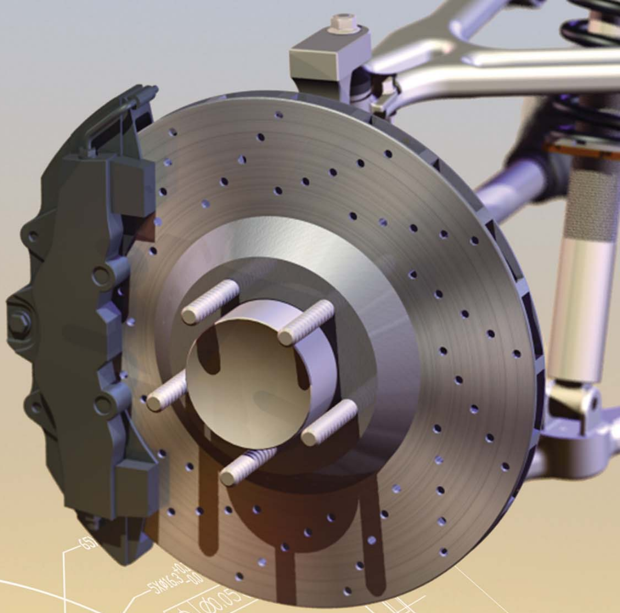
Richard G.
Budynas

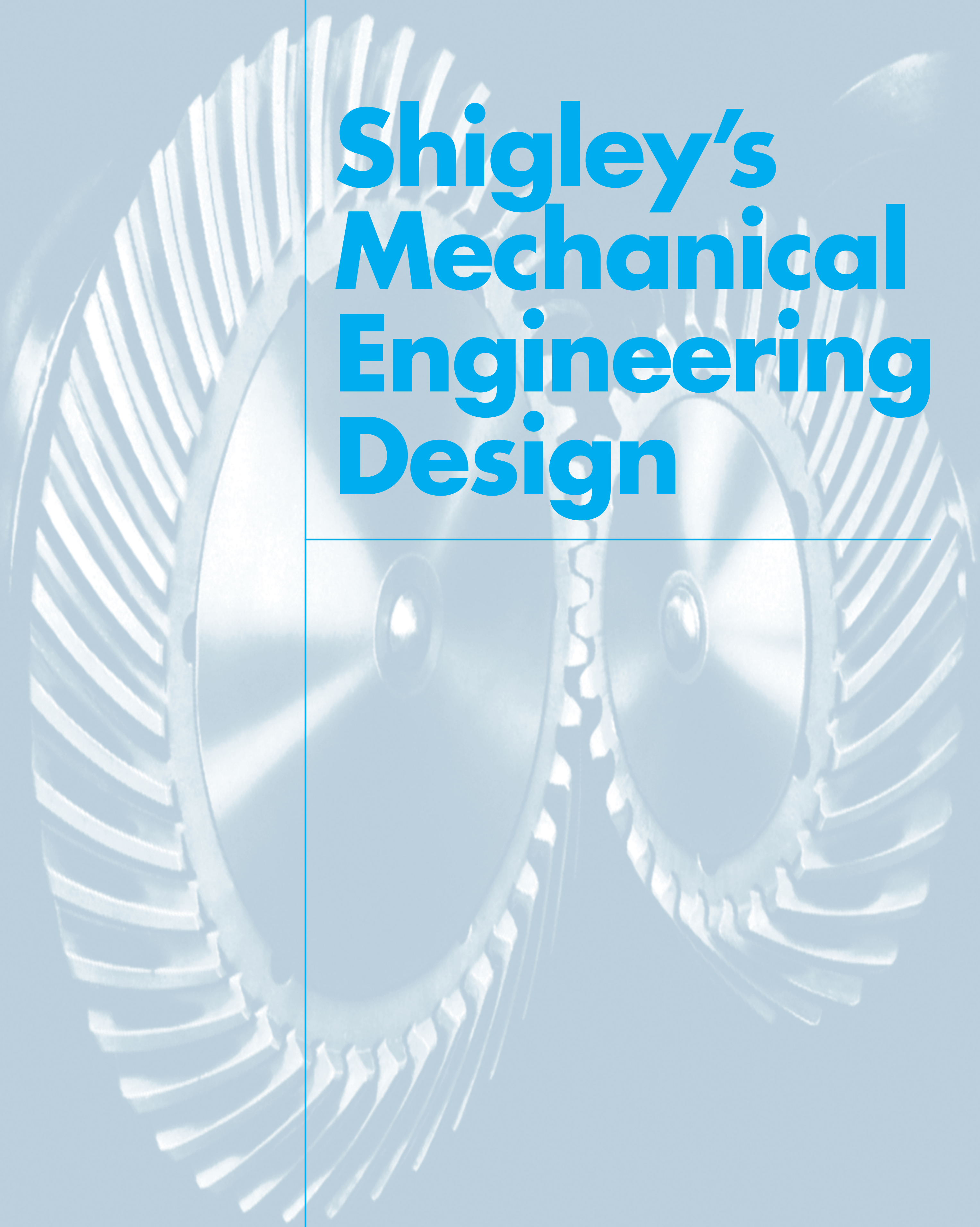
J. Keith
Nisbett



Tenth Edition

Shigley's Mechanical Engineering Design

Shigley's Mechanical Engineering Design



This page intentionally left blank

Shigley's Mechanical Engineering Design

Tenth Edition

Richard G. Budynas
Professor Emeritus, Kate Gleason College of Engineering, Rochester Institute of Technology

J. Keith Nisbett
Associate Professor of Mechanical Engineering, Missouri University of Science and Technology

Mc Graw Hill Education

McGraw Hill Education

SHIGLEY'S MECHANICAL ENGINEERING DESIGN, TENTH EDITION

Published by McGraw-Hill Education, 2 Penn Plaza, New York, NY 10121.

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 0 RJC/RJC 1 0 9 8 7 6 5 4

ISBN 978-0-07-339820-4
MHID 0-07-339820-9

Senior Vice President, Products & Markets: *Kurt L. Strand*
Vice President, General Manager, Products & Markets: *Marty Lange*
Vice President, Content Production & Technology Services: *Kimberly Meriwether-David*
Managing Director: *Thomas Timp*
Global Publisher: *Raghothaman Srinivasan*
Developmental Editor: *Vincent Bradshaw*
Director, Content Production: *Terri Schiesl*
Director of Development: *Rose Koos*
Marketing Manager: *Nick McFadden*
Project Manager: *Judi David*
Production Supervisor: *Jennifer Pickel*
Cover Designer: *Studio Montage, St. Louis, MO*
Cover Image: *Adam Nisbett*
Compositor: *Aptara®, Inc.*
Typeface: *10/12 Times LT Std*
Printer: *R. R. Donnelley*

All credits appearing on page or at the end of the book are considered to be an extension of the copyright page.

Library of Congress Cataloging-in-Publication Data

Budynas, Richard G. (Richard Gordon)
Shigley's mechanical engineering design.—Tenth edition / Richard G. Budynas, professor emeritus, Kate Gleason College of Engineering, Rochester Institute of Technology, J. Keith Nisbett, associate professor of mechanical engineering, Missouri University of Science and Technology.
pages cm—(Mcgraw-Hill series in mechanical engineering)
Includes index.
ISBN-13: 978-0-07-339820-4 (alk. paper)
ISBN-10: 0-07-339820-9 (alk. paper)
1. Machine design. I. Nisbett, J. Keith. II. Shigley, Joseph Edward. Mechanical engineering design. III. Title.
TJ230.S5 2014
621.8′15—dc23

2013035900

www.mhhe.com

Dedication

To my wife, Joanne, my family, and my late brother, Bill, who advised me to enter the field of mechanical engineering. In many respects, Bill had considerable insight, skill, and inventiveness.

Richard G. Budynas

To my wife, Kim, for her unwavering support.

J. Keith Nisbett

Dedication to Joseph Edward Shigley

Joseph Edward Shigley (1909–1994) is undoubtedly one of the most well-known and respected contributors in machine design education. He authored or coauthored eight books, including *Theory of Machines and Mechanisms* (with John J. Uicker, Jr.), and *Applied Mechanics of Materials*. He was coeditor-in-chief of the well-known *Standard Handbook of Machine Design*. He began *Machine Design* as sole author in 1956, and it evolved into *Mechanical Engineering Design*, setting the model for such textbooks. He contributed to the first five editions of this text, along with coauthors Larry Mitchell and Charles Mischke. Uncounted numbers of students across the world got their first taste of machine design with Shigley's textbook, which has literally become a classic. Nearly every mechanical engineer for the past half century has referenced terminology, equations, or procedures as being from "Shigley." McGraw-Hill is honored to have worked with Professor Shigley for more than 40 years, and as a tribute to his lasting contribution to this textbook, its title officially reflects what many have already come to call it—*Shigley's Mechanical Engineering Design*.

Having received a bachelor's degree in Electrical and Mechanical Engineering from Purdue University and a master of science in Engineering Mechanics from the University of Michigan, Professor Shigley pursued an academic career at Clemson College from 1936 through 1954. This led to his position as professor and head of Mechanical Design and Drawing at Clemson College. He joined the faculty of the Department of Mechanical Engineering of the University of Michigan in 1956, where he remained for 22 years until his retirement in 1978.

Professor Shigley was granted the rank of Fellow of the American Society of Mechanical Engineers in 1968. He received the ASME Mechanisms Committee Award in 1974, the Worcester Reed Warner Medal for outstanding contribution to the permanent literature of engineering in 1977, and the ASME Machine Design Award in 1985.

Joseph Edward Shigley indeed made a difference. His legacy shall continue.

About the Authors

Richard G. Budynas is Professor Emeritus of the Kate Gleason College of Engineering at Rochester Institute of Technology. He has more than 50 years experience in teaching and practicing mechanical engineering design. He is the author of a McGraw-Hill textbook, *Advanced Strength and Applied Stress Analysis,* Second Edition; and coauthor of a McGraw-Hill reference book, *Roark's Formulas for Stress and Strain,* Eighth Edition. He was awarded the BME of Union College, MSME of the University of Rochester, and the PhD of the University of Massachusetts. He is a licensed Professional Engineer in the state of New York.

J. Keith Nisbett is an Associate Professor and Associate Chair of Mechanical Engineering at the Missouri University of Science and Technology. He has more than 30 years of experience with using and teaching from this classic textbook. As demonstrated by a steady stream of teaching awards, including the Governor's Award for Teaching Excellence, he is devoted to finding ways of communicating concepts to the students. He was awarded the BS, MS, and PhD of the University of Texas at Arlington.

Brief Contents

Contents

Preface

Objectives

This text is intended for students beginning the study of mechanical engineering design. The focus is on blending fundamental development of concepts with practical specification of components. Students of this text should find that it inherently directs them into familiarity with both the basis for decisions and the standards of industrial components. For this reason, as students transition to practicing engineers, they will find that this text is indispensable as a reference text. The objectives of the text are to:

- Cover the basics of machine design, including the design process, engineering mechanics and materials, failure prevention under static and variable loading, and characteristics of the principal types of mechanical elements.
- Offer a practical approach to the subject through a wide range of real-world applications and examples.
- Encourage readers to link design and analysis.
- Encourage readers to link fundamental concepts with practical component specification.

New to This Edition

Enhancements and modifications to the tenth edition are described in the following summaries:

- A new Chap. 20, *Geometric Dimensioning and Tolerancing,* has been added to introduce an important topic in machine design. Most of the major manufacturing companies utilize geometric dimensioning and tolerancing (GD&T) as a standardized means of accurately representing machine parts and assemblies for the purposes of design, manufacture, and quality control. Unfortunately, many mechanical engineers do not have sufficient exposure to the notation and concepts of GD&T to interpret the drawings.

