carat," still used as a unit for gems, was derived from the carob seed.

As societies evolved, weights and measures became more complex. The invention of numbering systems and the science of mathematics made it possible to create whole systems of weights and measures suited to trade and commerce, land division, taxation, or scientific research. For these more sophisticated uses, it was necessary not only to weigh and measure more complex things, but also to do it accurately time after time and in different places. However, with limited international exchange of goods and communication of ideas, it is not surprising that different systems for the same purpose developed and became established in different parts of the world—even in different parts of a single continent.

The English System (U.S. Conventional System, USCS)

The measurement system commonly used in the United States today is nearly the same as that brought by the colonists from England. These measures had their origins in a variety of cultures—Babylonian, Egyptian, Roman, Anglo-Saxon, and Norman French. The ancient "digit," "palm," "span," and "cubit" units evolved into the "inch," "foot," and "yard" through a complicated transformation not yet fully understood.

Much of this material is excerpted from publications of the Office of Metric Programs. U.S. Department of Commerce.

Roman contributions include the use of the number 12 as a base (12 inches to the foot) and words from which we derive many of our present weights and measures names. For example, the 12 divisions of the Roman *pes*, or foot, were called *unciae*. Our words *inch* and *ounce* are both derived from that Latin word.

The "yard" as a measure of length can be traced back to the early Saxon kings. They wore a sash or girdle around the waist—which could be removed and used as a convenient measuring device. Thus the word *yard* comes from the Saxon word *gird* meaning the circumference of a person's waist.

Standardization of the various units and their combinations into a loosely related system of weights and measures sometimes occurred in fascinating ways. Tradition holds that King Henry I decreed that the yard should be the distance from the tip of his nose to the end of his thumb. The length of a furlong (or furrow-long) was established by early Tudor rulers as 220 yd. This led Queen Elizabeth I to declare, in the sixteenth century, that henceforth the traditional Roman mile of 5000 ft would be replaced by one of 5280 ft, making the mile exactly 8 furlongs and providing a convenient relationship between two previously ill-related measures.

Thus, through royal edicts, England by the eighteenth century had achieved a greater degree of standardization than the continental countries. The English units were well suited to commerce and trade because they had been developed and refined to meet commercial needs. Through colonization and dominance of world commerce during the seventeenth, eighteenth, and nineteenth centuries, the English system of weights and measures was spread to and established in many places, including the American colonies.

However, standards still differed to an extent undesirable for commerce among the 13 colonies. The need for greater uniformity led to clauses in the Articles of Confederation (ratified by the original colonies in 1781) and the Constitution of the United States (ratified in 1790) giving power to the Congress to fix uniform standards for weights and measures. Today, standards supplied to all the states by the National Bureau of Standards ensure uniformity throughout the country.

The Metric System

The need for a single worldwide coordinated measurement system was recognized over 300 years ago. Gabriel Mouton, Vicar of St. Paul in Lyons, proposed in 1670 a comprehensive decimal measurement system based on the length of 1 minute of arc of a great circle of the earth. In 1671 Jean Picard, a French astronomer, proposed the length of a pendulum beating seconds as the unit of length. Other proposals were made, but over a century elapsed before any action was taken.

In 1790, in the midst of the French Revolution, the National Assembly of France requested the French Academy of Sciences to "deduce an invariable standard for all the measures and all the weights." The Commission appointed by the Academy created a system that was, at once, simple and scientific. The unit of length was to be a portion of the earth's circumference. Measures for volume and mass were to be derived from the unit of length, thus relating the basic units of the system to each other and to nature. Furthermore, the larger and smaller versions of each unit were to be created by multiplying or dividing the basic units by 10 and its powers. This

feature provided a great convenience to users of the system, by eliminating the need for such calculations as dividing by 16 (to convert ounces to pounds) or by 12 (to convert inches to feet). Similar calculations in the metric system could be performed simply by shifting the decimal point. Thus the metric system is a *base-10* or *decimal system*.

The Commission assigned the name *metre* (which we spell *meter*) to the unit of length. This name was derived from the Greek word *metron*, meaning "a measure." The physical standard representing the meter was to be constructed so that it would equal one ten-millionth of the distance from the north pole to the equator along the meridian of the earth running near Dunkirk in France and Barcelona in Spain.

The metric unit of mass, called the *gram*, was defined as the mass of one cubic centimeter of water at its temperature of maximum density. The cubic decimeter (a cube one-tenth of a meter on each side) was chosen as the unit of fluid capacity. This measure was given the name *liter*.

Although the metric system was not accepted with enthusiasm at first, adoption by other nations occurred steadily after France made its use compulsory in 1840. The standardized character and decimal features of the metric system made it well suited to scientific and engineering work. Consequently, it is not surprising that the rapid spread of the system coincided with an age of rapid technological development. In the United States, by an act of Congress in 1866, it was made "lawful throughout the United States of America to employ the weights and measures of the metric system in all contracts, dealings or court proceedings." Since 1893, the internationally agreed-to metric standards have served as the fundamental weights and measures of the United States.

