Mechanical Engineering Design

FIFTH EDITION

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About the Authors

Charles R. Mischke has held positions on the faculty of the University of Kansas and was professor and chairman of Mechanical Engineering at Pratt Institute in New York. He is currently a professor at Iowa State University, involved in research activities and he works as a consultant to industry. He received the Ralph Teeter Award of the Society of Automotive Engineers in 1977 and Iowa State's Outstanding Teacher Award in 1980. He is the author of "Elements of Mechanical Analysis," "Introduction to Computer-Aided Design," "Mathematical Model Building," as well as many technical papers. He serves on the Reliability, Stress Analysis, and Failure Prevention Executive Committee of the American Society of Mechanical Engineers. Mischke is also a Fellow of the society. He is co-editor of the new Standard Handbook of Machine Design (McGraw-Hill). His B.S.M.E. and M.M.E. are from Cornell University.

Joseph E. Shigley is the well-known co-editor of the *Standard Handbook of Machine Design*. Shigley, Professor Emeritus, the University of Michigan, is a Fellow of the American Society of Mechanical Engineers. He received the ASME Mechanisms Committee Award in 1974, the Worcester Reed Warner Medal in 1977, and the Machine Design Award in 1985. He is the author or coauthor of eight books, including "Mechanical Engineering Design," "Theory of Machines and Mechanisms" (with J. J. Uicker, Jr.), and "Applied Mechanics of Materials" (all McGraw-Hill). He received his B.S.E.E. and B.S.M.E. from Purdue University and his M.S. from the University of Michigan.

Preface

This book has been written for engineering students who are beginning a course of study in mechanical engineering design. Such students will have acquired a set of engineering tools consisting, essentially, of mathematics, computer languages, and the ability to use the English language to express themselves in the spoken and written forms. Mechanical design involves a great deal of geometry, too; therefore, another useful tool is the ability to sketch and draw the various configurations which arise. Students will also have studied a number of basic engineering sciences, including physics, engineering mechanics, materials and processes, and the thermal-fluid sciences. These, the tools and sciences, constitute the foundation for the practice of engineering, and so, at this stage of undergraduate education, it is appropriate to introduce some professional aspects of engineering. These professional studies should integrate and use the tools and the sciences in the accomplishment of an engineering objective. The pressures upon the undergraduate curricula today require that we do this in the most efficient manner. Most engineering educators are agreed that mechanical design integrates and utilizes a greater number of the tools and the sciences than any other professional study. Mechanical design is also the very core of other professional and design types of studies in mechanical engineering. Thus studies in mechanical design seem to be the most effective method of starting the student in the practice of mechanical engineering.

One of the reasons for writing a new edition now is the recent increased emphasis on the creative aspects of design in so many colleges and universities. In the early 1950s a committee on evaluation of engineering education of the American Society for Engineering Education stated:

> Training for the creative and practical phases of economic design, involving analysis, synthesis, development and engineering research, is the most distinctive feature of professional engineering education.
>
> The technical goal of engineering education is preparation for performance of the functions of analysis and design or of the functions of construction, production or operation with full knowledge of analysis and design of the structure, machine, or process involved.

Though these goals were stated over a generation ago, they are valid today. Ways must be found to involve the engineering student in genuine design experiences.

The approach in this book is to suggest and to present short design problems or situations to illustrate the decision-making processes of design without demanding an inordinate amount of the student's precious time. A proposal to include a chapter or two devoted to realistic design projects was abandoned. Investigation revealed that such projects were rarely used more than once by instructors and hence the space could not be justified. Good, short design projects are certainly needed in the professional design studies. These are most effective when they are created from the instructor's own professional background and presented with the enthusiasm and thoroughness which this background allows. With such an approach new and updated projects can always be devised to meet current trends and ideas.

There are many additional reasons for publishing a new edition. The major factors for this one are:

- Product liability
- Reliability
- Quality control
- Personal computers
- New problems

Designing to a reliability specification, or to exceed specified minimums, and to a quality-control goal, will help to assure a design free from liability problems. At the request of some users, we have taken a dual approach to dimensional design. This combines the classical *factor-of-safety approach* and an optional *reliability* or *stochastic method*. These methods are presented in parallel with each other, but the stochastic method has been clearly designated for optional reading (headings for these sections are printed in black rather than color). The instructional time available, or a lack of student preparation, could require that only the factor-of-safety method be presented. Nevertheless the material used in the reliability approach will give the engineer much of the background needed to apply quality-control procedures in professional practice.

In developing the dual approach to design, we found it necessary to define the factor-of-safety method much more carefully and exactly than ever before. It is now a very sound well-documented approach. For this reason the factor-of-safety method, as presented here, also contributes to the first three goals detailed above.

Access to a personal computer or to a programmable calculator is now very important in mechanical-design studies. Their use makes it possible to solve many problems using numerical methods and eases much repetitive computation. Specific programs are not included in this book because of user's requests, and because most people prefer to create their own. The analyses presented together with programming suggestions should facilitate the use of computers and programmable calculators.