  During the time when GD&T was becoming most prevalent in manufacturing, many engineering schools were phasing out comprehensive drafting courses in favor of computerized CAD instruction. This was followed by another transition to 3D solid modeling, where the part was drawn with ideal dimensions. Unfortunately, this ability to draw a perfect part in three dimensions is all too often accompanied by a neglect of focus on how to accurately and uniquely represent the part for manufacture and inspection.

  A full understanding of GD&T is usually obtained through an intensive course or training program. Some mechanical engineers will benefit from such a rigorous training. *All* mechanical engineers, however, should be familiar with the basic concepts and notation. The purpose of the coverage of GD&T in this new chapter is to provide this foundational exposure that is essential for all machine designers.

  It is always a challenge to find time to include additional material in a course. To facilitate this, the chapter is arranged and presented at a level appropriate for students to learn in an independent study format. The problems at the end of the chapter are more like quiz questions, and are focused on checking comprehension of the most fundamental concepts. Instructors are encouraged to consider using this chapter as a reading assignment, coupled with even a minimal lecture or online discussion. Of course, there is ample material for expanded presentation and discussion as well.

- Chapter 1, *Introduction to Mechanical Engineering Design,* has been expanded to provide more insight into design practices. Further discussion of the development of the *design factor* is presented, as well as the statistical relationships between *reliability* and the *probability of failure,* and reliability and the design factor. Statistical considerations are provided here rather than in a chapter at the end of the text as in past editions. The section on Dimensions and Tolerances has been expanded to emphasize the designer's role in specifying dimensions and tolerances as a critical part of machine design.
- The chapter of the previous edition, *Statistical Considerations,* has been eliminated. However, the material of that chapter pertinent to this edition has been integrated within the sections that utilize statistics. The stand-alone section on stochastic methods in Chap. 6, *Fatigue Failure Resulting from Variable Loading,* has also been eliminated. This is based on user input and the authors' convictions that the excessive amount of development and data provided in that section was far too involved for the simple class of problems that could be solved. For instructors who still want access to this material, it is available on McGraw-Hill's Online Learning Center at www.mhhe.com/shigley.
- In Chap. 11, *Rolling-Contact Bearings,* the Weibull probability distribution is defined and related to bearing life.
- In conjunction with the Connect Engineering resource, the end-of-chapter problems have been freshly examined to ensure they are clearly stated with less room for vague interpretations. Approximately 50 percent of the problems are targeted for Connect implementation. With the problem parameterization available in this Web-based platform, students can be assigned basic problems with minimal duplication from student to student and semester to semester. For a good balance, this edition maintains many end-of-chapter problems that are open-ended and suitable for exploration and design.

Connect Engineering

The tenth edition continues to feature McGraw-Hill Connect Engineering, a Web-based assignment and assessment platform that allows instructors to deliver assignments, quizzes, and tests easily online. Students can practice important skills at their own pace and on their own schedule.

McGraw-Hill LearnSmart®

McGraw-Hill LearnSmart is an adaptive learning system designed to help students learn faster, study more efficiently, and retain more knowledge for greater success. Through a series of adaptive questions, Learnsmart pinpoints concepts the student does not understand and maps out a personalized study plan for success. It also lets instructors see exactly what students have accomplished, and it features a built-in assessment tool for graded assignments. Ask your McGraw-Hill Representative for more information, and visit www.mhlearnsmart.com for a demonstration.

McGraw-Hill SmartBook™

Powered by the intelligent and adaptive LearnSmart engine, SmartBook is the first and only continuously adaptive reading experience available today. Distinguishing what students know from what they don't, and honing in on concepts they are most likely to forget, SmartBook personalizes content for each student. Reading is no longer a passive and linear experience but an engaging and dynamic one, where students are more likely to master and retain important concepts, coming to class better prepared. SmartBook includes powerful reports that identify specific topics and learning objectives students need to study. These valuable reports also provide instructors insight into how students are progressing through textbook content and are useful for identifying class trends, focusing precious class time, providing personalized feedback to students, and tailoring assessment.

How does SmartBook work? Each SmartBook contains four components: Preview, Read, Practice, and Recharge. Starting with an initial preview of each chapter and key learning objectives, students read the material and are guided to topics for which they need the most practice based on their responses to a continuously adapting diagnostic. Read and practice continue until SmartBook directs students to recharge important material they are most likely to forget to ensure concept mastery and retention.

Electronic Textbooks

This text is available as an eBook at www.CourseSmart.com. At CourseSmart your students can take advantage of significant savings off the cost of a print textbook, reduce their impact on the environment, and gain access to powerful web tools for learning. CourseSmart eBooks can be viewed online or downloaded to a computer.

The eBooks allow students to do full text searches, add highlighting and notes, and share notes with classmates. CourseSmart has the largest selection of eBooks available anywhere. Visit www.CourseSmart.com to learn more and to try a sample chapter.

McGraw-Hill Create™

With McGraw-Hill Create, you can easily rearrange chapters, combine material from other content sources, and quickly upload content you have written, like your course syllabus or teaching notes. Find the content you need in Create by searching through thousands of leading McGraw-Hill textbooks. Arrange your book to fit your teaching style. Create even allows you to personalize your book's appearance by selecting the cover and adding your name, school, and course information. Order a Create book and you'll receive a complimentary print review copy in 3–5 business days or a complimentary electronic review copy (eComp) via e-mail in minutes. Go to www.mcgrawhillcreate.com today and register to experience how McGraw-Hill Create empowers you to teach your students your way.

Additional media offerings available at www.mhhe.com/shigley include:

Student Supplements

- *Fundamentals of Engineering (FE) exam questions for machine design.* Interactive problems and solutions serve as effective, self-testing problems as well as excellent preparation for the FE exam.

Instructor Supplements (under password protection)

- *Solutions manual.* The instructor's manual contains solutions to most end-of-chapter nondesign problems.
- *PowerPoint® slides.* Slides outlining the content of the text are provided in PowerPoint format for instructors to use as a starting point for developing lecture presentation materials. The slides include all figures, tables, and equations from the text.
- *C.O.S.M.O.S.* A complete online solutions manual organization system that allows instructors to create custom homework, quizzes, and tests using end-of-chapter problems from the text.

Acknowledgments

The authors would like to acknowledge those who have contributed to this text for over 50 years and nine editions. We are especially grateful to those who provided input to this tenth edition:

Expanded Connect Implementation

Peter J. Schuster, *California Polytechnic State University*

Drawings for GD&T Chapter

Glenn Traner, *Tech Manufacturing, LLC*

CAD Model Used in Cover Design

Jedrzej Galecki, *University of the West of England*

Reviewers

Kenneth Huebner, *Arizona State*
Gloria Starns, *Iowa State*
Tim Lee, *McGill University*
Robert Rizza, *MSOE*
Richard Patton, *Mississippi State University*
Stephen Boedo, *Rochester Institute of Technology*
Om Agrawal, *Southern Illinois University*
Arun Srinivasa, *Texas A&M*
Jason Carey, *University of Alberta*
Patrick Smolinski, *University of Pittsburgh*
Dennis Hong, *Virginia Tech*

List of Symbols

This is a list of common symbols used in machine design and in this book. Specialized use in a subject-matter area often attracts fore and post subscripts and superscripts. To make the table brief enough to be useful, the symbol kernels are listed. See Table 14–1, pp. 727–728 for spur and helical gearing symbols, and Table 15–1, pp. 781–782 for bevel-gear symbols.

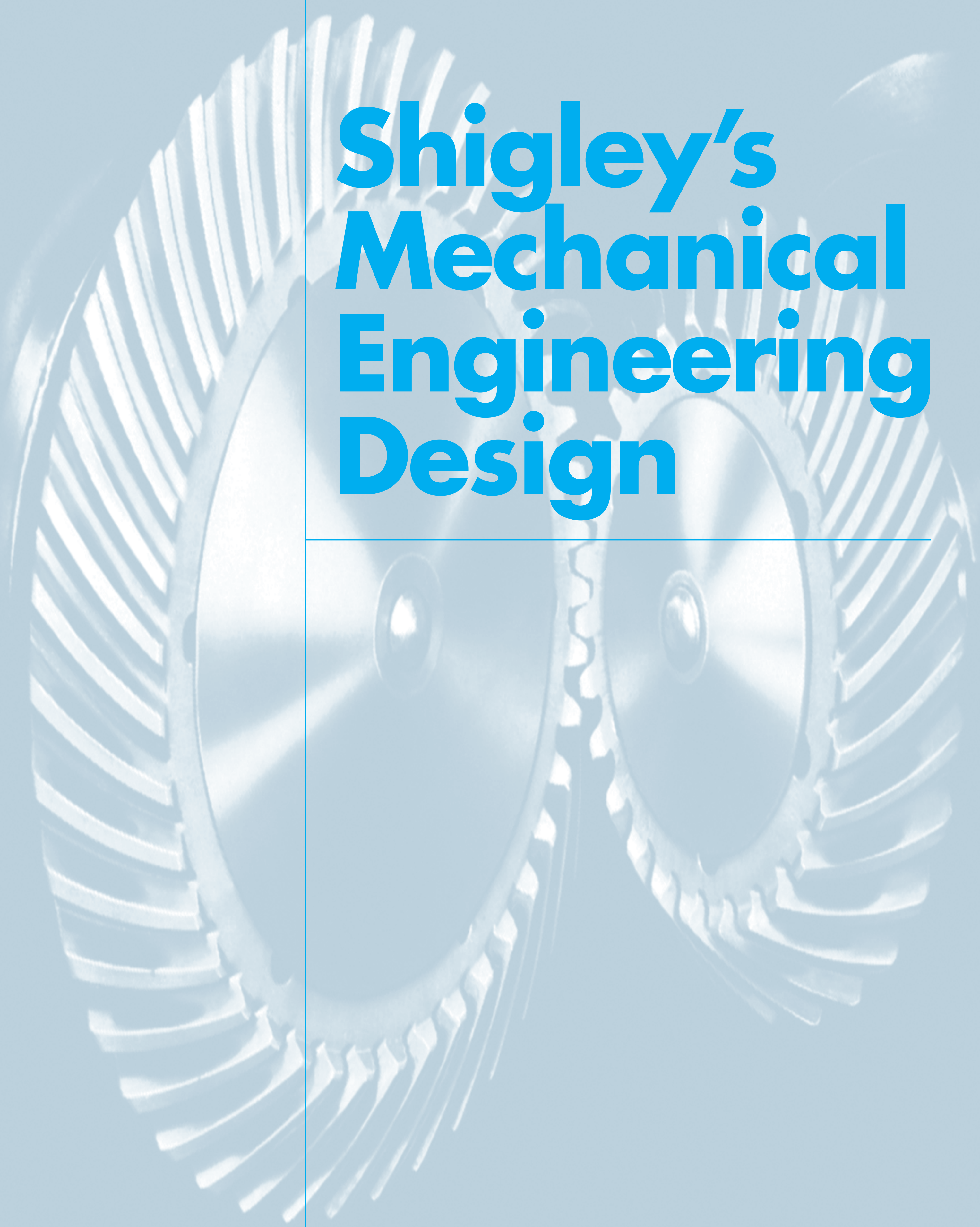
A	Area, coefficient
a	Distance
B	Coefficient
Bhn	Brinell hardness
b	Distance, Weibull shape parameter, range number, width
C	Basic load rating, bolted-joint constant, center distance, coefficient of variation, column end condition, correction factor, specific heat capacity, spring index
c	Distance, viscous damping, velocity coefficient
COV	Coefficient of variation
D	Diameter, helix diameter
d	Diameter, distance
E	Modulus of elasticity, energy, error
e	Distance, eccentricity, efficiency, Naperian logarithmic base
F	Force, fundamental dimension force
f	Coefficient of friction, frequency, function
fom	Figure of merit
G	Torsional modulus of elasticity
g	Acceleration due to gravity, function
H	Heat, power
H_B	Brinell hardness
HRC	Rockwell C-scale hardness
h	Distance, film thickness
$\hbar_{CR}$	Combined overall coefficient of convection and radiation heat transfer
I	Integral, linear impulse, mass moment of inertia, second moment of area
i	Index
i	Unit vector in x-direction
J	Mechanical equivalent of heat, polar second moment of area, geometry factor
j	Unit vector in the y-direction
K	Service factor, stress-concentration factor, stress-augmentation factor, torque coefficient
k	Marin endurance limit modifying factor, spring rate
k	Unit vector in the z-direction
L	Length, life, fundamental dimension length

