Fundamentals of Machine Component Design

ROBERT C. JUVINALL

KURT M. MARSHEK

SIXTH EDITION

WILEY

Appendix A-1a *Conversion Factors for British Gravitational, English, and SI Units*

Quantity	British Gravitational and English Units[a]	SI Unit[a]	Conversion Factor Equalities
Length	inch (in. or ″)	meter (m)	*1 in. = 0.0254 m = 25.4 mm
	foot (ft or ′)	meter (m)	*1 ft = 0.3048 m = 304.8 mm
	mile (mi U.S. statute)	kilometer (km)	1 mile = 1.609 km = 1609 m
Volume	gallon (gal U.S.)	meter^3 (m^3)	1 gal = 0.003785 m^3 = 3.785 liters
Force (weight)	pound (lb)	newton[d] (N)	1 lb = 4.448 N
Torque	pound-foot (lb·ft)	newton-meter (N·m)	1 lb·ft = 1.356 N·m
Work, Energy	foot-pound (ft·lb)	joule[c] (J)	1 ft·lb = 1.356 J
Power	foot-pound/second (ft·lb/s)	watt[g] (W)	1 ft·lb/s = 1.356 W
	horsepower[b] (hp)	kilowatt (kW)	1 hp = 0.746 kW
Stress,	pounds/in.^{2} (psi)	pascal[e] (Pa)	1 psi = 6895 Pa
Pressure	thousand pounds/in.^{2} (ksi)	megapascal (MPa)	1 ksi = 6.895 MPa
Mass (British)	slug[f]	kilogram (kg)	1 slug = 14.59 kg
Mass (English)	lbm[h]	kilogram (kg)	1 lbm = 0.454 kg = 454 grams

[a] The *larger* unit is underlined.

[b] 1 hp = 550 ft·lb/s; [c] 1 J = 1 N·m; [d] 1 N = 1 kg·m/s^2; [e] 1 Pa = 1 N/m^2; [f] 1 slug = 1 lb·s^2/ft; [g] 1 W = 1 J/s; [h] 1 slug = 32.2 lbm.

*An exact definition.

Appendix C-1 *Physical Properties of Common Metals*

	Modulus of Elasticity, E		Modulus of Rigidity, G		Poisson's Ratio, ν	Unit Weight, w (lb/in.^{3})	Density, ρ (Mg/m^3)	Coefficient of Thermal Expansion, α		Thermal Conductivity		Specific Heat	
Metal	**Mpsi**	**GPa**	**Mpsi**	**GPa**				**10^{-6}/°F**	**10^{-6}/°C**	**Btu/h-ft-°F**	**W/m-°C**	**Btu/lbm-°F**	**J/kg-°C**
Aluminum alloy	10.4[a]	72	3.9	27	0.32	0.10	2.8	12.0	22	100	173	0.22	920
Beryl. copper	18.5	127	7.2	50	0.29	0.30	8.3	9.3	17	85	147	0.10	420
Brass, Bronze	16	110	6.0	41	0.33	0.31	8.7	10.5	19	45	78	0.10	420
Copper	17.5	121	6.6	46	0.33	0.32	8.9	9.4	17	220	381	0.10	420
Iron, gray cast[b]	15	103	6.0	41	0.26	0.26	7.2	6.4	12	29	50	0.13	540
Magnesium alloy	6.5	45	2.4	17	0.35	0.065	1.8	14.5	26	55	95	0.28	1170
Nickel alloy	30	207	11.5	79	0.30	0.30	8.3	7.0	13	12	21	0.12	500
Steel, carbon	30	207	11.5	79	0.30	0.28	7.7	6.7	12	27	47	0.11	460
Steel, alloy	30	207	11.5	79	0.30	0.28	7.7	6.3	11	22	38	0.11	460
Steel, stainless	27.5	190	10.6	73	0.30	0.28	7.7	8.0	14	12	21	0.11	460
Titanium alloy	16.5	114	6.2	43	0.33	0.16	4.4	4.9	9	7	12	0.12	500
Zinc alloy	12	83	4.5	31	0.33	0.24	6.6	15.0	27	64	111	0.11	460

[a] Values given are representative. Exact values may vary with composition and processing, sometimes greatly.

[b] See Appendix C-3 for more detailed elastic properties of cast irons.

Note: See Appendix C-18 for physical properties of some plastics.

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This book was set in 10/12 TimesLTStd by SPi Global and printed and bound by Lightning Source Inc

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ISBN: 978-1-118-98768-1(PBK)
ISBN: 978-1-119-32155-2(EVALC)

Library of Congress Cataloging in Publication Data:

Names: Juvinall, Robert C., author. | Marshek, Kurt M., author.
Title: Fundamentals of machine component design / Robert C. Juvinall, Kurt M. Marshek.
Description: Sixth edition | Hoboken, NJ : John Wiley & Sons, 2017. | Includes bibliographical references and index. | Description based on print version record and CIP data provided by publisher; resource not viewed.
Identifiers: LCCN 2016054682 (print) | LCCN 2016056619(ebook) | ISBN 9781119342816 (Adobe PDF) | ISBN 9781119321538 (ePub) | ISBN 9781118987681 (pbk.)
Subjects: LCSH: Machine design. | Machine parts.
Classification: LCC TJ230 (print) | LCC TJ230 .J88 2017 (ebook) | DDC 621.8/15–dc23
LC record available at https://lccn.loc.gov/2016056619

The inside back cover will contain printing identification and country of origin if omitted from this page. In addition, if the ISBN on the back cover differs from the ISBN on this page, the one on the back cover is correct.

PREFACE

This book is intended as a text for first courses in Mechanical Engineering Design and as a reference for practicing engineers. It is assumed that the user has had basic courses in Mechanics, Strength of Materials, and Materials Properties. However, the first nine chapters of the book (Part I) serve to review as well as extend this basic background. The remaining chapters (Part II) deal with the application of these fundamentals to specific machine components.

Features of the sixth edition of the text include:

- ***Homework problems***—A large number of new problems are added that help the student focus on introductory concepts and definitions.
- ***Safety considerations***—The textbook continues to focus on real world safety issues adapted from actual case studies. For example, presented are an analysis of truck pick up tailgate cable failures, an unguarded in-running nip point of a treadmill belt drive, the sudden collapse of a cantilevered section of a walkway under demolition, the unexpected release of a hack squat machine carriage, the exposed shaft of an industrial finger jointer, and the safety of a two-wheeled, self-balancing electric personal transport.
- ***Engineering material selection***—New charts from Professor Ashby's material selection procedure form the basis for introducing the student to selection and use of common engineering materials.
- ***Elastic stability***—A design study presents an introduction to a captive cap that has two elastically stable positions: "opened" and "closed." The study references a patent and an exercise, the solution of which reveals a method of patent analysis.
- ***Abrasive wear***—A device for screening seal materials is studied. An associated homework problem introduces the student to a patented test apparatus used to select the best materials for tricone drilling bits.
- ***Impact absorber***—The concept of reducing impact forces and dissipating and dispersing impact loads is expanded to footwear with the introduction of a design study and homework problem involving a high heel shoe impact absorber.
- ***Fasteners***—A design case study introduces a fastening device that is comprised of multiple components. A flexible slotted circular binding band in effect acts like a worm gear, and a thread screw member acts like a worm in driving the joined ends of the circular band. A new related homework problem provides the student with an opportunity to fully understand a related patent.
- ***Suspension system***—A design study gives the student an opportunity to better understand a patented front and rear vehicle suspension system, and suspension related vehicle components.
- ***Microscale and nanoscale machine elements***—A chapter contributed by Professor Cullinan presents a detailed study of micro–nano machine elements, such as mechanical sensors, actuators, and bearings that are used in microelectromechanical (MEMS) and nanoelectromechanical systems (NEMS).

- ***Remote control racecars***—A design project case study authored by Professor Cullinan introduces readers to an exciting design-and-build racecar experience that involves design, analysis, experimentation, and evaluation, culminating with a student RC car race.
- ***Appendix***—The appendices have been edited and condensed to focus on supplemental material that is most necessary for reference work with the textbook.

Part I

Although much of Part I of the text is a review of earlier courses, we would like to call attention to several particular sections.