Many of the users of past editions of this book have expressed a need for new problems for student homework. Most of the problems in this edition are new; only a few were kept from previous editions and most of those have been revised.

The book now is in three parts. Part 1 is basic, and includes the introduction as well as definitions, stress analysis, deflection and stiffness determination, and the statistical tools needed for reliability and quality-control analyses. At some schools the students will be somewhat prepared in some of these topics, but only at some schools. But this basic material must still be presented in a comprehensive manner if only to serve basic reference purposes and to organize the terminology and symbolism.

Part 2 is on failure prevention, and it makes use of and integrates the fundamentals of Part 1 toward the goal of analyzing and designing mechanical elements to achieve satisfactory levels of safety, quality, reliability, and life.

Part 3 deals with the design and analysis of specific mechanical elements such as gears, clutches, springs, bearings, and the like. The new material in Parts 1 and 2 has greatly enhanced the development and presentation of the analyses presented in Part 3 and gives the instructor wider opportunities to augment, enrich, and address particular goals outside the scope of this book.

Chapter 1 contains an important introduction to the dual approach and a new section on preferred units.

In Chapter 2, new material on principal shear stresses and octahedral shear stresses has been added. Users have also requested more on equilibrium and free-body diagramming; these topics as well as all new problems have been added. The subject of stress concentration has been relocated and is now in Chapter 2. A new section on stresses in rings has been included.

In Chapter 3, on deflection and stiffness, additions and changes include (1) computer methods using numerical integration; (2) shock and impact and development of formulas using piecewise differential equations; (3) more on Castigliano's theorem, including indeterminate problems, rings, and other curved members; and (4) complete revision and rearrangement of the material on columns with new material on short compression members.

Chapter 4, on statistics, is completely new and replaces the old Chapter 5. The chapter now contains the background material needed to apply quality-control requirements and for the reliability analyses used in many of the chapters that follow. This chapter has been developed very carefully so as to contain the minimum amount of material necessary to develop these objectives, with particular attention paid to how the material is used in the chapters that follow. Some of the sections have been marked for optional reading for those who elect not to study the entire chapter.

Chapter 5, on materials, is a revision of the old Chapter 4. The changes include:

- New material on strength, cold work, and hardness, including stochastic properties
- Expanded sections on metal processing
- New sections on notch sensitivity and fracture toughness
- Completely new problems for home solution

Chapter 6 is the old Chapter 6 expanded to contain the dual factor-of-safety and reliability approach. The changes include a rewriting of the failure theories and the addition of other theories. The second part of the chapter is all new and contains the stochastic approach. This includes general interference theory, design and analysis, tolerance setting, and a numerical approach for mixed statistical distributions.

Chapter 7, on variable loading, or fatigue, has been substantially revised, though it is based on the previous outline. Because of the inclusion of the reliability method, it was necessary to research the endurance-limit modifying factors quite thoroughly. As a result these factors have been re-evaluated and, in our opinion, now express the available knowledge much more fairly than in the past. This is important whether the deterministic (factor-of-safety) method or the stochastic (reliability) approach is used. In accomplishing this objective some juggling of the various factors was done. The result has cleared some past confusion and produced a more logical and useful approach. The new sections dealing with fatigue strength as a random variable are presented as optional reading.

In addition to the complete revision of the Marin *k* factors, other new material in Chapter 7 includes:

- Fatigue strength treated as a random variable
- Reliability analyses
- More on load lines versus factor of safety
- Torsional fatigue under pulsating stresses
- Combined loading modes
- The fracture-mechanics approach to fatigue

Chapter 8 begins Part 3 with a presentation on screws, fasteners, and connections. The presentation of bolted joints in the previous edition provoked much discussion and analysis. Advantage was taken of the many user's comments, and a completely new presentation of the subject is a feature of this edition. All the methods of analyzing factor of safety of a preloaded bolted joint are presented together with their significance. The material on joint compression has been expanded and new material added on the use of cap screws, set screws, and keys.

The use of statistics in Chapters 9 and 10 make it possible, for example, to determine how tolerancing affects the performance of the element or design under study. The inclusion of such material in this edition adds substantially to the treatment of springs, for example, where it is shown how tolerancing of wire diameter, coil diameter, and free length of a helical spring affects the spring rate and deflection of the springs produced. The use of statistics in spring design is thus a valuable quality-control tool.

An important feature of this edition is the new arrangement of the material on gearing. Chapter 13 is now devoted to the basics of gearing. This includes fundamental concepts, descriptions and terminology of gears in general, gear trains, and force analysis. Chapter 14 deals with spur and helical gears and explains and uses the AGMA methods of analysis and design. This chapter is important because it explains the theory and basic thinking upon which the AGMA approach is established. Chapter 15 continues with AGMA methods applied to bevel gears. As a change of pace, however, worm and crossed-helical gears are treated using the British standards.

Chapter 17, dealing with belts, roller chain, and wire rope, has been substantially revised and, we think, improved.