$\mathscr{L}$	Life in hours
l	Length
M	Fundamental dimension mass, moment
$\mathbf{M}$	Moment vector
m	Mass, slope, strain-strengthening exponent
N	Normal force, number, rotational speed, number of cycles
n	Load factor, rotational speed, factor of safety
n_d	Design factor
P	Force, pressure, diametral pitch
PDF	Probability density function
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, reduction in area
$\mathbf{R}$	Vector reaction force
r	Radius
$\mathbf{r}$	Distance vector
S	Sommerfeld number, strength
s	Distance, sample standard deviation, stress
T	Temperature, tolerance, torque, fundamental dimension time
$\mathbf{T}$	Torque vector
t	Distance, time, tolerance
U	Strain energy
u	Strain energy per unit volume
V	Linear velocity, shear force
v	Linear velocity
W	Cold-work factor, load, weight
w	Distance, gap, load intensity
X	Coordinate, truncated number
x	Coordinate, true value of a number, Weibull parameter
Y	Coordinate
y	Coordinate, deflection
Z	Coordinate, section modulus, viscosity
z	Coordinate, dimensionless transform variable for normal distributions
α	Coefficient, coefficient of linear thermal expansion, end-condition for springs, thread angle
β	Bearing angle, coefficient
Δ	Change, deflection
δ	Deviation, elongation
ϵ	Eccentricity ratio, engineering (normal) strain
ε	True or logarithmic normal strain
Γ	Gamma function, pitch angle
γ	Pitch angle, shear strain, specific weight
λ	Slenderness ratio for springs
μ	Absolute viscosity, population mean
ν	Poisson ratio
ω	Angular velocity, circular frequency
ϕ	Angle, wave length

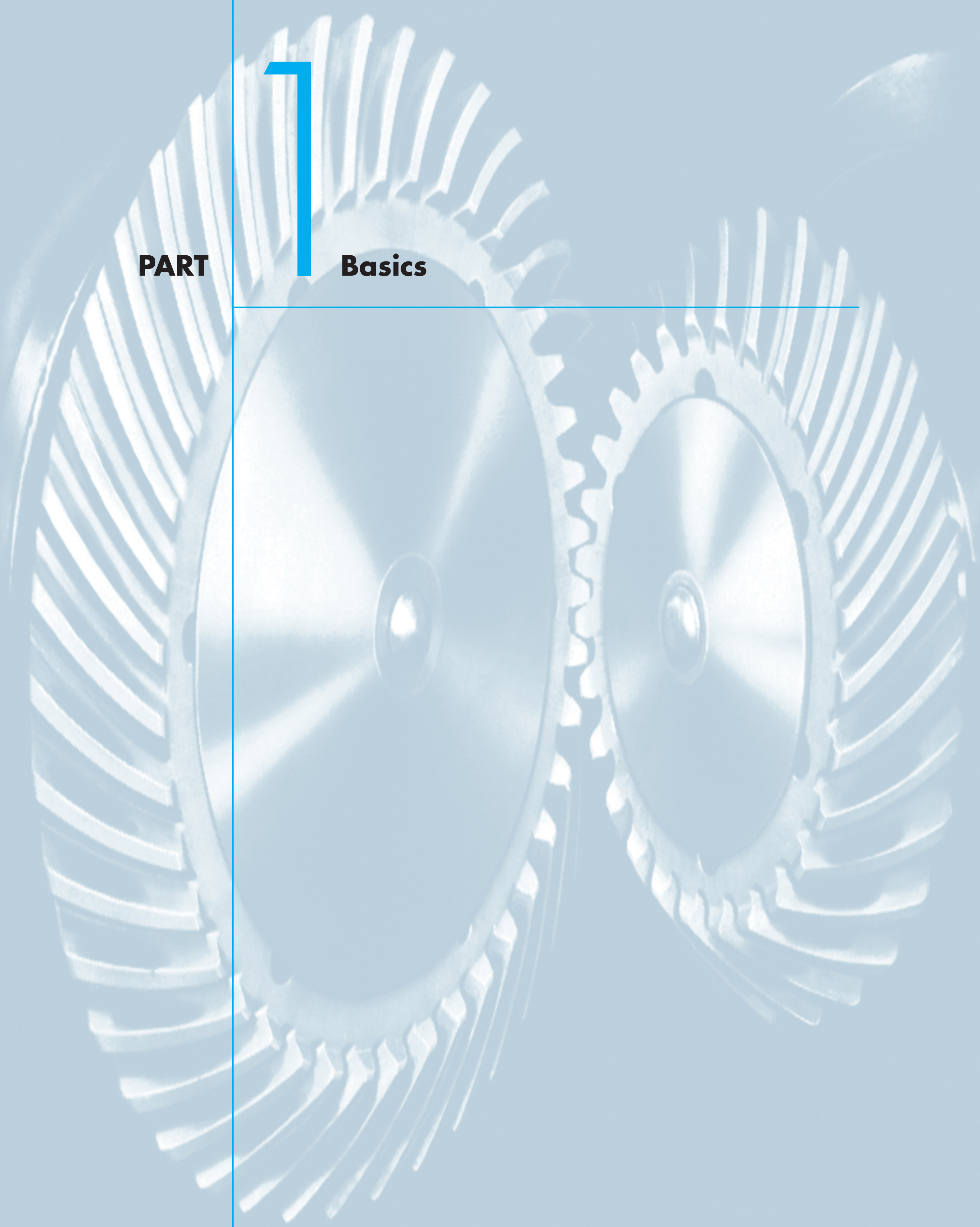
ψ	Slope integral
ρ	Radius of curvature, mass density
σ	Normal stress
σ'	Von Mises stress
$\hat{\sigma}$	Standard deviation
τ	Shear stress
θ	Angle, Weibull characteristic parameter
¢	Cost per unit weight
$	Cost

This page intentionally left blank

Shigley's Mechanical Engineering Design



PART 1 Basics



1 Introduction to Mechanical Engineering Design

Chapter Outline

Mechanical design is a complex process, requiring many skills. Extensive relationships need to be subdivided into a series of simple tasks. The complexity of the process requires a sequence in which ideas are introduced and iterated.

We first address the nature of design in general, and then mechanical engineering design in particular. Design is an iterative process with many interactive phases. Many resources exist to support the designer, including many sources of information and an abundance of computational design tools. Design engineers need not only develop competence in their field but they must also cultivate a strong sense of responsibility and professional work ethic.

There are roles to be played by codes and standards, ever-present economics, safety, and considerations of product liability. The survival of a mechanical component is often related through stress and strength. Matters of uncertainty are ever-present in engineering design and are typically addressed by the design factor and factor of safety, either in the form of a deterministic (absolute) or statistical sense. The latter, statistical approach, deals with a design's *reliability* and requires good statistical data.

In mechanical design, other considerations include dimensions and tolerances, units, and calculations.

This book consists of four parts. Part 1, *Basics,* begins by explaining some differences between design and analysis and introducing some fundamental notions and approaches to design. It continues with three chapters reviewing material properties, stress analysis, and stiffness and deflection analysis, which are the principles necessary for the remainder of the book.

Part 2, *Failure Prevention,* consists of two chapters on the prevention of failure of mechanical parts. Why machine parts fail and how they can be designed to prevent failure are difficult questions, and so we take two chapters to answer them, one on preventing failure due to static loads, and the other on preventing fatigue failure due to time-varying, cyclic loads.

In Part 3, *Design of Mechanical Elements,* the concepts of Parts 1 and 2 are applied to the analysis, selection, and design of specific mechanical elements such as shafts, fasteners, weldments, springs, rolling contact bearings, film bearings, gears, belts, chains, and wire ropes.

Part 4, *Special Topics,* provides introductions to two important methods used in mechanical design, finite element analysis and geometric dimensioning and tolerancing. This is optional study material, but some sections and examples in Parts 1 to 3 demonstrate the use of these tools.

There are two appendixes at the end of the book. Appendix A contains many useful tables referenced throughout the book. Appendix B contains answers to selected end-of-chapter problems.

1–1 Design

To design is either to formulate a plan for the satisfaction of a specified need or to solve a specific problem. If the plan results in the creation of something having a physical reality, then the product must be functional, safe, reliable, competitive, usable, manufacturable, and marketable.

Design is an innovative and highly iterative process. It is also a decision-making process. Decisions sometimes have to be made with too little information, occasionally with just the right amount of information, or with an excess of partially contradictory information. Decisions are sometimes made tentatively, with the right reserved to adjust as more becomes known. The point is that the engineering designer has to be personally comfortable with a decision-making, problem-solving role.

Design is a communication-intensive activity in which both words and pictures are used, and written and oral forms are employed. Engineers have to communicate effectively and work with people of many disciplines. These are important skills, and an engineer's success depends on them.

A designer's personal resources of creativeness, communicative ability, and problem-solving skill are intertwined with the knowledge of technology and first principles. Engineering tools (such as mathematics, statistics, computers, graphics, and languages) are combined to produce a plan that, when carried out, produces a product that is *functional, safe, reliable, competitive, usable, manufacturable, and marketable,* regardless of who builds it or who uses it.

1–2 Mechanical Engineering Design

Mechanical engineers are associated with the production and processing of energy and with providing the means of production, the tools of transportation, and the techniques of automation. The skill and knowledge base are extensive. Among the disciplinary bases are mechanics of solids and fluids, mass and momentum transport, manufacturing processes, and electrical and information theory. Mechanical engineering design involves all the disciplines of mechanical engineering.

Real problems resist compartmentalization. A simple journal bearing involves fluid flow, heat transfer, friction, energy transport, material selection, thermomechanical treatments, statistical descriptions, and so on. A building is environmentally controlled. The heating, ventilation, and air-conditioning considerations are sufficiently specialized that some speak of heating, ventilating, and air-conditioning design as if it is separate and distinct from mechanical engineering design. Similarly, internal-combustion engine design, turbomachinery design, and jet-engine design are sometimes considered discrete entities. Here, the leading string of words preceding the word design is merely a product descriptor. Similarly, there are phrases such as machine design, machine-element design, machine-component design, systems design, and fluid-power design. All of these phrases are somewhat more focused *examples* of mechanical engineering design. They all draw on the same bodies of knowledge, are similarly organized, and require similar skills.

1–3 Phases and Interactions of the Design Process

What is the design process? How does it begin? Does the engineer simply sit down at a desk with a blank sheet of paper and jot down some ideas? What happens next? What factors influence or control the decisions that have to be made? Finally, how does the design process end?

The complete design process, from start to finish, is often outlined as in Fig. 1–1. The process begins with an identification of a need and a decision to do something about it. After many iterations, the process ends with the presentation of the plans for satisfying the need. Depending on the nature of the design task, several design phases may be repeated throughout the life of the product, from inception to termination. In the next several subsections, we shall examine these steps in the design process in detail.