- Sections 1.2, 1.3, and 1.4 deal with three of the broadest aspects of engineering—safety, ecology, and social significance. These are concerns to which today's students are particularly responsive.
- Section 1.7 presents a methodology for solving machine component problems. Embodied in this methodology is a sample problem format that includes a restatement, solution, and comments for the problem under the headings: known, find, schematic, decisions, assumptions, analysis, and comments. *Decisions* are choices made by the designer. Since design is an iterative decision-making process of synthesis, whenever the heading "decisions" is utilized, a design problem is presented. If a solution is presented without decisions being made, the problem is one of analysis. The inclusion of the category "decisions" allows the student to see clearly the difference between design and analysis. Once appropriate decisions have been made, analysis can follow. *Assumptions*, which are used in solving a problem, are statements about beliefs; for example, the material is homogeneous throughout. The design engineer and the student need to understand what assumptions are made in solving a problem. The listing of assumptions provides more opportunities for students of machine design to "think before doing." *Comments* present key aspects of the solution and discuss how better results might be obtained by making different design decisions, relaxing certain assumptions, and so on.
- Sections 1.8, 1.9, and 1.10 review fundamental energy relationships. Most students at this level need to gain insight and understanding concerning such basic matters as the relationship between work input to a rotating camshaft and work output at a translating follower, and the relationship between engine power, vehicle speed, and fuel consumption.
- Most teachers of Mechanical Engineering Design lament the weakness of their students in the area of free-body diagram analysis of loads. Unless the loading on a machine component is properly established, subsequent design or analysis is of little value. Section 2.2 is directed toward helping relieve this common deficiency and its associated problems.
- References are often an invaluable resource for the student as they provide in depth coverage of topics to which the text may only be able to devote a single paragraph. As such, *MIL-HDBK-17* is introduced to the student in Chapter 3 and *MIL-HDBK-5J* in Appendix F. These two references provide a wealth of pragmatic engineering knowledge regarding engineering materials and composites. The use of these volumes, along with the chapter references, has the ability to dramatically enhance a student's knowledge base.
- An elementary treatment of residual stresses is included in Chapter 4. An understanding of the basic concepts involved is vital to modern stress analysis, particularly when fatigue is present.
- Castigliano's method for determining elastic deflections and redundant reactions is included in Chapter 5. This method permits a ready solution to many problems not amenable to traditional elementary methods.

- Chapter 6 on Failure Theories, Safety Factors, Stress Intensity Factors, and Reliability includes introductory treatments of fracture mechanics and interference theory of statistical reliability prediction.
- Chapter 7 focuses on impact, which is also called shock, sudden, or impulsive loading.
- Chapter 8 contains a simplified, condensed, and introductory version of Fatigue Design and Fatigue Crack Growth. This chapter is particularly important, and represents primarily new material for most students.
- Chapter 9 deals with the various kinds of surface deterioration experienced by machine components. This is of great importance because more machine parts "fail" (cease to be suitable for performing their intended function) because of surface damage than from actual breakage.

Part II

Part II is concerned with the application of the fundamentals to specific machine components. In engineering practice, problems involving the design, analysis, or application of machine members can seldom be solved by applying the fundamentals alone. As critically important as a knowledge of the underlying sciences is, it is seldom sufficient. Almost always some empirical information must be used, and good engineering judgment brought to bear. Actual engineering design problems seldom have only one correct answer. For example, engineering staffs of competing companies arrive at different product designs as solutions to the same problem. And these solutions change as new technology, new materials, new manufacturing methods, and new marketing conditions prevail. For many students, the course based on this text will provide their first experience in dealing with these kinds of professional engineering problems.

Most engineers find that this aspect of engineering adds to the interest and excitement of their profession. There is a close parallel between engineers and medical doctors in this respect: Both must solve real-life problems *now*, making full use of the best available scientific information. Engineers must design engines and build electronic apparatus even though scientists are still seeking a more complete knowledge of combustion and electricity. Similarly, medical doctors cannot tell their patients to await treatment until more research has been completed.

Even though the fundamentals treated in Part I are seldom *sufficient* for solving engineering problems relating to machine components, it is important that they be applied fully and consistently. In particular, a special effort has been made in Part II to deal with fatigue and surface considerations in a manner consistent with the treatment given in Chapters 8 and 9. This sometimes results in the development of procedures that vary in detail from those given in the specialized literature, but this discrepancy is not of major importance. What *is* of major importance is helping the student learn to approach engineering problems by applying the fundamentals and other scientific knowledge as extensively as possible, and then supplementing these with empirical data and judgment as required to get good solutions within available time limitations.

Few engineering schools allot sufficient time to cover all the machine components treated in Part II. In addition, many components are not treated in the book, and even more are not yet in existence. For these reasons, each component is treated not only as an end in itself, but also as a representative example of applying basic fundamentals and necessary empirical information to solve practical engineering problems.

Throughout Part II, the reader will find numerous instances in which ingenuity, insight, and imagination are called for in order to deal effectively with engineering problems associated with an individual machine component. The next step in the study of Mechanical Engineering Design usually involves the conception and design of a complete machine. As an introduction to this next step, the final two chapters of the book (Chapters 21 and 22), present (1) a case study of the design of the first commercially successful automotive automatic transmission, and (2) a case study of the design of remote control vehicles. These chapters can be found on the website for this text, http://www.wiley.com/college/juvinall. Here, as with numerous other designs of complete machines, one cannot help being impressed and inspired by the insights, ingenuity, and imagination (as well as the prolonged diligent effort) displayed by engineers and engineering students. Also illustrated in these case studies is the way that the design of any one component is often influenced by the design of related parts.

Because engineers will inevitably need to continue to deal with SI, British gravitational, and English engineering units, all three systems are used in the text and problems. Recalling the NASA/JPL Mars Climate Orbiter, where the root cause of the loss of the Orbiter spacecraft was the failed translation of English units into metric units in a segment of ground-base, navigation-related mission software, should help to remind the student just how important it is to understand and apply units properly.

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ACKNOWLEDGMENTS

It is impossible to give adequate recognition to the many individuals who have contributed substantially to our own professional thinking reflected in this book. Five of the earliest of this distinguished group are Professor Robert R. Slaymaker and Professor Daniel K. Wright of Case Western Reserve University, Professor Ralph I. Stephens of the University of Iowa, Professor Ali Seireg of the University of Wisconsin–Madison, and Professor Walter L. Starkey of Ohio State University. We have often wondered how strongly our gravitating to the area of mechanical engineering design was influenced by the fact that we first studied the subject under outstanding engineers, superb teachers, and gentlemen whom we greatly admired. (Those of us in engineering education easily forget how much students are influenced by the character and the professional attitudes and practices of their instructors.)

We would like to recognize with sincere thanks the several engineering authorities who reviewed individual chapters of the first edition and offered valuable suggestions. Among these are Joseph Datsko (University of Michigan), Robert J. Finkelston (Standard Pressed Steel Co.), Robert Frayer (Federal Mogul Corp.), Alex Gomza (Grumman Aerospace Corp.), Evan L. Jones (Chrysler Corp.), Vern A. Phelps (University of Michigan), Robert R. Slaymaker (Case Western Reserve University), Gus S. Tayeh (New Departure Hyatt Bearings), Paul R. Trumpler (Trumpler Associates), Lew Wallace (Gleason Machine Div.), James E. West (FAG Bearings Corp.), Charles Williams (Federal Mogul Corp.), Ward O. Winer (Georgia Institute of Technology), and William Wood (Associated Spring Barnes Group). In addition to expressing our deep gratitude to these individuals, we would like to state clearly that the responsibility for each chapter is solely ours. If the reader finds errors, or points of view with which he or she disagrees, there should be no inference that these are due to anyone except the authors. Moreover, we would like to state that, while every effort has been made to ensure the accuracy and conformity with good engineering practice of all the material contained in this book, there is no guarantee, stated or implied, that mechanical components designed on the basis of this text will in all instances be proper and safe. Mechanical engineering design is sufficiently complex that its actual practice should always take advantage of the specialized literature in the area involved, the background of experience with related components, and, most importantly, appropriate tests to establish proper and safe performance in critical cases.

We would also like to express appreciation to Professors James Barber, Panos Papalambros, and Mohammed Zarrugh at the University of Michigan who made valuable suggestions as a result of teaching from preliminary versions of the first edition. Our thanks go as well to their students and to our students, who contributed important improvements. We would like to express particular thanks to Professor Emeritus Herbert H. Alvord of the University of Michigan who generously permitted us the use of his extensive collection of problems, which he developed for his own classes. We also thank Professors J. Darrell Gibson (Rose Hulman Institute of Technology), Donald A. Smith (University of Wyoming), and Petru-Aurelian Simionescu (Texas A&M—CC), and Professors Michael D. Bryant, Eric P. Fahrenthold, Kristin L. Wood, and Rui Huang at the University of Texas who offered valuable suggestions.