SI: The International System of Units

International cooperation aimed at standardization of length and mass units was the purpose of the Metric Convention, a treaty signed in 1875 by 17 countries, including the United States. Established with this agreement were the General Conference of Weights and Measures, to meet every six years; the International Bureau of Weights and Measures (located near Paris); and other machinery to implement the decisions of the General Conference.

In 1960, the General Conference adopted an extensive revision and simplification of the system. The name *Système International d'Unités* (International System of Units), with the abbreviation SI, was adopted for this modernized metric system.

The U.S. Congress passed the Metric Conversion Act in 1975, which declared it to be national policy to coordinate and plan the increasing use of the metric system within the United States. The Department of Commerce's Office of Metric Programs has the role of aiding in this conversion. That name implies a certain confusion of terms, for the scientific and engineering communities seek the adoption not of the metric system, but of SI. Of course, the name was chosen for its familiarity.

Current Status

As of this writing, only Burma and the United States are not "metric," or "SI." But even some traditionally metric nations have not totally adopted SI.

In the United States, the automobile industry has been a leader; more than 90 percent of car components are now specified in SI. Heavy equipment and computer manufacturers substantially use SI. Much of the packaging industry, and film, tires, cigarettes, liquor, pharmaceuticals, wine, and soft drink, use SI. In some states gasoline is dispensed by the liter. International sports use SI units exclusively (track and field events, swimming, etc.).

SI in Machine Design

Those units of SI commonly used in machine design are described below. There are numerous others, naturally, applicable to other fields.

The SI base units are the following:

1. *Length*: the meter (m), which was originally (1793) defined as a certain fraction of the earth's circumference, then later as the distance between two marks on a bar kept at the French Bureau of Standards. It was redefined recently by the Geneva Conference in terms of the distance traveled in vacuum by a certain wavelength of light.
2. *Mass*: the kilogram (kg), equal to the mass of the standard kilogram kept at the International Bureau of Weights and Measures.
3. *Time*: the second (s), defined in terms of the period of a certain radiation of cesium 133.

Other base units not necessary for this text are those for electric current, temperature, luminous intensity, and substance.

Units for developed quantities are derived from the base units. Four of these bear special names and are of importance in this text.

1. *Force*: the newton (N), the force which will impart to a 1-kg mass an acceleration of 1 m/s^2 . (The pull of gravity, i.e., the weight, of a large apple is roughly a newton.)
2. *Energy*: the joule (J), or a newton-meter ($\text{N} \cdot \text{m}$).
3. *Power*: the watt (W), or a joule per second (J/s).
4. *Pressure or stress*: the pascal (Pa), or a newton per square meter (N/m^2). Engineering stresses usually run in millions of pascals, hence the megapascal (MPa) is most commonly seen.

Note that *weight* has become an obsolete term in this system. One can speak of a kilogram of butter, but the reference is to a mass, not the force exerted on it by gravity, which would be expressed in newtons.

Numerous other units without a name are also derived, e.g., those for velocity, acceleration, torque, density.

It has been recognized that some units in very common use will persist. For example,

Units of time: minute, hour, etc.

Angular measure in degrees

Liquid volume in liters (1000 cm^3 or 10^{-3} m^3)

Tonne ($1000 \text{ kg} = 2200$ English pounds, commonly called a *metric ton* or a *long ton*)

Large and small quantities are designated by prefixes already in common use:

Size	Prefix	Symbol
10^9	giga	G
10^6	mega	M
10^3	kilo	k
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ

(There are others inapplicable in this text.)

The English use of the decimal period is to continue, for example, 1.93, 0.35. Where a number of digits precede or follow the decimal point, they are to be written in groups of three, without commas, such as 2 013 567.2 or 0.005 6. The computer practice of showing multiples of 10 by E ($1.03\text{E} - 02 = 0.0103$) will be common (used in this text). Useful conversion factors are printed on the inside cover of this book. Here are some numbers which you will find useful to commit to memory:

$$25.4 \times \text{in} = \text{mm}$$

$$2.2 \times \text{kg} = \text{lbm}$$

$$4.45 \times \text{lbf} = \text{N}$$

$$6900 \times \text{psi} = \text{Pa}$$

Various journals now require submission of articles in SI. The American Society of Mechanical Engineers foresees a period of some years with the USCS and SI systems both in common use, and it is in line with that view that the examples and problems of this text are divided between the two. There is also the question of getting people used to what sounds right in the new scheme. If a stress of several million pounds per square inch turns up in a problem solution, one suspects an error. What about several hundred megapascals?

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