Identification of need generally starts the design process. Recognition of the need and phrasing the need often constitute a highly creative act, because the need may be

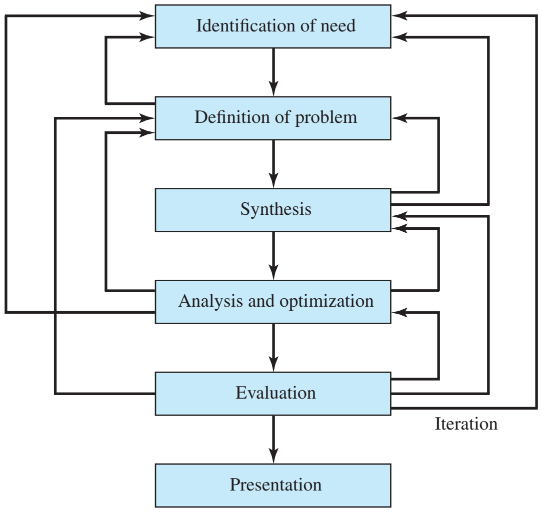


Figure 1–1

The phases in design, acknowledging the many feedbacks and iterations.

only a vague discontent, a feeling of uneasiness, or a sensing that something is not right. The need is often not evident at all; recognition can be triggered by a particular adverse circumstance or a set of random circumstances that arises almost simultaneously. For example, the need to do something about a food-packaging machine may be indicated by the noise level, by a variation in package weight, and by slight but perceptible variations in the quality of the packaging or wrap.

There is a distinct difference between the statement of the need and the definition of the problem. The *definition of problem* is more specific and must include all the specifications for the object that is to be designed. The specifications are the input and output quantities, the characteristics and dimensions of the space the object must occupy, and all the limitations on these quantities. We can regard the object to be designed as something in a black box. In this case we must specify the inputs and outputs of the box, together with their characteristics and limitations. The specifications define the cost, the number to be manufactured, the expected life, the range, the operating temperature, and the reliability. Specified characteristics can include the speeds, feeds, temperature limitations, maximum range, expected variations in the variables, dimensional and weight limitations, etc.

There are many implied specifications that result either from the designer's particular environment or from the nature of the problem itself. The manufacturing processes that are available, together with the facilities of a certain plant, constitute restrictions on a designer's freedom, and hence are a part of the implied specifications. It may be that a small plant, for instance, does not own cold-working machinery. Knowing this, the designer might select other metal-processing methods that can be performed in the plant. The labor skills available and the competitive situation also constitute implied constraints. Anything that limits the designer's freedom of choice is a constraint. Many materials and sizes are listed in supplier's catalogs, for instance, but these are not all easily available and shortages frequently occur. Furthermore, inventory economics requires that a manufacturer stock a minimum number of materials and sizes. An example of a specification is given in Sec. 1–18. This example is for a case study of a power transmission that is presented throughout this text.

The *synthesis* of a scheme connecting possible system elements is sometimes called the *invention of the concept* or *concept design*. This is the first and most important step in the synthesis task. Various schemes must be proposed, investigated, and quantified in terms of established metrics.[1] As the fleshing out of the scheme progresses, analyses must be performed to assess whether the system performance is satisfactory or better, and, if satisfactory, just how well it will perform. System schemes that do not survive analysis are revised, improved, or discarded. Those with potential are optimized to determine the best performance of which the scheme is capable. Competing schemes are compared so that the path leading to the most competitive product can be chosen. Figure 1–1 shows that synthesis and *analysis and optimization* are intimately and iteratively related.

We have noted, and we emphasize, that design is an iterative process in which we proceed through several steps, evaluate the results, and then return to an earlier phase of the procedure. Thus, we may synthesize several components of a system, analyze and optimize them, and return to synthesis to see what effect this has on the remaining parts of the system. For example, the design of a system to transmit power requires attention to the design and selection of individual components (e.g., gears, bearings, shaft). However, as is often the case in design, these components are not independent. In order to design the shaft for stress and deflection, it is necessary to know the applied forces. If the forces are transmitted through gears, it is necessary to know the gear specifications in order to determine the forces that will be transmitted to the shaft. But stock gears come with certain bore sizes, requiring knowledge of the necessary shaft diameter. Clearly, rough estimates will need to be made in order to proceed through the process, refining and iterating until a final design is obtained that is satisfactory for each individual component as well as for the overall design specifications. Throughout the text we will elaborate on this process for the case study of a power transmission design.

Both analysis and optimization require that we construct or devise abstract models of the system that will admit some form of mathematical analysis. We call these models mathematical models. In creating them it is our hope that we can find one that will simulate the real physical system very well. As indicated in Fig. 1–1, *evaluation* is a significant phase of the total design process. Evaluation is the final proof of a successful design and usually involves the testing of a prototype in the laboratory. Here we wish to discover if the design really satisfies the needs. Is it reliable? Will it compete successfully with similar products? Is it economical to manufacture and to use? Is it easily maintained and adjusted? Can a profit be made from its sale or use? How likely is it to result in product-liability lawsuits? And is insurance easily and cheaply obtained? Is it likely that recalls will be needed to replace defective parts or systems? The project designer or design team will need to address a myriad of engineering and non-engineering questions.

Communicating the design to others is the final, vital *presentation* step in the design process. Undoubtedly, many great designs, inventions, and creative works have been lost to posterity simply because the originators were unable or unwilling to properly explain their accomplishments to others. Presentation is a selling job. The engineer, when presenting a new solution to administrative, management, or supervisory persons, is attempting to sell or to prove to them that their solution is a better one. Unless this can be done successfully, the time and effort spent on obtaining the

[1]An excellent reference for this topic is presented by Stuart Pugh, *Total Design—Integrated Methods for Successful Product Engineering,* Addison-Wesley, 1991. A description of the *Pugh method* is also provided in Chap. 8, David G. Ullman, *The Mechanical Design Process,* 3rd ed., McGraw-Hill, 2003.

solution have been largely wasted. When designers sell a new idea, they also sell themselves. If they are repeatedly successful in selling ideas, designs, and new solutions to management, they begin to receive salary increases and promotions; in fact, this is how anyone succeeds in his or her profession.

Design Considerations

Sometimes the strength required of an element in a system is an important factor in the determination of the geometry and the dimensions of the element. In such a situation we say that strength is an important *design consideration.* When we use the expression design consideration, we are referring to some characteristic that influences the design of the element or, perhaps, the entire system. Usually quite a number of such characteristics must be considered and prioritized in a given design situation. Many of the important ones are as follows (not necessarily in order of importance):

1 Functionality
2 Strength/stress
3 Distortion/deflection/stiffness
4 Wear
5 Corrosion
6 Safety
7 Reliability
8 Manufacturability
9 Utility
10 Cost
11 Friction
12 Weight
13 Life
14 Noise
15 Styling
16 Shape
17 Size
18 Control
19 Thermal properties
20 Surface
21 Lubrication
22 Marketability
23 Maintenance
24 Volume
25 Liability
26 Remanufacturing/resource recovery

Some of these characteristics have to do directly with the dimensions, the material, the processing, and the joining of the elements of the system. Several characteristics may be interrelated, which affects the configuration of the total system.

1–4 Design Tools and Resources

Today, the engineer has a great variety of tools and resources available to assist in the solution of design problems. Inexpensive microcomputers and robust computer software packages provide tools of immense capability for the design, analysis, and simulation of mechanical components. In addition to these tools, the engineer always needs technical information, either in the form of basic science/engineering behavior or the characteristics of specific off-the-shelf components. Here, the resources can range from science/engineering textbooks to manufacturers' brochures or catalogs. Here too, the computer can play a major role in gathering information.[2]

Computational Tools

Computer-aided design (CAD) software allows the development of three-dimensional (3-D) designs from which conventional two-dimensional orthographic views with

[2]An excellent and comprehensive discussion of the process of "gathering information" can be found in Chap. 4, George E. Dieter, *Engineering Design, A Materials and Processing Approach,* 3rd ed., McGraw-Hill, New York, 2000.

automatic dimensioning can be produced. Manufacturing tool paths can be generated from the 3-D models, and in some cases, parts can be created directly from a 3-D database by using a rapid prototyping and manufacturing method (stereolithography)—*paperless manufacturing!* Another advantage of a 3-D database is that it allows rapid and accurate calculations of mass properties such as mass, location of the center of gravity, and mass moments of inertia. Other geometric properties such as areas and distances between points are likewise easily obtained. There are a great many CAD software packages available such as Aries, AutoCAD, CadKey, I-Deas, Unigraphics, Solid Works, and ProEngineer, to name a few.

The term *computer-aided engineering* (CAE) generally applies to all computer-related engineering applications. With this definition, CAD can be considered as a subset of CAE. Some computer software packages perform specific engineering analysis and/or simulation tasks that assist the designer, but they are not considered a tool for the creation of the design that CAD is. Such software fits into two categories: engineering-based and non-engineering-specific. Some examples of engineering-based software for mechanical engineering applications—software that might also be integrated within a CAD system—include finite-element analysis (FEA) programs for analysis of stress and deflection (see Chap. 19), vibration, and heat transfer (e.g., Algor, ANSYS, and MSC/NASTRAN); computational fluid dynamics (CFD) programs for fluid-flow analysis and simulation (e.g., CFD++, FIDAP, and Fluent); and programs for simulation of dynamic force and motion in mechanisms (e.g., ADAMS, DADS, and Working Model).

Examples of non-engineering-specific computer-aided applications include software for word processing, spreadsheet software (e.g., Excel, Lotus, and Quattro-Pro), and mathematical solvers (e.g., Maple, MathCad, MATLAB,[3] Mathematica, and TKsolver).

Your instructor is the best source of information about programs that may be available to you and can recommend those that are useful for specific tasks. One caution, however: Computer software is no substitute for the human thought process. *You* are the driver here; the computer is the vehicle to assist you on your journey to a solution. Numbers generated by a computer can be far from the truth if you entered incorrect input, if you misinterpreted the application or the output of the program, if the program contained bugs, etc. It is your responsibility to assure the validity of the results, so be careful to check the application and results carefully, perform benchmark testing by submitting problems with known solutions, and monitor the software company and user-group newsletters.

Acquiring Technical Information

We currently live in what is referred to as the *information age,* where information is generated at an astounding pace. It is difficult, but extremely important, to keep abreast of past and current developments in one's field of study and occupation. The reference in footnote 2 provides an excellent description of the informational resources available and is highly recommended reading for the serious design engineer. Some sources of information are:

- *Libraries (community, university, and private).* Engineering dictionaries and encyclopedias, textbooks, monographs, handbooks, indexing and abstract services, journals, translations, technical reports, patents, and business sources/brochures/catalogs.

[3]MATLAB is a registered trademark of The MathWorks, Inc.

- *Government sources.* Departments of Defense, Commerce, Energy, and Transportation; NASA; Government Printing Office; U.S. Patent and Trademark Office; National Technical Information Service; and National Institute for Standards and Technology.
- *Professional societies.* American Society of Mechanical Engineers, Society of Manufacturing Engineers, Society of Automotive Engineers, American Society for Testing and Materials, and American Welding Society.
- *Commercial vendors.* Catalogs, technical literature, test data, samples, and cost information.
- *Internet.* The computer network gateway to websites associated with most of the categories listed above.[4]

This list is not complete. The reader is urged to explore the various sources of information on a regular basis and keep records of the knowledge gained.

1–5 The Design Engineer's Professional Responsibilities

In general, the design engineer is required to satisfy the needs of *customers* (management, clients, consumers, etc.) and is expected to do so in a competent, responsible, ethical, and professional manner. Much of engineering course work and practical experience focuses on competence, but when does one begin to develop engineering responsibility and professionalism? To start on the road to success, you should start to develop these characteristics early in your educational program. You need to cultivate your professional work ethic and process skills before graduation, so that when you begin your formal engineering career, you will be prepared to meet the challenges.