Appreciation is expressed to those who have reviewed this and previous editions: Kuang-Hua Chang, University of Oklahoma, Tim Dalrymple, University of Florida, Hamid Davoodi, North Carolina State University, Thomas Grimm, Michigan Technological University, Thomas Haas,

Virginia Commonwealth University, Liwei Lin, University of California at Berkeley, Frank Owen, California Polytechnic State University, San Luis Obispo, Wendy Reffeor, Grand Valley State University, John Schueller, University of Florida, William Semke, University of North Dakota, Albert Shih, University of Michigan, Donald Smith, University of Wyoming, John Thacker, University of Virginia, and Raymond Yee, San Jose State University, Steve Daniewicz, Mississippi State University, Richard Englund, Penn State University, Ernst Kiesling, Texas Tech University, Edward R. Evans Jr., Penn State Erie, The Behrend College, Thomson R. Grimm, Michigan Technological University, Dennis Hong, Virginia Polytechnic Institute and State University, E. William Jones, Mississippi State University, Gloria Starns, Iowa State University, and Andreas Polycarpou, University of Illinois at Urbana–Champaign.

We would like to personally thank Professor Roger Bradshaw, University of Louisville, for contributing Appendix F as well as related sets of homework problems and solutions for Chapter 3 and Chapter 8, and Professor Krishnan Suresh, University of Wisconsin–Madison, for contributing Appendices G, H, I, and J.

Special thanks also to Professor Michael Cullian, the University of Texas at Austin, for authoring Chapter 20 and Chapter 22.

We deeply appreciate the understanding and encouragement of our wives, Arleene and Linda, during the preparation of this book, which preempted time belonging, by all reasonable standards, to important family and social activities.

CONTENTS

Preface v
Acknowledgments ix
Symbols xix

PART 1 FUNDAMENTALS 1

1 Mechanical Engineering Design in Broad Perspective 1
1.1 An Overview of the Subject 1
1.2 Safety Considerations 2
1.3 Ecological Considerations 7
1.4 Societal Considerations 8
1.5 Overall Design Considerations 10
1.6 Systems of Units 12
1.7 Methodology for Solving Machine Component Problems 14
1.8 Work and Energy 16
1.9 Power 18
1.10 Conservation of Energy 19

2 Load Analysis 39
2.1 Introduction 39
2.2 Equilibrium Equations and Free-Body Diagrams 39
2.3 Beam Loading 49
2.4 Locating Critical Sections—Force Flow Concept 52
2.5 Load Division Between Redundant Supports 54
2.6 Force Flow Concept Applied to Redundant Ductile Structures 56

3 Materials 84
3.1 Introduction 84
3.2 The Static Tensile Test—“Engineering” Stress–Strain Relationships 85
3.3 Implications of the “Engineering” Stress–Strain Curve 86
3.4 The Static Tensile Test—“True” Stress–Strain Relationships 89
3.5 Energy-Absorbing Capacity 90
3.6 Estimating Strength Properties from Penetration Hardness Tests 91
3.7 Use of “Handbook” Data for Material Strength Properties 94
3.8 Machinability 95
3.9 Cast Iron 95
3.10 Steel 96
3.11 Nonferrous Alloys 98
3.12 Plastics and Composites 100
3.13 Materials Selection Charts 105
3.14 Engineering Material Selection Process 107

4 Static Body Stresses 121
4.1 Introduction 121
4.2 Axial Loading 121
4.3 Direct Shear Loading 123
4.4 Torsional Loading 124
4.5 Pure Bending Loading, Straight Beams 126
4.6 Pure Bending Loading, Curved Beams 127
4.7 Transverse Shear Loading in Beams 132
4.8 Induced Stresses, Mohr Circle Representation 138
4.9 Combined Stresses—Mohr Circle Representation 140
4.10 Stress Equations Related to Mohr's Circle 143
4.11 Three-Dimensional Stresses 144
4.12 Stress Concentration Factors, K_t 148
4.13 Importance of Stress Concentration 151
4.14 Residual Stresses Caused by Yielding—Axial Loading 153
4.15 Residual Stresses Caused by Yielding—Bending and Torsional Loading 157
4.16 Thermal Stresses 159
4.17 Importance of Residual Stresses 161

5 Elastic Strain, Deflection, and Stability 178
5.1 Introduction 178
5.2 Strain Definition, Measurement, and Mohr Circle Representation 179
5.3 Analysis of Strain—Equiangular Rosettes 181
5.4 Analysis of Strain—Rectangular Rosettes 183
5.5 Elastic Stress–Strain Relationships and Three-Dimensional Mohr Circles 185
5.6 Deflection and Spring Rate—Simple Cases 187
5.7 Beam Deflection 189
5.8 Determining Elastic Deflections by Castigliano's Method 192
5.9 Redundant Reactions by Castigliano's Method 203
5.10 Euler Column Buckling—Elastic Instability 207
5.11 Equivalent Column Length for Various End Conditions 209
5.12 Column Design Equations—J. B. Johnson Parabola 210
5.13 Eccentric Column Loading—the Secant Formula 214
5.14 Equivalent Column Stresses 215
5.15 Other Types of Buckling 216
5.16 Finite Element Analysis 217

6 Failure Theories, Safety Factors, and Reliability 227
6.1 Introduction 227
6.2 Types of Failure 229
6.3 Fracture Mechanics—Basic Concepts 230
6.4 Fracture Mechanics—Applications 231
6.5 The "Theory" of Static Failure Theories 240
6.6 Maximum-Normal-Stress Theory 242
6.7 Maximum-Shear-Stress Theory 242
6.8 Maximum-Distortion-Energy Theory (Maximum-Octahedral-Shear-Stress Theory) 243
6.9 Mohr Theory and Modified Mohr Theory 245
6.10 Selection and Use of Failure Theories 246
6.11 Safety Factors—Concept and Definition 248
6.12 Safety Factors—Selection of a Numerical Value 250
6.13 Reliability 252

6.14 Normal Distributions 253
6.15 Interference Theory of Reliability Prediction 254

7 Impact 264
7.1 Introduction 264
7.2 Stress and Deflection Caused by Linear and Bending Impact 266
7.3 Stress and Deflection Caused by Torsional Impact 273
7.4 Effect of Stress Raisers on Impact Strength 276

8 Fatigue 287
8.1 Introduction 287
8.2 Basic Concepts 287
8.3 Standard Fatigue Strengths (S_n') for Rotating Bending 289
8.4 Fatigue Strengths for Reversed Bending and Reversed Axial Loading 294
8.5 Fatigue Strength for Reversed Torsional Loading 295
8.6 Fatigue Strength for Reversed Biaxial Loading 296
8.7 Influence of Surface and Size on Fatigue Strength 297
8.8 Summary of Estimated Fatigue Strengths for Completely Reversed Loading 299
8.9 Effect of Mean Stress on Fatigue Strength 299
8.10 Effect of Stress Concentration with Completely Reversed Fatigue Loading 308
8.11 Effect of Stress Concentration with Mean Plus Alternating Loads 310
8.12 Fatigue Life Prediction with Randomly Varying Loads 317
8.13 Effect of Surface Treatments on the Fatigue Strength of a Part 320
8.14 Mechanical Surface Treatments—Shot Peening and Others 322
8.15 Thermal and Chemical Surface-Hardening Treatments (Induction Hardening, Carburizing, and Others) 323
8.16 Fatigue Crack Growth 323
8.17 General Approach for Fatigue Design 327

9 Surface Damage 341
9.1 Introduction 341
9.2 Corrosion: Fundamentals 341
9.3 Corrosion: Electrode and Electrolyte Heterogeneity 344
9.4 Design for Corrosion Control 345
9.5 Corrosion Plus Static Stress 348
9.6 Corrosion Plus Cyclic Stress 350
9.7 Cavitation Damage 350
9.8 Types of Wear 351
9.9 Adhesive Wear 351
9.10 Abrasive Wear 353
9.11 Fretting 354
9.12 Analytical Approach to Wear 355
9.13 Curved-Surface Contact Stresses 358
9.14 Surface Fatigue Failures 364
9.15 Closure 365