Chapter 18, on the design and analysis of shafting, is now the final chapter. It occupies this important position in order to make available *all* the material of the previous chapters in its development. This is a completely new chapter, and it treats the design of shafting from the initial concept to the final detail drawing. The subject of reliability of shafting is treated thoroughly together with a detailed illustrative example. This chapter also contains all new home problems together with some interesting short design projects.

Improvements in the appendix include new tables needed for stochastic analysis, which include a new table of values for the normal distribution and one on the gamma function. The subject of limits and fits is now treated using the more logical International System. And the former tables on threaded fasteners are replaced with shorter and more useful displays.

This edition has been significantly influenced by the publisher's reviewers. Their comments and suggestions were sound and worthwhile and, indeed, kept us from straying too far from the central theme of the book. They made known the need for certain additional topics and alternate presentations; these ideas were of considerable value to us and most have been included. These reviewers were:

Richard M. Alexander, Texas A & M University
Eugene J. Fisher, University of Santa Clara
Geza Kardos, Carleton University
Alois van Eyken, Queen's University
John L. Mathieson, State University of New York, Maritime College
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We have also received much help and many valuable suggestions from the users of the previous edition. We thank them very much and have listed their names under the acknowledgements.

We are both grateful to Iowa State University for granting a sabbatical leave to Professor Mischke which permitted extended visitation with the user-community both on campus and in industry. This helped frame the scope and treatment of the material in this edition. We acknowledge the contribution that this opportunity made to the usefulness of this edition.

Our editors were John J. Corrigan, successor to Anne C. Duffy, and James W. Bradley. The copy reader was Richard K. Mickey. There is a great deal more involved in the publication of a book than that of printing a typed manuscript and rendering the drawings executed by the writers. The editors and their backup people take the raw manuscript and subject it to a very detailed procedure, leading, eventually, to the finished product. We think they have done a great job with our book. We hope you do, too.

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List of Symbols

See Table 14-1, page 586, for gearing symbols

A Area, coefficient

A Area variate, vector

a Distance

B Coefficient, life

B Vector

b Distance, Weibull shape parameter

C Basic load rating, bolted-joint constant, center distance, coefficient of variation, column end condition, constant, correction factor, heating coefficient, specific heat, spring index

c Distance

D Helix diameter

E Energy, error quantity, modulus of elasticity

e Distance, eccentricity, efficiency

F Force

F Force variate, force vector

f Coefficient of friction, frequency

G Modulus of rigidity

g Acceleration due to gravity

H Heat, power

H_B Brinell hardness

h distance, film thickness

I	Integral, mass moment of inertia, second moment of area
$\mathbf{I}$	Variate of I
$\mathbf{i}$	Unit vector in x direction
J	Mechanical equivalent of heat, polar second moment of area
$\mathbf{j}$	Unit vector in y direction
K	Stress-concentration factor, stress-correction factor, torque coefficient
k	Endurance-limit modifying factor
$\mathbf{k}$	Unit vector in z direction
L	Length, life
l	Length
M	Moment
$\mathbf{M}$	Moment vector
m	Mass, slope, strain-strengthening exponent
N	Normal force, number, rotational speed
n	Factor of safety, load factor, rotational speed
P	Force, unit bearing load
p	pitch, pressure, probability
Q	First moment of area, imaginary force, volume
q	Distributed load, notch sensitivity
R	Radius, reaction force, reliability, Rockwell hardness, stress ratio
$\mathbf{R}$	Vector reaction force
r	Correlation coefficient, radius
$\mathbf{r}$	Length vector
S	Sommerfeld number, strength
$\mathbf{S}$	Variate of S
s	Distance, sample standard deviation
T	Temperature, tolerance, torque
$\mathbf{T}$	Torque vector
t	Distance, time
U	Strain energy
u	Unit strain energy
V	Linear velocity, shear force
v	Linear velocity
W	Cold-work factor, load, weight
w	Distance, unit load
X	Coordinate
$\mathbf{x}$	Variate of x
x	Coordinate, Weibull guaranteed parameter

Y Coordinate

$\mathbf{y}$ Variate of y

y Coordinate, deflection

Z Coordinate, section modulus, viscosity

$\mathbf{z}$ Variate of z

z Coordinate, unit standard deviation

α Coefficient, coefficient of thermal expansion, end-condition constant (for springs), thread angle

β Bearing angle, coefficient

δ Deviation, elongation

ϵ Eccentricity ratio, engineering unit strain

ε True or logarithmic strain

Γ Gamma function

γ Pitch angle, shear strain, unit weight

λ Slenderness ratio (for springs)

μ Absolute viscosity, coefficient of friction, population mean

ν Poisson's ratio

ω Angular velocity, circular frequency

ϕ Angle, wavelength

ψ Slope integral

ρ Radius of curvature

σ Normal stress

$\boldsymbol{\sigma}$ Normal stress variate

$\hat{\sigma}$ Population standard deviation

τ Shear stress

θ Angle, Weibull characteristic parameter

Contents

*Italic section numbers denote optional-reading sections.