It is not obvious to some students, but communication skills play a large role here, and it is the wise student who continuously works to improve these skills—*even if it is not a direct requirement of a course assignment!* Success in engineering (achievements, promotions, raises, etc.) may in large part be due to competence but if you cannot communicate your ideas clearly and concisely, your technical proficiency may be compromised.

You can start to develop your communication skills by keeping a neat and clear journal/logbook of your activities, entering dated entries frequently. (Many companies require their engineers to keep a journal for patent and liability concerns.) Separate journals should be used for each design project (or course subject). When starting a project or problem, in the definition stage, make journal entries quite frequently. Others, as well as yourself, may later question why you made certain decisions. Good chronological records will make it easier to explain your decisions at a later date.

Many engineering students see themselves after graduation as practicing engineers designing, developing, and analyzing products and processes and consider the need of good communication skills, either oral or writing, as secondary. This is far from the truth. Most practicing engineers spend a good deal of time communicating with others, writing proposals and technical reports, and giving presentations and interacting with engineering and nonengineering support personnel. You have the time now to sharpen your communication skills. When given an assignment to write or

[4]Some helpful Web resources, to name a few, include www.globalspec.com, www.engnetglobal.com, www.efunda.com, www.thomasnet.com, and www.uspto.gov.

make any presentation, technical *or* nontechnical, accept it enthusiastically, and work on improving your communication skills. It will be time well spent to learn the skills now rather than on the job.

When you are working on a design problem, it is important that you develop a systematic approach. Careful attention to the following action steps will help you to organize your solution processing technique.

- *Understand the problem.* Problem definition is probably the most significant step in the engineering design process. Carefully read, understand, and refine the problem statement.
- *Identify the knowns.* From the refined problem statement, describe concisely what information is known and relevant.
- *Identify the unknowns and formulate the solution strategy.* State what must be determined, in what order, so as to arrive at a solution to the problem. Sketch the component or system under investigation, identifying known and unknown parameters. Create a flowchart of the steps necessary to reach the final solution. The steps may require the use of free-body diagrams; material properties from tables; equations from first principles, textbooks, or handbooks relating the known and unknown parameters; experimentally or numerically based charts; specific computational tools as discussed in Sec. 1–4; etc.
- *State all assumptions and decisions.* Real design problems generally do not have unique, ideal, closed-form solutions. Selections, such as the choice of materials, and heat treatments, require decisions. Analyses require assumptions related to the modeling of the real components or system. All assumptions and decisions should be identified and recorded.
- *Analyze the problem.* Using your solution strategy in conjunction with your decisions and assumptions, execute the analysis of the problem. Reference the sources of all equations, tables, charts, software results, etc. Check the credibility of your results. Check the order of magnitude, dimensionality, trends, signs, etc.
- *Evaluate your solution.* Evaluate each step in the solution, noting how changes in strategy, decisions, assumptions, and execution might change the results, in positive or negative ways. Whenever possible, incorporate the positive changes in your final solution.
- *Present your solution.* Here is where your communication skills are important. At this point, you are selling yourself and your technical abilities. If you cannot skillfully explain what you have done, some or all of your work may be misunderstood and unaccepted. Know your audience.

As stated earlier, all design processes are interactive and iterative. Thus, it may be necessary to repeat some or all of the above steps more than once if less than satisfactory results are obtained.

In order to be effective, all professionals must keep current in their fields of endeavor. The design engineer can satisfy this in a number of ways by: being an active member of a professional society such as the American Society of Mechanical Engineers (ASME), the Society of Automotive Engineers (SAE), and the Society of Manufacturing Engineers (SME); attending meetings, conferences, and seminars of societies, manufacturers, universities, etc.; taking specific graduate courses or programs at universities; regularly reading technical and professional journals; etc. An engineer's education does not end at graduation.

The design engineer's professional obligations include conducting activities in an ethical manner. Reproduced here is the *Engineers' Creed* from the National Society of Professional Engineers (NSPE)[5]:

As a Professional Engineer I dedicate my professional knowledge and skill to the advancement and betterment of human welfare.
I pledge:
To give the utmost of performance;
To participate in none but honest enterprise;
To live and work according to the laws of man and the highest standards of professional conduct;
To place service before profit, the honor and standing of the profession before personal advantage, and the public welfare above all other considerations.
In humility and with need for Divine Guidance, I make this pledge.

1–6 Standards and Codes

A *standard* is a set of specifications for parts, materials, or processes intended to achieve uniformity, efficiency, and a specified quality. One of the important purposes of a standard is to limit the multitude of variations that can arise from the arbitrary creation of a part, material, or process.

A *code* is a set of specifications for the analysis, design, manufacture, and construction of something. The purpose of a code is to achieve a specified degree of safety, efficiency, and performance or quality. It is important to observe that safety codes *do not* imply *absolute safety.* In fact, absolute safety is impossible to obtain. Sometimes the unexpected event really does happen. Designing a building to withstand a 120 mi/h wind does not mean that the designers think a 140 mi/h wind is impossible; it simply means that they think it is highly improbable.

All of the organizations and societies listed below have established specifications for standards and safety or design codes. The name of the organization provides a clue to the nature of the standard or code. Some of the standards and codes, as well as addresses, can be obtained in most technical libraries or on the Internet. The organizations of interest to mechanical engineers are:

Aluminum Association (AA)
American Bearing Manufacturers Association (ABMA)
American Gear Manufacturers Association (AGMA)
American Institute of Steel Construction (AISC)
American Iron and Steel Institute (AISI)
American National Standards Institute (ANSI)
American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)
American Society of Mechanical Engineers (ASME)
American Society of Testing and Materials (ASTM)
American Welding Society (AWS)

[5]Adopted by the National Society of Professional Engineers, June 1954. "The Engineer's Creed." Reprinted by permission of the National Society of Professional Engineers. NSPE also publishes a much more extensive *Code of Ethics for Engineers* with rules of practice and professional obligations. For the current revision, July 2007 (at the time of this book's printing), see the website www.nspe.org/Ethics/CodeofEthics/index.html.

ASM International
British Standards Institution (BSI)
Industrial Fasteners Institute (IFI)
Institute of Transportation Engineers (ITE)
Institution of Mechanical Engineers (IMechE)
International Bureau of Weights and Measures (BIPM)
International Federation of Robotics (IFR)
International Standards Organization (ISO)
National Association of Power Engineers (NAPE)
National Institute for Standards and Technology (NIST)
Society of Automotive Engineers (SAE)

1–7 Economics

The consideration of cost plays such an important role in the design decision process that we could easily spend as much time in studying the cost factor as in the study of the entire subject of design. Here we introduce only a few general concepts and simple rules.

First, observe that nothing can be said in an absolute sense concerning costs. Materials and labor usually show an increasing cost from year to year. But the costs of processing the materials can be expected to exhibit a decreasing trend because of the use of automated machine tools and robots. The cost of manufacturing a single product will vary from city to city and from one plant to another because of overhead, labor, taxes, and freight differentials and the inevitable slight manufacturing variations.

Standard Sizes

The use of standard or stock sizes is a first principle of cost reduction. An engineer who specifies an AISI 1020 bar of hot-rolled steel 53 mm square has added cost to the product, provided that a bar 50 or 60 mm square, both of which are preferred sizes, would do equally well. The 53-mm size can be obtained by special order or by rolling or machining a 60-mm square, but these approaches add cost to the product. To ensure that standard or preferred sizes are specified, designers must have access to stock lists of the materials they employ.

A further word of caution regarding the selection of preferred sizes is necessary. Although a great many sizes are usually listed in catalogs, they are not all readily available. Some sizes are used so infrequently that they are not stocked. A rush order for such sizes may add to the expense and delay. Thus you should also have access to a list such as those in Table A–17 for preferred inch and millimeter sizes.

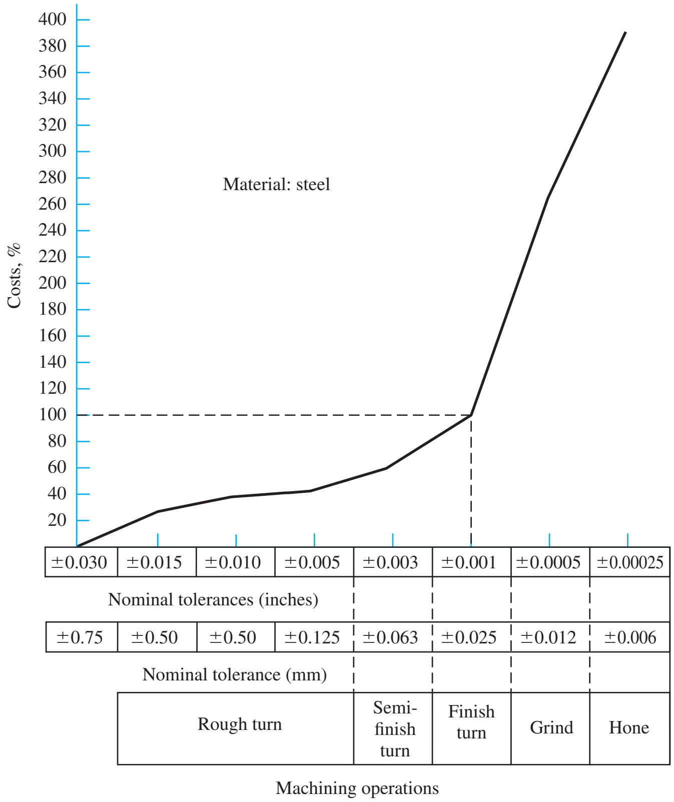
There are many purchased parts, such as motors, pumps, bearings, and fasteners, that are specified by designers. In the case of these, too, you should make a special effort to specify parts that are readily available. Parts that are made and sold in large quantities usually cost somewhat less than the odd sizes. The cost of rolling bearings, for example, depends more on the quantity of production by the bearing manufacturer than on the size of the bearing.

Large Tolerances

Among the effects of design specifications on costs, tolerances are perhaps most significant. Tolerances, manufacturing processes, and surface finish are interrelated and influence the producibility of the end product in many ways. Close tolerances

Figure 1–2

Cost versus tolerance/machining process. *(From David G. Ullman,* The Mechanical Design Process, *3rd ed., McGraw-Hill, New York, 2003.)*



may necessitate additional steps in processing and inspection or even render a part completely impractical to produce economically. Tolerances cover dimensional variation and surface-roughness range and also the variation in mechanical properties resulting from heat treatment and other processing operations.

Since parts having large tolerances can often be produced by machines with higher production rates, costs will be significantly smaller. Also, fewer such parts will be rejected in the inspection process, and they are usually easier to assemble. A plot of cost versus tolerance/machining process is shown in Fig. 1–2, and illustrates the drastic increase in manufacturing cost as tolerance diminishes with finer machining processing.

Breakeven Points

Sometimes it happens that, when two or more design approaches are compared for cost, the choice between the two depends on a set of conditions such as the quantity of production, the speed of the assembly lines, or some other condition. There then occurs a point corresponding to equal cost, which is called the *breakeven point.*

As an example, consider a situation in which a certain part can be manufactured at the rate of 25 parts per hour on an automatic screw machine or 10 parts per hour on a hand screw machine. Let us suppose, too, that the setup time for the automatic is 3 h and that the labor cost for either machine is $20 per hour, including overhead. Figure 1–3 is a graph of cost versus production by the two methods. The breakeven point for this example corresponds to 50 parts. If the desired production is greater than 50 parts, the automatic machine should be used.