PART 2 APPLICATIONS **373**

10 Threaded Fasteners and Power Screws 373
10.1 Introduction 373
10.2 Thread Forms, Terminology, and Standards 373

10.3 Power Screws 377
10.4 Static Screw Stresses 386
10.5 Threaded Fastener Types 390
10.6 Fastener Materials and Methods of Manufacture 392
10.7 Bolt Tightening and Initial Tension 392
10.8 Thread Loosening and Thread Locking 396
10.9 Bolt Tension with External Joint-Separating Force 399
10.10 Bolt (or Screw) Selection for Static Loading 403
10.11 Bolt (or Screw) Selection for Fatigue Loading: Fundamentals 409
10.12 Bolt Selection for Fatigue Loading: Using Special Test Data 415
10.13 Increasing Bolted-Joint Fatigue Strength 418

11 Rivets, Welding, and Bonding 428
11.1 Introduction 428
11.2 Rivets 428
11.3 Welding Processes 429
11.4 Welded Joints Subjected to Static Axial and Direct Shear Loading 433
11.5 Welded Joints Subjected to Static Torsional and Bending Loading 436
11.6 Fatigue Considerations in Welded Joints 441
11.7 Brazing and Soldering 443
11.8 Adhesives 443

12 Springs 450
12.1 Introduction 450
12.2 Torsion Bar Springs 450
12.3 Coil Spring Stress and Deflection Equations 451
12.4 Stress and Strength Analysis for Helical Compression Springs—Static Loading 456
12.5 End Designs of Helical Compression Springs 458
12.6 Buckling Analysis of Helical Compression Springs 459
12.7 Design Procedure for Helical Compression Springs—Static Loading 460
12.8 Design of Helical Compression Springs for Fatigue Loading 463
12.9 Helical Extension Springs 471
12.10 Beam Springs (Including Leaf Springs) 472
12.11 Torsion Springs 477
12.12 Miscellaneous Springs 479

13 Lubrication and Sliding Bearings 496
13.1 Types of Lubricants 496
13.2 Types of Sliding Bearings 496
13.3 Types of Lubrication 497
13.4 Basic Concepts of Hydrodynamic Lubrication 498
13.5 Viscosity 500
13.6 Temperature and Pressure Effects on Viscosity 504
13.7 Petroff's Equation for Bearing Friction 505
13.8 Hydrodynamic Lubrication Theory 507
13.9 Design Charts for Hydrodynamic Bearings 510
13.10 Lubricant Supply 516
13.11 Heat Dissipation and Equilibrium Oil Film Temperature 518
13.12 Bearing Materials 519
13.13 Hydrodynamic Bearing Design 521
13.14 Boundary and Mixed-Film Lubrication 526
13.15 Thrust Bearings 528
13.16 Elastohydrodynamic Lubrication 529

14 Rolling-Element Bearings **535**
- 14.1 Comparison of Alternative Means for Supporting Rotating Shafts 535
- 14.2 History of Rolling-Element Bearings 537
- 14.3 Rolling-Element Bearing Types 537
- 14.4 Design of Rolling-Element Bearings 543
- 14.5 Fitting of Rolling-Element Bearings 546
- 14.6 “Catalogue Information” for Rolling-Element Bearings 547
- 14.7 Bearing Selection 551
- 14.8 Mounting Bearings to Provide Properly for Thrust Load 558

15 Spur Gears **564**
- 15.1 Introduction and History 564
- 15.2 Geometry and Nomenclature 565
- 15.3 Interference and Contact Ratio 573
- 15.4 Gear Force Analysis 576
- 15.5 Gear-Tooth Strength 579
- 15.6 Basic Analysis of Gear-Tooth-Bending Stress (Lewis Equation) 580
- 15.7 Refined Analysis of Gear-Tooth-Bending Strength: Basic Concepts 582
- 15.8 Refined Analysis of Gear-Tooth-Bending Strength: Recommended Procedure 584
- 15.9 Gear-Tooth Surface Durability—Basic Concepts 590
- 15.10 Gear-Tooth Surface Fatigue Analysis—Recommended Procedure 593
- 15.11 Spur Gear Design Procedures 597
- 15.12 Gear Materials 601
- 15.13 Gear Trains 602

16 Helical, Bevel, and Worm Gears **616**
- 16.1 Introduction 616
- 16.2 Helical-Gear Geometry and Nomenclature 617
- 16.3 Helical-Gear Force Analysis 621
- 16.4 Helical Gear-Tooth-Bending and Surface Fatigue Strengths 624
- 16.5 Crossed Helical Gears 625
- 16.6 Bevel Gear Geometry and Nomenclature 626
- 16.7 Bevel Gear Force Analysis 628
- 16.8 Bevel Gear-Tooth-Bending and Surface Fatigue Strengths 629
- 16.9 Bevel Gear Trains; Differential Gears 632
- 16.10 Worm Gear Geometry and Nomenclature 633
- 16.11 Worm Gear Force and Efficiency Analysis 635
- 16.12 Worm-Gear-Bending and Surface Fatigue Strengths 640
- 16.13 Worm Gear Thermal Capacity 642

17 Shafts and Associated Parts (online at www.wiley.com/college/juvinall) **653**
- 17.1 Introduction 653
- 17.2 Provision for Shaft Bearings 653
- 17.3 Mounting Parts onto Rotating Shafts 654
- 17.4 Rotating-Shaft Dynamics 657
- 17.5 Overall Shaft Design 661
- 17.6 Keys, Pins, and Splines 665
- 17.7 Couplings and Universal Joints 668

18 Clutches and Brakes (online at www.wiley.com/college/juvinall) **681**
- 18.1 Introduction 681

18.2 Disk Clutches 681
18.3 Disk Brakes 686
18.4 Energy Absorption and Cooling 687
18.5 Cone Clutches and Brakes 688
18.6 Short-Shoe Drum Brakes 690
18.7 External Long-Shoe Drum Brakes 693
18.8 Internal Long-Shoe Drum Brakes 699
18.9 Band Brakes 701
18.10 Materials 704

19 Belts, Chains, and Other Components (online at www.wiley.com/college/juvinall) 714
19.1 Introduction 714
19.2 Flat Belts 714
19.3 V-Belts 716
19.4 Toothed Belts 720
19.5 Roller Chains 720
19.6 Inverted-Tooth Chains 722
19.7 History of Hydrodynamic Drives 724
19.8 Fluid Couplings 724
19.9 Hydrodynamic Torque Converters 727

20 Micro/Nanoscale Machine Elements (online at www.wiley.com/college/juvinall) 737
20.1 Introduction 737
20.2 Micro and Nanoscale Actuators 738
20.3 Micro and Nanoscale Bearings 744
20.4 Micro and Nanoscale Sensors 748
20.5 Conclusions 760

21 Machine Component Interrelationships—A Case Study (online at www.wiley.com/college/juvinall) 763
21.1 Introduction 763
21.2 Description of Original Hydra-Matic Transmission 763
21.3 Free-Body Diagram Determination of Gear Ratios and Component Loads 766
21.4 Gear Design Considerations 769
21.5 Brake and Clutch Design Considerations 771
21.6 Miscellaneous Design Considerations 772

22 Design and Fabrication of the Mechanical Systems for a Remote Control Car—A Design Project Case Study (online at www.wiley.com/college/juvinall) 775
22.1 Case Study Summary 775
22.2 Project Components 776
22.3 Project Organization 778
22.4 System Design Considerations 779
22.5 RC Car Race 783

A Units 785
A-1a Conversion Factors for British Gravitational, English, and SI Units 785
A-1b Conversion Factor Equalities Listed by Physical Quantity 786
A-2a Standard SI Prefixes 788
A-2b SI Units and Symbols 789

A-3 Suggested SI Prefixes for Stress Calculations 790
A-4 Suggested SI Prefixes for Linear-Deflection Calculations 790
A-5 Suggested SI Prefixes for Angular-Deflection Calculations 790

B Properties of Sections and Solids 791
B-1a Properties of Sections 791
B-1b Dimensions and Properties of Steel Pipe and Tubing Sections 792
B-2 Mass and Mass Moments of Inertia of Homogeneous Solids 794

C Material Properties and Uses 795
C-1 Physical Properties of Common Metals 795
C-2 Tensile Properties of Some Metals 796
C-3a Typical Mechanical Properties and Uses of Gray Cast Iron 797
C-3b Mechanical Properties and Typical Uses of Malleable Cast Iron 798
C-3c Average Mechanical Properties and Typical Uses of Ductile (Nodular) Iron 799
C-4a Mechanical Properties of Selected Carbon and Alloy Steels 800
C-4b Typical Uses of Plain Carbon Steels 802
C-5a Properties of Some Water-Quenched and Tempered Steels 803
C-5b Properties of Some Oil-Quenched and Tempered Carbon Steels 804
C-5c Properties of Some Oil-Quenched and Tempered Alloy Steels 805
C-6 Effect of Mass on Strength Properties of Steel 806
C-7 Mechanical Properties of Some Carburizing Steels 807
C-8 Mechanical Properties of Some Wrought Stainless Steels (Approximate Median Expectations) 808
C-9 Mechanical Properties of Some Iron-Based Superalloys 809
C-10 Mechanical Properties, Characteristics, and Typical Uses of Some Wrought Aluminum Alloys 810
C-11 Tensile Properties, Characteristics, and Typical Uses of Some Cast-Aluminum Alloys 811
C-12 Temper Designations for Aluminum and Magnesium Alloys 812
C-13 Mechanical Properties of Some Copper Alloys 813
C-14 Mechanical Properties of Some Magnesium Alloys 814
C-15 Mechanical Properties of Some Nickel Alloys 815
C-16 Mechanical Properties of Some Wrought-Titanium Alloys 816
C-17 Mechanical Properties of Some Zinc Casting Alloys 817
C-18a Representative Mechanical Properties of Some Common Plastics 818
C-18b Properties of Some Common Glass-Reinforced and Unreinforced Thermoplastic Resins 819
C-18c Typical Applications of Common Plastics 820
C-19 Material Names and Applications 821
C-20 Designer’s Subset of Engineering Materials 824
C-21 Processing Methods Used Most Frequently with Different Materials 825
C-22 Joinability of Materials 826
C-23 Materials for Machine Components 827
C-24 Relations Between Failure Modes and Material Properties 829

D Shear, Moment, and Deflection Equations for Beams (online at www.wiley.com/college/juvinall) 830
D-1 Cantilever Beams 830
D-2 Simply Supported Beams 831
D-3 Beams with Fixed Ends 833

E Fits and Tolerances (online at www.wiley.com/college/juvinall) 834
E-1 Fits and Tolerances for Holes and Shafts 834
E-2 Standard Tolerances for Cylindrical Parts 835
E-3 Tolerance Grades Produced from Machining Processes 836

F MIL-HDBK-5J, Department of Defense Handbook: Metallic Materials and Elements for Aerospace Vehicle Structures (online at www.wiley.com/college/juvinall) 837
F-1 Introduction 837
F-2 Overview of Data in *MIL-HDBK-5J* 837
F-3 Advanced Formulas and Concepts Used in *MIL-HDBK-5J* 838
F-4 Mechanical and Physical Properties of 2024 Aluminum Alloy 842
F-5 Fracture Toughness and Other Miscellaneous Properties 848
F-6 Conclusion 850

G Force Equilibrium: A Vectorial Approach (online at www.wiley.com/college/juvinall) 852
G-1 Vectors: A Review 852
G-2 Force and Moments Equilibrium 853

H Normal Distributions (online at www.wiley.com/college/juvinall) 855
H-1 Standard Normal Distribution Table 855
H-2 Converting to Standard Normal Distribution 857
H-3 Linear Combination of Normal Distributions 857

I S-N Formula (online at www.wiley.com/college/juvinall) 858
I-1 S-N Formula 858
I-2 Illustrative Example 859

J Gear Terminology and Contact-Ratio Analysis (online at www.wiley.com/college/juvinall) 860
J-1 Nominal Spur-Gear Quantities 860
J-2 Actual Quantities 862
J-3 Illustrative Example 863

Index 865

SYMBOLS

A	area, cross-sectional area, arm of planetary gear
A	point A
A_0	original unloaded cross-sectional area
a	influence coefficient
a, a	acceleration
a	crack depth, radius of contact area of two spheres
A_c	effective clamped area
a_{cr}	critical crack depth
A_f	final area
A_r	area reduction
A_t	tensile stress area, tensile stress area of the thread
$\overline{B}$	actual backlash
b	section width, half width of contact area measured perpendicular to axes of two parallel contacting cylinders, gear face width, band width
C	spring index, overall heat transfer coefficient, rated load capacity, heat transfer coefficient, constant (material property)
C	specific heat
c	distance from the neutral axis to the extreme fiber, half of crack length, radial clearance, center distance, distance between shafts, crack length
$\bar{c}$	distance from the centroidal axis to the extreme inner fiber, actual distance between gear and pinion centers
c_{cr}	critical crack length
CR	contact ratio
$\overline{CR}$	actual contact ratio
CG	center of gravity
C_G	gradient factor or gradient constant
c_i	distance from the neutral axis to the extreme inner fiber
C_L	load factor
C_{Li}	life factor
c_o	distance from the neutral axis to the extreme outer fiber
CP	center of aerodynamic pressure
C_p	elastic coefficient
C_R	reliability factor
c_ρ	volumetric specific heat
C_{req}	required value of C
C_s	surface factor
D	diameter, mean coil diameter, velocity factor
d	diameter, major diameter, nominal diameter, wire diameter
d_{av}	average diameter
d_b	diameter of base circle
d_c	collar (or bearing) diameter
dc/dN	crack propagation rate
$(dc/dN)_o$	crack propagation rate at $(\Delta K)_o$
d_g	pitch diameter of gear
d_i	minor diameter of the internal thread
d_m	mean diameter
d_p	pitch diameter, pitch diameter of pinion
d_r	root (or minor) diameter
E	modulus of elasticity, elastic proportionality constant, tensile elastic modulus
E	modulus of elasticity (tension)
E_p	plastic strain
e	distance between the neutral axis and the centroidal axis, efficiency, eccentricity, train value, edge distance for joint, percent elongation at break
e/D	edge margin
E_b	Young's modulus for the bolt
E_c	Young's modulus for clamped member, compression modulus of elasticity
E_s	secant modulus
E_t	tangent modulus
F	force, compressive force between the surfaces
f	relative hardenability effectiveness, coefficient of friction
$\mathbf{F}$, F	force
F_a	axial force
F_b	bolt axial load
F_{bru}	bearing ultimate strength
F_{bry}	bearing yield strength
F_c	clamping force
f_c	collar (or bearing) coefficient of friction
F_d	drag force, dynamic load

F_{cy}	compression yield strength
F_e	equivalent radial load, equivalent static force, external force
$\mathbf{F}_{\mathrm{ext}}$	external force vector applied on a member
F_{ga}	gear axial force
F_{gr}	gear radial force
F_{gt}	gear tangential force
F_i	initial tensile force, initial clamping force
$\mathbf{F}_{\mathrm{int}}$	internal force vector at a cross-section
F_n	normal force
f_n	natural frequency
F_r	radial load, radial force
F_s	strength capacity
F_{solid}	force when solid
F_{su}	shear ultimate strength
F_t	thrust force, tendon force, tangential force, thrust load
F_{tu}	tensile ultimate strength
F_{ty}	tensile yield strength
F_w	wear capacity
F_{wa}	worm axial force
F_{wr}	worm radial force
F_{wt}	worm tangential force
G	torsional or shear modulus of elasticity
g	gravitational acceleration or acceleration of gravity, grip length
g_c	constant of proportionality, $32.2\ \mathrm{lbm\text{-}ft/lb\text{-}s^2}$
H	surface hardness, time rate of heat dissipation
h	section depth, height of fall, leg length, weld size, film thickness, height
h_0	minimum film thickness
H_B	Brinell hardness number
I	polar moment of inertia, moment of inertia, geometry factor, stress invariant
i	integer
I_x	moment of inertia about x axis
J	polar moment of inertia, spur gear geometry factor
K	curvature factor, spring rate for angular deflection, stress intensity factor, wear coefficient
k	spring rate, thermal conductivity, spring rate for linear deflection, number of standard deviations, shaft spring rate
K	thermal conductivity
K'	section property
K_{I}	stress intensity factor for tensile loading (mode I)
$K_{\mathrm{I}c}$	critical stress intensity factor for tensile loading (mode I)
K_a	application factor
K_B	constant of proportionality
k_b	spring constant for the bolt
K_c	fracture toughness or critical stress intensity factor
k_c	spring constant for clamped members
KE	kinetic energy
K_f	fatigue stress concentration factor
K_i	curvature factor for inner fiber, effective stress concentration factor for impact loading, constant used for calculating initial bolt-tightening force
K_m	mounting factor
K_{max}	stress intensity factor at σ_{max}
K_{min}	stress intensity factor at σ_{min}
k_{ms}	mean stress factor
K_o	curvature factor for outer fiber, overload factor, critical stress intensity factor for infinite plate with central crack in uniaxial tension
K_r	life adjustment reliability factor
k_r	reliability factor
K_s	stress concentration factor for static loading
K_t	theoretical or geometric stress concentration factor
k_t	temperature factor
K_v	velocity or dynamic factor
K_w	Wahl factor, material and geometry factor
L	length, contact length measured parallel to the axis of contacting cylinder, lead, length of weld, life corresponding to radial load F_r, or life required by the application, pitch cone length
L_0	original unloaded length
L_e	equivalent length
L_f	final length, free length
L_R	life corresponding to rated capacity
L_s	solid height
L, ST, LT	longitudinal direction, short transverse direction, long transverse direction
M	moment, internal bending moment, bending moment
M_0	redundant moment
m	mass, strain-hardening exponent, module (used only with SI or metric units)
m'	mass per unit length of belt
$\mathbf{M}_{\mathrm{ext}}$	external moment vector applied on a member
M_f	moment of friction forces