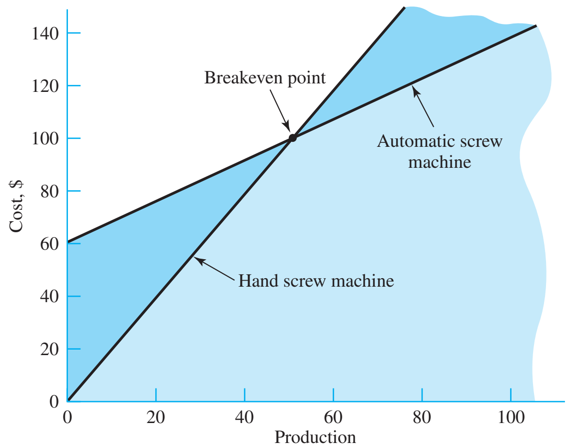


Figure 1–3

A breakeven point.

Cost Estimates

There are many ways of obtaining relative cost figures so that two or more designs can be roughly compared. A certain amount of judgment may be required in some instances. For example, we can compare the relative value of two automobiles by comparing the dollar cost per pound of weight. Another way to compare the cost of one design with another is simply to count the number of parts. The design having the smaller number of parts is likely to cost less. Many other cost estimators can be used, depending upon the application, such as area, volume, horsepower, torque, capacity, speed, and various performance ratios.[6]

1–8 Safety and Product Liability

The *strict liability* concept of product liability generally prevails in the United States. This concept states that the manufacturer of an article is liable for any damage or harm that results because of a defect. And it doesn't matter whether the manufacturer knew about the defect, or even could have known about it. For example, suppose an article was manufactured, say, 10 years ago. And suppose at that time the article could not have been considered defective on the basis of all technological knowledge then available. Ten years later, according to the concept of strict liability, the manufacturer is still liable. Thus, under this concept, the plaintiff needs only to prove that the article was defective and that the defect caused some damage or harm. Negligence of the manufacturer need not be proved.

The best approaches to the prevention of product liability are good engineering in analysis and design, quality control, and comprehensive testing procedures. Advertising managers often make glowing promises in the warranties and sales literature for a product. These statements should be reviewed carefully by the engineering staff to eliminate excessive promises and to insert adequate warnings and instructions for use.

[6]For an overview of estimating manufacturing costs, see Chap. 11, Karl T. Ulrich and Steven D. Eppinger, *Product Design and Development,* 3rd ed., McGraw-Hill, New York, 2004.

1–9 Stress and Strength

The survival of many products depends on how the designer adjusts the maximum stresses in a component to be less than the component's strength at critical locations. The designer must allow the maximum stress to be less than the strength by a sufficient margin so that despite the uncertainties, failure is rare.

In focusing on the stress-strength comparison at a critical (controlling) location, we often look for "strength in the geometry and condition of use." Strengths are the magnitudes of stresses at which something of interest occurs, such as the proportional limit, 0.2 percent-offset yielding, or fracture (see Sec. 2–1). In many cases, such events represent the stress level at which loss of function occurs.

Strength is a property of a material or of a mechanical element. The strength of an element depends on the choice, the treatment, and the processing of the material. Consider, for example, a shipment of springs. We can associate a strength with a specific spring. When this spring is incorporated into a machine, external forces are applied that result in load-induced stresses in the spring, the magnitudes of which depend on its geometry and are independent of the material and its processing. If the spring is removed from the machine undamaged, the stress due to the external forces will return to zero. But the strength remains as one of the properties of the spring. Remember, then, that *strength is an inherent property of a part,* a property built into the part because of the use of a particular material and process.

Various metalworking and heat-treating processes, such as forging, rolling, and cold forming, cause variations in the strength from point to point throughout a part. The spring cited above is quite likely to have a strength on the outside of the coils different from its strength on the inside because the spring has been formed by a cold winding process, and the two sides may not have been deformed by the same amount. Remember, too, therefore, that a strength value given for a part may apply to only a particular point or set of points on the part.

In this book we shall use the capital letter S to denote *strength,* with appropriate subscripts to denote the type of strength. Thus, S_y is a yield strength, S_u an ultimate strength, S_{sy} a shear yield strength, and S_e an endurance strength.

In accordance with accepted engineering practice, we shall employ the Greek letters σ(sigma) and τ(tau) to designate normal and shear *stresses,* respectively. Again, various subscripts will indicate some special characteristic. For example, σ_1 is a principal normal stress, σ_y a normal stress component in the y direction, and σ_r a normal stress component in the radial direction.

Stress is a state property at a *specific point* within a body, which is a function of load, geometry, temperature, and manufacturing processing. In an elementary course in mechanics of materials, stress related to load and geometry is emphasized with some discussion of thermal stresses. However, stresses due to heat treatments, molding, assembly, etc. are also important and are sometimes neglected. A review of stress analysis for basic load states and geometry is given in Chap. 3.

1–10 Uncertainty

Uncertainties in machinery design abound. Examples of uncertainties concerning stress and strength include

- Composition of material and the effect of variation on properties.
- Variations in properties from place to place within a bar of stock.
- Effect of processing locally, or nearby, on properties.

- Effect of nearby assemblies such as weldments and shrink fits on stress conditions.
- Effect of thermomechanical treatment on properties.
- Intensity and distribution of loading.
- Validity of mathematical models used to represent reality.
- Intensity of stress concentrations.
- Influence of time on strength and geometry.
- Effect of corrosion.
- Effect of wear.
- Uncertainty as to the length of any list of uncertainties.

Engineers must accommodate uncertainty. Uncertainty always accompanies change. Material properties, load variability, fabrication fidelity, and validity of mathematical models are among concerns to designers.

There are mathematical methods to address uncertainties. The primary techniques are the deterministic and stochastic methods. The deterministic method establishes a *design factor* based on the absolute uncertainties of a loss-of-function parameter and a maximum allowable parameter. Here the parameter can be load, stress, deflection, etc. Thus, the design factor n_d is defined as

$$n_d = \frac{\text{loss-of-function parameter}}{\text{maximum allowable parameter}} \tag{1–1}$$

If the parameter is load (as would be the case for column buckling), then the maximum allowable load can be found from

$$\text{Maximum allowable load} = \frac{\text{loss-of-function load}}{n_d} \tag{1–2}$$

EXAMPLE 1–1

Consider that the maximum load on a structure is known with an uncertainty of ±20 percent, and the load causing failure is known within ±15 percent. If the load causing failure is *nominally* 2000 lbf, determine the design factor and the maximum allowable load that will offset the absolute uncertainties.

Solution

To account for its uncertainty, the loss-of-function load must increase to 1/0.85, whereas the maximum allowable load must decrease to 1/1.2. Thus to offset the absolute uncertainties the design factor, from Eq. (1–1), should be

Answer

$$n_d = \frac{1/0.85}{1/1.2} = 1.4$$

From Eq. (1–2), the maximum allowable load is found to be

Answer

$$\text{Maximum allowable load} = \frac{2000}{1.4} = 1400 \text{ lbf}$$

Stochastic methods are based on the statistical nature of the design parameters and focus on the probability of survival of the design's function (that is, on reliability). This is discussed further in Secs. 1–12 and 1–13.

1–11 Design Factor and Factor of Safety

A general approach to the allowable load versus loss-of-function load problem is the deterministic design factor method, and sometimes called the classical method of design. The fundamental equation is Eq. (1–1) where n_d is called the *design factor.* All loss-of-function modes must be analyzed, and the mode leading to the smallest design factor governs. After the design is completed, the *actual* design factor may change as a result of changes such as rounding up to a standard size for a cross section or using off-the-shelf components with higher ratings instead of employing what is calculated by using the design factor. The factor is then referred to as the *factor of safety, n.* The factor of safety has the same definition as the design factor, but it generally differs numerically.

Since stress may not vary linearly with load (see Sec. 3–19), using load as the loss-of-function parameter may not be acceptable. It is more common then to express the design factor in terms of a stress and a relevant strength. Thus Eq. (1–1) can be rewritten as

$$n_d = \frac{\text{loss-of-function strength}}{\text{allowable stress}} = \frac{S}{\sigma(\text{or } \tau)} \tag{1–3}$$

The stress and strength terms in Eq. (1–3) must be of the same type and units. Also, the stress and strength must apply to the same critical location in the part.

EXAMPLE 1–2

A rod with a cross-sectional area of A and loaded in tension with an axial force of $P = 2000$ lbf undergoes a stress of $\sigma = P/A$. Using a material strength of 24 kpsi and a *design factor* of 3.0, determine the minimum diameter of a solid circular rod. Using Table A–17, select a preferred fractional diameter and determine the rod's *factor of safety*.

Solution

Since $A = \pi d^2/4$, $\sigma = P/A$, and from Eq. (1–3), $\sigma = S/n_d$, then

$$\sigma = \frac{P}{A} = \frac{P}{\pi d^2/4} = \frac{S}{n_d}$$

Solving for d yields

Answer

$$d = \left(\frac{4Pn_d}{\pi S}\right)^{1/2} = \left(\frac{4(2000)3}{\pi(24\,000)}\right)^{1/2} = 0.564 \text{ in}$$

From Table A–17, the next higher preferred size is $\frac{5}{8}$ in $= 0.625$ in. Thus, when n_d is replaced with n in the equation developed above, the factor of safety n is

Answer

$$n = \frac{\pi S d^2}{4P} = \frac{\pi(24\,000)0.625^2}{4(2000)} = 3.68$$

Thus rounding the diameter has increased the actual design factor.

It is tempting to offer some recommendations concerning the assignment of the design factor for a given application.[7] The problem in doing so is with the evaluation

[7]If the reader desires some examples of assigning design factor values see David G. Ullman, *The Mechanical Design Process*, 4th ed., McGraw-Hill, New York, 2010, App. C.

of the many uncertainties associated with the loss-of-function modes. The reality is, the designer must attempt to account for the variance of all the factors that will affect the results. Then, the designer must rely on experience, company policies, and the many codes that may pertain to the application (e.g. the ASME Boiler and Pressure Vessel Code) to arrive at an appropriate design factor. An example might help clarify the intricacy of assigning a design factor.

EXAMPLE 1–3

A vertical round rod is to be used to support a hanging weight. A person will place the weight on the end without dropping it. The diameter of the rod can be manufactured within ± 1 percent of its nominal dimension. The support ends can be centered within ± 1.5 percent of the nominal diameter dimension. The weight is known within ± 2 percent of the nominal weight. The strength of the material is known within ± 3.5 percent of the nominal strength value. If the designer is using nominal values and the nominal stress equation, $\sigma_{\text{nom}} = P/A$ (as in the previous example), determine what design factor should be used so that the stress does not exceed the strength.

Solution

There are two hidden factors to consider here. The first, due to the possibility of eccentric loading, the maximum stress *is not* $\sigma = P/A$ (review Chap. 3). Second, the person may not be placing the weight onto the rod support end *gradually,* and the load application would then be considered dynamic.