$\mathbf{M}_{\text{int}}$	generalized internal moment vector at a cross-section
M_n	moment of normal forces
N	fatigue life, total normal load, number of active coil turns, number of teeth, number of friction interfaces, number of cycles
n	rotating speed, number of cycles, normal force, number of equally spaced planet gears, index (subscript), Ramberg-Osgood parameter
N'	virtual number of teeth
N.A.	neutral axis
n_c	critical speed
N_e	number of teeth
N_t	total number of turns, number of teeth in the sprocket
P	load, cumulative probability of failure, bearing unit load, average film pressure, radial load per unit of projected bearing area, pitch point, diametral pitch (used only with English units), diameter or number of teeth of planet, band force, load (force), uniform load
$\overline{P}$	actual pitch
p	frequency of occurrence, probability of failure, surface interface pressure, pitch, film pressure, circular pitch, uniform level of interface pressure, pressure
$\overline{p}$	actual circular pitch
p_0	maximum contact pressure
p_a	axial pitch
p_b	base pitch
P_c	tension created by centrifugal force
P_{cr}	critical load
PE	potential energy
p_{max}	allowable pressure, maximum normal pressure
p_n	circular pitch measured in a plane normal to the teeth
Q	heat energy transferred to the system, load, total tangential force, flow rate, mass flow rate
q	number of revolutions, notch sensitivity factor, tangential force
Q_f	volume of lubricant per-unit time flowing across
Q_s	side leakage rate
R	radius, transmission speed ratio, area ratio, radius of curvature, diameter or number of teeth of ring or annulus gear, ratio of gear and pinion diameter, load ratio, fatigue cycle stress ratio
r	radius, reliability
$\overline{r}$	radial distance to the centroidal axis
$r_{a(\text{max})}$	maximum noninterfering addendum circle radius of pinion or gear
$r_{\text{ag}}^{\text{max}}$	maximum allowable addendum radius on the gear to avoid interference
$r_{\text{ap}}^{\text{max}}$	maximum allowable addendum radius on the pinion to avoid interference
$r_{\text{ap}}, r_{\text{ag}}$	addendum radii of the mating pinion and gear
r_b	base circle radius, back cone radius
$r_{\text{bp}}, r_{\text{bg}}$	base circle radii of the mating pinion and gear
r_c	chordal radius
r_f	friction radius
$\overline{r}_g$	actual pitch radius of gear
r_i	inner radius
$\overline{r}_p$	actual pitch radius of pinion
R_m	modulus of resilience
r_n	radial distance to the neutral axis
r_o	outer radius
S	linear displacement, total rubbing distance, Saybolt viscometer measurement in seconds, bearing characteristic number or Sommerfeld variable, diameter or number of teeth of sun gear, slip
S_{cr}	critical unit load
S_e	elastic limit
S_{eq}	equivalent stress—see Table F.4
SF	safety factor
S_{fe}	surface fatigue strength
S_H	surface endurance strength
S–N	fatigue stress versus cycles
S_{max}	maximum fatigue cycle stress—see Table F.4
S_n	endurance limit
S'_n	standard fatigue strength for rotating bending
S_p	proof load (strength)
S_{sy}	shear yield strength
S_u	ultimate strength, ultimate tensile strength
S_{uc}	ultimate strength in compression
S_{us}	ultimate shear strength, ultimate torsional shear strength
S_{ut}	ultimate strength in tension
S_y	yield strength
S_{yc}	yield strength in compression
S_{yt}	yield strength in tension
T	torque, brake torque, band brake torque
t	time, thickness, nut thickness, throat length
T_a	alternating torque
t_a	air temperature, ambient air temperature
T_e	equivalent static torque

T_f	friction torque
T_m	modulus of toughness, mean torque
t_o	average oil film temperature, oil temperature
t_s	average temperature of heat-dissipating surfaces
U	stored elastic energy, impact kinetic energy, laminar flow velocity
U'	complementary energy
V	internal transverse shear force, shear force, volume
$\mathbf{V}, V$	linear velocity, gear pitch line velocity
v	velocity at impact, sliding velocity
V_{60}	cutting speed in feet per minute for 60-min tool life under standard cutting conditions
V_{av}	average velocity
V_g	gear tangential velocity, pitch line velocity of the gear
V_{gt}	velocity of gear at contact point in tangent direction
V_{pt}	velocity of pinion at contact point in tangent direction
V_{gn}	velocity of gear at contact point in normal direction
V_{pn}	velocity of pinion at contact point in normal direction
V_s	sliding velocity
V_w	worm tangential velocity
W	work done, weight, volume of material worn away, total axial load
$\dot{W}$	power
w	load, load intensity, gravitational force, width
Y	Lewis form factor based on diametral pitch or module, configuration factor
y	distance from the neutral axis, Lewis form factor
Y_{cr}	configuration factor at critical crack size
Z	section modulus

Greek Letters

α	angular acceleration, coefficient of thermal expansion, angles measured clockwise positive from the 0° gage to the principal strain axes numbers 1 and 2, factor by which the compressive strength is reduced through buckling tendencies, thread angle, contact angle, cone angle, normalized crack size
α_{cr}	normalized critical crack size
α_1	normalized crack size at c_1
α_2	normalized crack size at c_2
α_n	thread angle measured in the normal plane
Δ	deflection, material parameter important in computing contact stress
δ, δ	deflection
δ	linear deflection, wear depth
ΔA	change in area
ΔE	change in total energy of the system
ΔKE	change in kinetic energy of the system
ΔK	stress intensity range
ΔK_o	stress intensity range at the point o
ΔL	change in length
ΔPE	change in gravitational potential energy of the system
ΔN_{12}	number of cycles during crack growth from c_1 to c_2
δ_s	solid deflection
δ_{st}	deflection caused by static loading (static deflection)
ΔT	temperature change
ΔU	change in internal energy of the system
λ	lead angle, helix angle, ratio of actual to ideal distance between gear and pinion centers
ϕ	angle between the principal axes and the x and y axes, angle giving position of minimum film thickness, pressure angle, angle of wrap
ϕ_n	pressure angle measured in a plane normal to the teeth
$\overline{\phi}$	actual pressure angle
γ	pitch cone angle
$\gamma_{xy}, \gamma_{xz}, \gamma_{yz}$	shear strains
μ	mean, viscosity
μ	Poisson's ratio—see Appendix F
ν	Poisson's ratio
ϵ	normal strain
$\epsilon_1, \epsilon_2, \epsilon_3$	principal strains
ϵ_f	strain at fracture
ϵ_p	plastic strain
ϵ_T	"true" normal strain
ϵ_{Tf}	true normal strain at fracture
$\epsilon_x, \epsilon_y, \epsilon_z$	normal strains
θ	angular displacement, angular deflection, slope
$\theta_{P_{\text{max}}}$	position of maximum film pressure
ρ	mass density, radial distance
σ	normal stress, standard deviation, uniform uniaxial tensile stress

$\sigma_1, \sigma_2, \sigma_3$	principal stresses in 1, 2, and 3 directions
σ_0	square root of strain-strengthening proportionality constant
σ_a	alternating stress (or stress amplitude)
σ_e	equivalent stress
σ_{ea}	equivalent alternating bending stress
σ_{em}	equivalent mean bending stress
σ_{eq}	equivalent stress
σ_g	gross-section tensile stress
σ_H	surface fatigue stress
σ_i	maximum normal stress in the inner surface
σ_m	mean stress
$\sigma_{\max}$	maximum normal stress
$\sigma_{\min}$	minimum normal stress
σ_{nom}	nominal normal stress
σ_o	maximum normal stress in the outer surface
σ_T	“true” normal stress
σ_x	normal stress acting along *x* axis
σ_y	normal stress acting along *y* axis
τ	shear stress, natural period of vibration
τ_a	alternating shear stress
τ_{av}	average shear stress
τ_{initial}	initial shear stress
τ_m	mean shear stress
$\tau_{\max}$	maximum shear stress
τ_{nom}	nominal shear stress
τ_{solid}	shear stress when solid
τ_{xy}	shear stress acting on an *x* face in the *y* direction
υ	kinematic viscosity
ω	angular velocity, impact angular velocity
ω_g	angular velocity of gear
ω_n	natural frequency
ω_p	angular velocity of pinion
ψ	helix angle, spiral angle

Mechanical Engineering Design in Broad Perspective

1

1.1 An Overview of the Subject

The essence of engineering is *the* utilization of the resources and laws of nature to benefit humanity. Engineering is an applied science in the sense that it is concerned with understanding scientific principles and applying them to achieve a designated goal. Mechanical engineering design is a major segment of engineering; it deals with the conception, design, development, refinement, and application of machines and mechanical apparatus of all kinds.

For many students, mechanical engineering design is one of their first *professional engineering courses*—as distinguished from background courses in science and mathematics. Professional engineering is concerned with obtaining *solutions* to practical problems. These solutions must reflect an understanding of the underlying sciences, but usually this understanding is not enough; empirical knowledge and "engineering judgment" are also involved. For example, scientists do not completely understand electricity, but this does not prevent electrical engineers from developing highly useful electrical devices. Similarly, scientists do not completely understand combustion processes or metal fatigue, but mechanical engineers use the understanding available to develop highly useful combustion engines. As more scientific understanding becomes available, engineers are able to devise better solutions to practical problems. Moreover, the engineering process of solving problems often highlights areas particularly appropriate for more intensive scientific research. There is a strong analogy between the engineer and the physician. Neither is a scientist whose primary concern is with uncovering basic knowledge, but both *use* scientific knowledge—supplemented by empirical information and professional judgment—in solving immediate and pressing problems.

Because of the professional nature of the subject, most problems in mechanical engineering design do not have a *single* right answer. Consider, for example, the problem of designing a household refrigerator. There is a nearly endless number of workable designs, none of which could be called an "incorrect" answer. But of the "correct" answers, some are obviously *better* than others because they reflect a more sophisticated knowledge of the underlying technology, a more ingenious concept of basic design, a more effective and economical utilization of existing production technology, a more pleasing aesthetic appearance, and so on. It is precisely at this point, of course, that one finds the challenge and excitement of modern engineering. Engineers today are concerned with the design and development of products for a society different from any that existed previously, and they have more knowledge available to them than did engineers in the past. Hence, they are able to produce distinctly *better* solutions to meet today's needs. How much better depends on their ingenuity, imagination, depth of understanding of the need involved, and of the technology that bears on the solutions, and so on.

This book is primarily concerned with the design of specific *components* of machines or mechanical systems. Competence in this area is basic to the consideration and synthesis of complete machines and systems in subsequent courses and in professional practice. It will be seen that even in the design of a single bolt or spring, the engineer must use the best available scientific understanding together with empirical information, good judgment, and often a degree of ingenuity, in order to produce the best product for today's society.

The technical considerations of mechanical component design are largely centered around two main areas of concern: (1) stress–strain–strength relationships involving the *bulk* of a solid member and (2) surface phenomena including friction, lubrication, wear, and environmental deterioration. Part One of the book is concerned with the fundamentals involved, and Part Two with applications to specific machine components. The components chosen are widely used and will be somewhat familiar to the student. It is not feasible or desirable for the student to study the detailed design considerations associated with *all* machine elements. Hence, the emphasis in treating those selected here is on the *methods* and *procedures* used so that the student will gain competence in applying these methods and procedures to mechanical components in general.

When considering a complete machine, the engineer invariably finds that the requirements and constraints of the various components are interrelated. The design of an automotive engine valve spring, for example, depends on the space available for the spring. This, in turn, represents a compromise with the space requirements for the valve ports, coolant passages, spark plug clearance, and so on. This situation adds a whole new dimension to the imagination and ingenuity required of engineers as they seek to determine an optimum design for a combination of related components. This aspect of mechanical engineering design is illustrated by a "case study" at http://www.wiley.com/college/juvinall.

In addition to the traditional technological and economic considerations fundamental to the design and development of mechanical components and systems, the modern engineer has become increasingly concerned with the broader considerations of safety, ecology, and overall "quality of life." These topics are discussed briefly in the following sections.

1.2 Safety Considerations

It is natural that, in the past, engineers gave first consideration to the functional and economic aspects of new devices. After all, unless devices can be made to function usefully, they are of no further engineering interest. Furthermore, if a new device cannot be produced for a cost that is affordable by contemporary society, it is a waste of engineering time to pursue it further. But the engineers who have gone before us have succeeded in developing a multitude of products that do function usefully, and that can be produced economically. Partly because of this, increasing engineering effort is now being devoted to broader considerations relating to the influence of engineered products on people and on the environment.

Personnel safety is a consideration that engineers have always kept in mind but now demands increasing emphasis. In comparison with such relatively straightforward computations as stress and deflection, determination of safety is likely to be an elusive and indefinite matter, complicated by psychological and sociological factors. But this should only add to the appeal of the task for an engineer. It challenges him or her to assemble all pertinent facts, and then to make good decisions reflecting understanding, imagination, ingenuity, and judgment.

The important first step in developing engineering competence in the safety area is cultivating an *awareness* of its importance. Product safety is of great concern to legislators, attorneys, judges, jurors, insurance executives, and so forth. But none of these individuals can contribute directly to the safety of a product; they can only underscore the urgency of giving appropriate emphasis to safety in the *engineering development* of a product. It is the *engineer* who must carry out the development of safe products.

Safety is inherently a *relative* matter, and value judgments must be made regarding trade-offs between safety, cost, weight, and so on. Some years ago the first author was associated with a particularly safety-conscious company and was in the position of frequently admonishing the staff safety engineer to reduce further the inevitable hazards associated with the company's equipment.

When pushed a little too far one day, this engineer responded, “Look, I have made this model foolproof, but I can never make it *damn* foolproof! If someone tries hard enough, he can hurt himself with this machine!” The next day this gentleman inadvertently proved his point when he accidentally dropped the new model prototype on his foot and broke a toe! But the point to be made here is that when society makes decisions relative to safety requirements, engineers should contribute important input.

1.2.1 Imagination and Ingenuity

Following awareness, the second main point of safety engineering is *ingenuity*. The engineer must be imaginative and ingenious enough to *anticipate* potentially hazardous situations relating to a product. The old maxim that anything that *can* happen probably *will* happen sooner or later is relevant. The following are four cases in point, all involving costly liability suits.