Consider the eccentricity first. With eccentricity, a bending moment will exist giving an additional stress of $\sigma = 32\,M/(\pi d^3)$ (see Sec. 3–10). The bending moment is given by $M = Pe$, where e is the eccentricity. Thus, the maximum stress in the rod is given by

$$\sigma = \frac{P}{A} + \frac{32Pe}{\pi d^3} = \frac{P}{\pi d^2/4} + \frac{32Pe}{\pi d^3} \tag{1}$$

Since the eccentricity tolerance is expressed as a function of the diameter, we will write the eccentricity as a percentage of d. Let $e = k_e d$, where k_e is a constant. Thus, Eq. (1) is rewritten as

$$\sigma = \frac{4P}{\pi d^2} + \frac{32Pk_e d}{\pi d^3} = \frac{4P}{\pi d^2}(1 + 8k_e) \tag{2}$$

Applying the tolerances to achieve the maximum the stress can reach gives

$$\begin{aligned}\sigma_{\text{max}} &= \frac{4P(1 + 0.02)}{\pi[d(1 - 0.01)]^2}[1 + 8(0.015)] = 1.166\left(\frac{4P}{\pi d^2}\right) \\ &= 1.166\sigma_{\text{nom}}\end{aligned} \tag{3}$$

Suddenly applied loading is covered in Sec. 4–17. If a weight is dropped from a height, h, from the support end, the maximum load in the rod is given by Eq. (4–59) which is

$$F = W + W\left(1 + \frac{hk}{W}\right)^{1/2}$$

where F is the force in the rod, W is the weight, and k is the rod's spring constant. Since the person is not dropping the weight, $h = 0$, and with $W = P$, then $F = 2P$. This assumes the person is *not* gradually placing the weight on, and there is no damping in the rod. Thus Eq. (3) is modified by substituting $2P$ for P and the maximum stress is

$$\sigma_{\max} = 2(1.166)\,\sigma_{\text{nom}} = 2.332\,\sigma_{\text{nom}}$$

The minimum strength is

$$S_{\min} = (1 - 0.035)\,S_{\text{nom}} = 0.965\,S_{\text{nom}}$$

Equating the maximum stress to the minimum strength gives

$$2.332\,\sigma_{\text{nom}} = 0.965\,S_{\text{nom}}$$

From Eq. (1–3), the design factor using nominal values should be

Answer

$$n_d = \frac{S_{\text{nom}}}{\sigma_{\text{nom}}} = \frac{2.332}{0.965} = 2.42$$

Obviously, if the designer takes into account all of the uncertainties in this example and accounts for all of the tolerances in the stress and strength in the calculations, a design factor of one would suffice. However, in practice, the designer would probably use the nominal geometric and strength values with the simple $\sigma = P/A$ calculation. The designer would probably not go through the calculations given in the example and would assign a design factor. This is where the experience factor comes in. The designer should make a list of the loss-of-function modes and estimate a factor, n_i, for each. For this example, the list would be

Loss-of-function	**Estimated accuracy**	**n_i**
Geometry dimensions	Good tolerances	1.05
Stress calculation		
Dynamic load	Not gradual loading	2.0*
Bending	Slight possibility	1.1
Strength data	Well known	1.05

*Minimum

Each term directly affects the results. Therefore, for an estimate, we evaluate the product of each term

$$n_d = \prod n_i = 1.05(2.0)(1.1)(1.05) = 2.43$$

1–12 Reliability and Probability of Failure

In these days of greatly increasing numbers of liability lawsuits and the need to conform to regulations issued by governmental agencies such as EPA and OSHA, it is very important for the designer and the manufacturer to know the reliability of their product. The *reliability method* of design is one in which we obtain the distribution of stresses and the distribution of strengths and then relate these two in order to achieve an acceptable success rate. The statistical measure of the probability that a mechanical element will not fail in use is called the *reliability* of that element and as we will see, is related to the *probability of failure,* p_f.

Figure 1–4

The shape of the normal distribution curve: (*a*) small $\hat{\sigma}$; (*b*) large $\hat{\sigma}$.

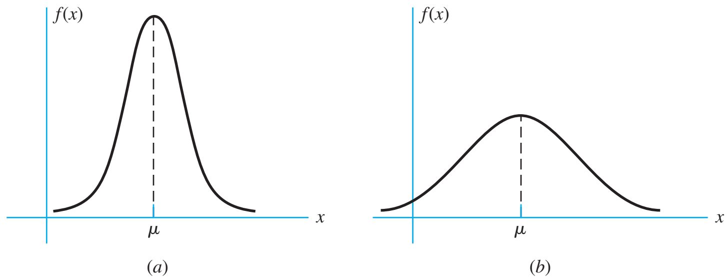
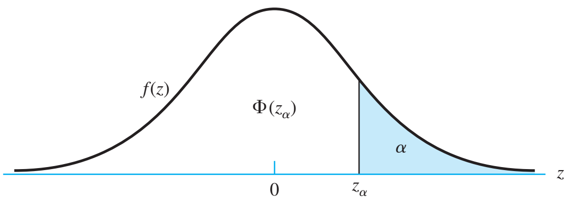


Figure 1–5

Transformed normal distribution function of Table A–10.



Probability of Failure

The probability of failure, p_f, is obtained from the *probability density function* (PDF), which represents the distribution of events within a given range of values. A number of standard discrete and continuous probability distributions are commonly applicable to engineering problems. The two most important continuous probability distributions for our use in this text are the *Gaussian* (*normal*) *distribution* and the *Weibull distribution*. We will describe the normal distribution in this section and in Sec. 2–2. The Weibull distribution is widely used in rolling-contact bearing design and will be described in Chap. 11.

The continuous Gaussian (normal) distribution is an important one whose *probability density function* (PDF) is expressed in terms of its mean, μ_x, and its standard deviation[8] $\hat{\sigma}_x$ as

$$f(x) = \frac{1}{\hat{\sigma}_x\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu_x}{\hat{\sigma}_x}\right)^2\right] \tag{1–4}$$

Plots of Eq. (1–4) are shown in Fig. 1–4 for small and large standard deviations. The bell-shaped curve is taller and narrower for small values of $\hat{\sigma}$ and shorter and broader for large values of $\hat{\sigma}$. Note that the area under each curve is unity. That is, the probability of all events occurring is one (100 percent).

To obtain values of p_f, integration of Eq. (1–4) is necessary. This can come easily from a table if the variable x is placed in dimensionless form. This is done using the transform

$$z = \frac{x-\mu_x}{\hat{\sigma}_x} \tag{1–5}$$

The integral of the transformed normal distribution is tabulated in Table A–10, where α is defined, and is shown in Fig. 1–5. The value of the normal density function is used so often, and manipulated in so many equations, that it has its own particular symbol, $\Phi(z)$. The transform variant z has a mean value of zero and a standard deviation of unity. In Table A–10, the probability of an observation less than z is $\Phi(z)$ for negative values of z and $1 - \Phi(z)$ for positive values of z.

[8]The symbol σ is normally used for the standard deviation. However, in this text σ is used for stress. Consequently, we will use $\hat{\sigma}$ for the standard deviation.

EXAMPLE 1–4

In a shipment of 250 connecting rods, the mean tensile strength is found to be $\bar{S} = 45$ kpsi and has a standard deviation of $\hat{\sigma}_S = 5$ kpsi.

(*a*) Assuming a normal distribution, how many rods can be expected to have a strength less than $S = 39.5$ kpsi?

(*b*) How many are expected to have a strength between 39.5 and 59.5 kpsi?

Solution

(*a*) Substituting in Eq. (1–5) gives the transform z variable as

$$z_{39.5} = \frac{x - \mu_x}{\hat{\sigma}_x} = \frac{S - \bar{S}}{\hat{\sigma}_S} = \frac{39.5 - 45}{5} = -1.10$$

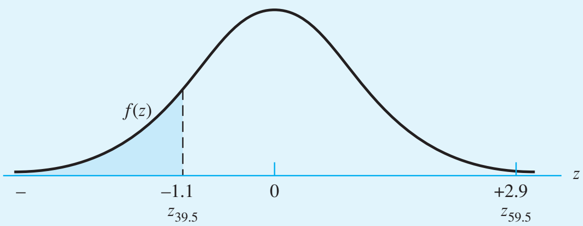
The probability that the strength is less than 39.5 kpsi can be designated as $F(z) = \Phi(z_{39.5}) = \Phi(-1.10)$. Using Table A–10, and referring to Fig. 1–6, we find $\Phi(z_{39.5}) = 0.1357$. So the number of rods having a strength less than 39.5 kpsi is,

Answer

$$N\Phi(z_{39.5}) = 250(0.1357) = 33.9 \approx 34 \text{ rods}$$

because $\Phi(z_{39.5})$ represents the *proportion* of the population N having a strength less than 39.5 kpsi.

Figure 1–6



(*b*) Corresponding to $S = 59.5$ kpsi, we have

$$z_{59.5} = \frac{59.5 - 45}{5} = 2.90$$

Referring again to Fig. 1–6, we see that the probability that the strength is less than 59.5 kpsi is $F(z) = \Phi(z_{59.5}) = \Phi(2.90)$. Since the z variable is positive, we need to find the value complementary to unity. Thus, from Table A–10

$$\Phi(2.90) = 1 - \Phi(-2.90) = 1 - 0.001\,87 = 0.998\,13$$

The probability that the strength lies between 39.5 and 59.5 kpsi is the area between the ordinates at $z_{39.5}$ and $z_{59.5}$ in Fig. 1–6. This probability is found to be

$$p = \Phi(z_{59.5}) - \Phi(z_{39.5}) = \Phi(2.90) - \Phi(-1.10)$$
$$= 0.998\,13 - 0.1357 = 0.862\,43$$

Therefore the number of rods expected to have strengths between 39.5 and 59.5 kpsi is

Answer

$$Np = 250(0.862) = 215.5 \approx 216 \text{ rods}$$

Events typically arise as *discrete distributions,* which can be approximated by continuous distributions. Consider N samples of events. Let x_i be the value of an event ($i = 1,2, \ldots k$) and f_i is the class frequency or number of times the event x_i occurs within the class frequency range. The *discrete* mean, $\bar{x}$, and standard deviation, defined as s_x, are given by

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{k} f_i x_i \tag{1–6}$$

$$s_x = \sqrt{\frac{\sum_{i=1}^{k} f_i x_i^2 - N\bar{x}^2}{N-1}} \tag{1–7}$$

EXAMPLE 1–5

Five tons of 2-in round rods of 1030 hot-rolled steel have been received for workpiece stock. Nine standard-geometry tensile test specimens have been machined from random locations in various rods. In the test report, the ultimate tensile strength was given in kpsi. The data in the ranges 62–65, 65–68, 68–71 and 71–74 kpsi is given in histographic form as follows:

S_{ut} (kpsi)	63.5	66.5	69.5	72.5
f	2	2	3	2

where the values of S_{ut} are the midpoints of each range. Find the mean and standard deviation of the data.

Solution

Table 1–1 provides a tabulation of the calculations for the solution.

Table 1–1

Class Midpoint x, kpsi	Class Frequency f	Extension fx	fx^2
63.5	2	127	8 064.50
66.5	2	133	8 844.50
69.5	3	208.5	14 480.75
72.5	2	145	10 513.50
	Σ 9	613.5	41 912.25

From Eq. (1–6),

Answer

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{k} f_i x_i = \frac{1}{9}(613.5) = 68.16667 = 68.2 \text{ kpsi}$$

From Eq. (1–7),

Answer

$$s_x = \sqrt{\frac{\sum_{i=1}^{k} f_i x_i^2 - N\bar{x}^2}{N-1}} = \sqrt{\frac{41\,912.25 - 9(68.16667^2)}{9-1}}$$
$$= 3.39 \text{ kpsi}$$

Reliability

The reliability R can be expressed by

$$R = 1 - p_f \tag{1–8}$$

where p_f is the *probability of failure,* given by the number of instances of failures per total number of possible instances. The value of R falls in the range $0 \leq R \leq 1$. A reliability of $R = 0.90$ means that there is a 90 percent chance that the part will perform its proper function without failure. The failure of 6 parts out of every 1000 manufactured, $p_f = 6/1000$, might be considered an acceptable failure rate for a certain class of products. This represents a reliability of $R = 1 - 6/1000 = 0.994$ or 99.4 percent.

In the *reliability method of design,* the designer's task is to make a judicious selection of materials, processes, and geometry (size) so as to achieve a specific reliability goal. Thus, if the objective reliability is to be 99.4 percent, as above, what combination of materials, processing, and dimensions is needed to meet this goal?

If a mechanical system fails when any one component fails, the system is said to be a *series system.* If the reliability of component i is R_i in a series system of n components, then the reliability of the system is given by

$$R = \prod_{i=1}^{n} R_i \tag{1–9}$$

For example, consider a shaft with two bearings having reliabilities of 95 percent and 98 percent. From Eq. (1–9), the overall reliability of the shaft system is then

$$R = R_1 R_2 = 0.95(0.98) = 0.93$$

or 93 percent.

Analyses that lead to an assessment of reliability address uncertainties, or their estimates, in parameters that describe the situation. Stochastic variables such as stress, strength, load, or size are described in terms of their means, standard deviations, and distributions. If bearing balls are produced by a manufacturing process in which a diameter distribution is created, we can say upon choosing a ball that there is uncertainty as to size. If we wish to consider weight or moment of inertia in rolling, this size uncertainty can be considered to be *propagated* to our knowledge of weight or inertia. There are ways of estimating the statistical parameters describing weight and inertia from those describing size and density. These methods are variously called *propagation of error, propagation of uncertainty,* or *propagation of dispersion.* These methods are integral parts of analysis or synthesis tasks when probability of failure is involved.

It is important to note that good statistical data and estimates are essential to perform an acceptable reliability analysis. This requires a good deal of testing and validation of the data. In many cases, this is not practical and a deterministic approach to the design must be undertaken.

1–13 Relating Design Factor to Reliability

Reliability is the statistical probability that machine systems and components will perform their intended function satisfactorily without failure. Stress and strength are statistical in nature and very much tied to the reliability of the stressed component. Consider the probability density functions for stress and strength, σ and S, shown in

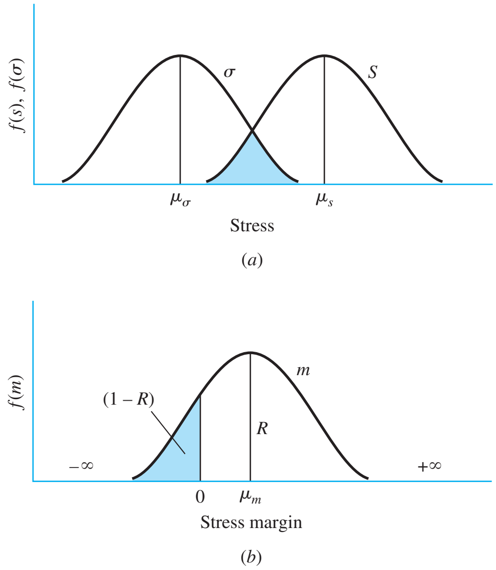


Figure 1–7

Plots of density functions showing how the interference of S and σ is used to explain the stress margin m. (a) Stress and strength distributions. (b) Distribution of interference; the reliability R is the area of the density function for $m > 0$; the interference is the area $(1 - R)$.

Fig. 1–7a. The mean values of stress and strength are $\bar{\sigma} = \mu_\sigma$ and $\bar{S} = \mu_S$, respectively. Here, the "average" design factor is

$$\bar{n}_d = \frac{\mu_S}{\mu_\sigma} \tag{a}$$

The *margin of safety* for any value of stress σ and strength S is defined as

$$m = S - \sigma \tag{b}$$

The average of the margin of safety is $\bar{m} = \mu_S - \mu_\sigma$. However, for the overlap of the distributions shown by the shaded area in Fig. 1–7a, the stress exceeds the strength. Here, the margin of safety is negative, and these parts are expected to fail. This shaded area is called the *interference* of σ and S.

Figure 1–7b shows the distribution of m, which obviously depends on the distributions of stress and strength. The reliability that a part will perform without failure, R, is the area of the margin of safety distribution for $m > 0$. The interference is the area, $1 - R$, where parts are expected to fail. Assuming that σ and S each have a normal distribution, the stress margin m will also have a normal distribution. Reliability is the probability p that $m > 0$. That is,

$$R = p(S > \sigma) = p(S - \sigma > 0) = p(m > 0) \tag{c}$$

To find the probability that $m > 0$, we form the z variable of m and substitute $m = 0$. Noting that $\mu_m = \mu_S - \mu_\sigma$, and[9] $\hat{\sigma}_m = (\hat{\sigma}_S^2 + \hat{\sigma}_\sigma^2)^{1/2}$, use Eq. (1–5) to write

$$z = \frac{m - \mu_m}{\hat{\sigma}_m} = \frac{0 - \mu_m}{\hat{\sigma}_m} = -\frac{\mu_m}{\hat{\sigma}_m} = -\frac{\mu_S - \mu_\sigma}{(\hat{\sigma}_S^2 + \hat{\sigma}_\sigma^2)^{1/2}} \tag{1–10}$$

[9]Note: If a and b are normal distributions, and $c = a \pm b$, then c is a normal distribution with a mean of $\mu_c = \mu_a \pm \mu_b$, and a standard deviation of $\hat{\sigma}_c = (\hat{\sigma}_a^2 + \hat{\sigma}_b^2)^{1/2}$. Tabular results for means and standard deviations for simple algebraic operations can be found in R. G. Budynas and J. K. Nisbett, *Shigley's Mechanical Engineering Design,* 9th ed., McGraw-Hill, New York, 2011, Table 20-6, p. 993.

Comparing Fig. 1–7*b* with Table A–10, we see that

$$\begin{aligned} R &= 1 - \Phi(z) \qquad z \le 0 \\ &= \Phi(z) \qquad z > 0 \end{aligned} \tag{d}$$

To relate to the design factor, $\bar{n}_d = \mu_S/\mu_\sigma$, divide each term on the right side of Eq. (1–10) by μ_σ and rearrange as shown:

$$\begin{aligned} z &= -\frac{\dfrac{\mu_S}{\mu_\sigma} - 1}{\left[\dfrac{\hat{\sigma}_S^2}{\mu_\sigma^2} + \dfrac{\hat{\sigma}_\sigma^2}{\mu_\sigma^2}\right]^{1/2}} = -\frac{\bar{n}_d - 1}{\left[\dfrac{\hat{\sigma}_S^2}{\mu_\sigma^2}\dfrac{\mu_S^2}{\mu_S^2} + \dfrac{\hat{\sigma}_\sigma^2}{\mu_\sigma^2}\right]^{1/2}} \\ &= -\frac{\bar{n}_d - 1}{\left[\dfrac{\mu_S^2}{\mu_\sigma^2}\dfrac{\hat{\sigma}_S^2}{\mu_S^2} + \dfrac{\hat{\sigma}_\sigma^2}{\mu_\sigma^2}\right]^{1/2}} = -\frac{\bar{n}_d - 1}{\left[\bar{n}_d^2\dfrac{\hat{\sigma}_S^2}{\mu_S^2} + \dfrac{\hat{\sigma}_\sigma^2}{\mu_\sigma^2}\right]^{1/2}} \end{aligned} \tag{e}$$

Introduce the terms $C_S = \hat{\sigma}_S/\mu_S$ and $C_\sigma = \hat{\sigma}_\sigma/\mu_\sigma$, called the *coefficients of variance* for strength and stress, respectively. Equation (*e*) is then rewritten as

$$z = -\frac{\bar{n}_d - 1}{\sqrt{\bar{n}_d^2 C_S^2 + C_\sigma^2}} \tag{1–11}$$

Squaring both sides of Eq. (1–11) and solving for $\bar{n}_d$ results in

$$\bar{n}_d = \frac{1 \pm \sqrt{1 - (1 - z^2C_S^2)(1 - z^2C_\sigma^2)}}{1 - z^2C_S^2} \tag{1–12}$$

The plus sign is associated with $R > 0.5$, and the minus sign with $R \le 0.5$.

Equation (1–12) is remarkable in that it relates the design factor $\bar{n}_d$ to the reliability goal R (through z) and the coefficients of variation of the strength and stress.

EXAMPLE 1–6

A round cold-drawn 1018 steel rod has 0.2 percent mean yield strength $\bar{S}_y = 78.4$ kpsi with a standard deviation of 5.90 kpsi. The rod is to be subjected to a mean static axial load of $\bar{P} = 50$ kip with a standard deviation of 4.1 kip. Assuming the strength and load have normal distributions, what value of the design factor $\bar{n}_d$ corresponds to a reliability of 0.999 against yielding? Determine the corresponding diameter of the rod.

Solution

For strength, $C_S = \hat{\sigma}_S/\mu_S = 5.90/78.4 = 0.0753$. For stress,

$$\sigma = \frac{P}{A} = \frac{4P}{\pi d^2}$$

Since the tolerance on the diameter will be an order of magnitude less than that of the load or strength, the diameter will be treated deterministically. Thus, statistically, the stress is linearly proportional to the load, and $C_\sigma = C_P = \hat{\sigma}_P/\mu_P = 4.1/50 = 0.082$. From Table A–10, for $R = 0.999$, $z = -3.09$. Then, Eq. (1–12) gives

Answer

$$\bar{n}_d = \frac{1 + \sqrt{1 - [1 - (-3.09)^2(0.0753)^2][1 - (-3.09)^2(0.082)^2]}}{1 - (-3.09)^2(0.0753)^2} = 1.416$$

The diameter is found deterministically from

$$\bar{\sigma} = \frac{4\bar{P}}{\pi d^2} = \frac{\bar{S}_y}{\bar{n}_d}$$

Solving for d gives

Answer
$$d = \sqrt{\frac{4\bar{P}\bar{n}_d}{\pi \bar{S}_y}} = \sqrt{\frac{4(50)(1.416)}{\pi(78.4)}} = 1.072 \text{ in}$$

1–14 Dimensions and Tolerances

Part of a machine designer's task is to specify the parts and components necessary for a machine to perform its desired function. Early in the design process, it is usually sufficient to work with nominal dimensions to determine function, stresses, deflections, and the like. However, eventually it is necessary to get to the point of specificity that every component can be purchased and every part can be manufactured. For a part to be manufactured, its essential shape, dimensions, and tolerances must be communicated to the manufacturers. This is usually done by means of a machine drawing, which may either be a multiview drawing on paper, or digital data from a CAD file. Either way, the drawing usually represents a legal document between the parties involved in the design and manufacture of the part. It is essential that the part be defined precisely and completely so that it can only be interpreted in one way. The designer's intent must be conveyed in such a way that any manufacturer can make the part and/or component to the satisfaction of any inspector.

Common Dimensioning Terminology

Before going further, we will define a few terms commonly used in dimensioning.

- *Nominal size.* The size we use in speaking of an element. For example, we may specify a $1\frac{1}{2}$-in pipe or a $\frac{1}{2}$-in bolt. Either the theoretical size or the actual measured size may be quite different. The theoretical size of a $1\frac{1}{2}$-in pipe is 1.900 in for the outside diameter. And the diameter of the $\frac{1}{2}$-in bolt, say, may actually measure 0.492 in.
- *Limits.* The stated maximum and minimum dimensions.
- *Tolerance.* The difference between the two limits.
- *Bilateral tolerance.* The variation in both directions from the basic dimension. That is, the basic size is between the two limits, for example, 1.005 ± 0.002 in. The two parts of the tolerance need not be equal.
- *Unilateral tolerance.* The basic dimension is taken as one of the limits, and variation is permitted in only one direction, for example,

$$1.005\,^{+0.004}_{-0.000} \text{ in}$$

- *Clearance*. A general term that refers to the mating of cylindrical parts such as a bolt and a hole. The word clearance is used only when the internal member is smaller than the external member. The *diametral clearance* is the measured difference in the two diameters. The *radial clearance* is the difference in the two radii.
- *Interference.* The opposite of clearance, for mating cylindrical parts in which the internal member is larger than the external member (e.g., press-fits).