1. A large open area with a high ceiling was to be heated and cooled with three cubical units, each suspended from the ceiling by long steel rods at four corners. The cubicles were being fitted with heat exchangers, blowers, and filters by workers inside and on top of the enclosures. The flexibility of the long support rods permitted the cubicles to swing back and forth, and the workers sometimes enjoyed getting their cubicle swinging with considerable amplitude. Fatigue failure of a support rod caused the death of one worker. Since large steam pipes (not yet installed at the time of the accident) prevented significant sway of the completed units, and the rods were designed with a safety factor of 17 (based on static weight of the completed cubicles), no further thought was given to safety. No one responsible for the design and installation of the units had reviewed the installation sequence with the imagination and ingenuity needed to foresee this hazard.
2. A boy was seriously injured by collision with a car when the brakes on his new bicycle failed to respond in an emergency. The cause was discovered to be interference between a fitting on the three-speed shift mechanism and a sharp edge on the caliper brake handle. Both the shift control mechanism and the brake handle were of unusual design. Both were safe within themselves and were safe when used in combination with a conventional design of the other member. But when these two unusual members were used together, it was easy for them to be mounted on the handlebar in such a position that the travel of the brake handle was limited, thereby preventing full application of the brake. Again, no one responsible for the overall design of the bicycle foresaw this hazardous situation.
3. A worker lost a hand in a 400-ton punch press despite wearing safety cuffs that were cam-actuated to pull the hands out of the danger zone before the ram came down. The cause was a loosened setscrew that permitted the cam to rotate with respect to its supporting shaft, thereby delaying hand retraction until *after* the ram came down. This case illustrates the old adage that “A chain is no stronger than its weakest link.” Here, an otherwise very positive and strong safety device was nullified because of the inexcusably weak link of the setscrew. A very little imagination and ingenuity on the part of the engineer responsible for this design would have brought this hazard to light before the unit was released for production.
4. A crawling infant lost the ends of three fingers as he attempted to climb up an “exercycle” being ridden by an older sister. When placed on the bottom chain, the infant’s hand was immediately drawn into the crank sprocket. In order to minimize cost, the exercycle was very properly designed to take advantage of many high-production, low-cost parts used on a standard bicycle. Unfortunately, however, the chain guard, which provides adequate protection for a bicycle, is totally inadequate for the exercycle. Was it too much to expect that the engineer responsible for this design would have enough imagination to foresee this hazard?

Should he or she not have been sufficiently ingenious to devise an alternative guard design that would be economically and otherwise feasible? Should it be necessary for this kind of imagination and ingenuity to be forced upon the engineer by legislation devised and enacted by nonengineers?

1.2.2 Techniques and Guidelines

Once the engineer is sufficiently *aware* of safety considerations, and accepts this challenge to his or her *imagination and ingenuity*, there are certain techniques and guidelines that are often helpful. Six of these are suggested in the following.

1. *Review the total life cycle* of the product from initial production to final disposal, with an eye toward uncovering significant hazards. Ask yourself what kinds of situations can reasonably develop during the various stages of manufacturing, transporting, storing, installing, using, servicing, and so on.
2. Be sure that the safety provisions represent a *balanced approach*. Do not accept a dollar penalty to eliminate one hazard and overlook a twenty-cent possibility for eliminating an equal hazard. And, like the punch press example just given, do not focus attention on how strong the wrist cuffs are while overlooking how weak the cam attachment is.
3. *Make safety an integral feature* of the basic design wherever possible, rather than "adding on" safety devices after the basic design has been completed. An example of this was the development of an electrostatic hand-operated paint gun. Earlier stationary-mounted electrostatic paint guns had metal atomizing heads operating at 100,000 volts. A handgun version, incorporating elaborate guards and shields, was quickly recognized as impractical. Instead, a fundamentally new electric circuit design combined with a nonmetallic head was developed so that even if the operator came in contact with the high-voltage head, he or she would receive no shock; the voltage automatically dropped as a hand approached the head, and the head itself had a low enough capacitance to avoid significant discharge to the operator.
4. Use a *"fail-safe" design* where feasible. The philosophy here is that precaution is taken to avoid failure, but if failure *does* occur, the design is such that the product is still "safe"; that is, the failure will not be catastrophic. For example, the first commercial jet aircraft were the British Comets. Some of these experienced catastrophic failure when fatigue cracks started in the outer aluminum "skin" at the corners of the windows (caused by alternately pressurizing the cabin at high altitude and relieving the pressurizing stresses at ground level). Soon after the cracks were initiated, the fuselage skin ripped disastrously (somewhat like a toy rubber balloon). After the cause of the crashes was determined, subsequent commercial jet aircraft incorporated the fail-safe feature of bonding the outer panels to the longitudinal and circumferential frame members of the fuselage. Thus, even if a crack does start, it can propagate only to the nearest bonded seam. The relatively short cracks in no way impair the safety of the aircraft. (This particular fail-safe feature can be illustrated by ripping an old shirt. Once a tear has been started, it is easily propagated to a seam, but it is extremely difficult to propagate the tear through the seam, or "tear stopper.") Fail-safe designs often incorporate *redundant* members so that if one load-carrying member fails, a second member is able to assume the full load. This is sometimes known as the "belt *and* suspenders" design philosophy. (In extreme cases, a "safety pin" may be employed as a third member.)
5. Check *government and industry standards* (such as OSHA and ANSI) and the pertinent technical literature to be sure that legal requirements are complied with, and that advantage is taken of the relevant safety experience of others. The OSHA regulations may be

downloaded from the government's web site at http://www.osha.gov. A search for specific titles of ANSI standards can be conducted at http://www.ansi.org. For regional, national, foreign, and international standards and regulatory documents, see http://www.nssn.org.

6. Provide *warnings* of all significant hazards that remain after the design has been made as safe as reasonably possible. The engineers who developed the product are in the best position to identify these hazards. The warnings should be designed to bring the information to the attention of the persons in jeopardy in the most positive manner feasible. Conspicuous warning signs attached permanently to the machine itself are usually best. There are OSHA and ANSI standards pertaining to warning signs. More complete warning information is often appropriately included in an instruction or operating manual that accompanies the machine.

To apply these techniques and guidelines in an alternative procedural form, consider the following list from [9]:

1. Delineate the scope of product uses.
2. Identify the environments within which the product will be used.
3. Describe the user population.
4. Postulate all possible hazards, including estimates of probability of occurrence and seriousness of resulting harm.
5. Delineate alternative design features or production techniques, including warnings and instructions, that can be expected to effectively mitigate or eliminate the hazards.
6. Evaluate such alternatives relative to the expected performance standards of the product, including the following:
   a. Other hazards that may be introduced by the alternatives.
   b. Their effect on the subsequent usefulness of the product.
   c. Their effect on the ultimate cost of the product.
   d. A comparison to similar products.
7. Decide which features to include in the final design.

The National Safety Council, see www.nsc.org, publishes a hierarchy of design that sets guidelines for designing equipment that will minimize injuries. The order of design priority is [10][1]:

1. *Design to eliminate hazards and minimize risk.* From the very beginning, the top priority should be to eliminate hazards in the design process.
2. *Incorporate safety devices.* If hazards cannot be eliminated or the risks adequately reduced through design selection, the next step is to reduce the risks to an acceptable level. This can be achieved with the use of guarding or other safety devices.
3. *Provide warning devices.* In some cases, identified hazards cannot be eliminated or their risks reduced to an acceptable level through initial design decisions or through the incorporated safety devices. Warnings are a potential solution.
4. *Develop and implement safe operating procedures and employee safety training programs.* Safe operating procedures and training are essential in minimizing injuries

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[1] Bracketed numbers in the text correspond to numbered references at the end of the chapter.

when it is impractical to eliminate hazards or reduce their risks to an acceptable level through design selection, incorporating safety devices, or with warning devices.

5. *Use personal protective equipment.* When all other techniques cannot eliminate or control a hazard, employees should be given personal protective equipment to prevent injuries and illnesses.

1.2.3 Documentation of a Product Design

The documentation of a product design is costly yet necessary to support possible litigation. Such documentation has been categorized [9] as in the following table.

Design Documentation Categories

Category	Description
Hazard and risk data	Historical, field, and/or laboratory testing, causation analyses
Design safety formulation	Fault-tree, failure modes, hazard analyses
Warnings and instruction formulations	Methodology for development and selection
Standards	The use of in-house, voluntary, and mandated design or performance requirements
Quality assurance program	Methodology for procedure selection and production records
Product performance	Reporting procedures, complaint file, follow-up data acquisition and analysis, recall, retrofit, instruction, and warning modification
Decision making	The "how," "who," and "why" of the process

By documenting a design during the process, a safer product is generally produced. Also, imagination and ingenuity can sometimes be stimulated by requiring documentation of a product design.

1.2.4 Nontechnical Aspects

Safety engineering inherently includes important *nontechnical aspects* that are related to the *individuals* involved. Engineers must be aware of these if their safety-related efforts are to be effective. Three specific points within this category are suggested.

1. *Capabilities* and *characteristics* of individuals, both physiological and psychological. When the device is used or serviced, the strength, reach, and endurance requirements must be well within the physiological limitations of the personnel involved. The arrangement of instruments and controls, and the nature of the mental operating requirements, must be compatible with psychological factors. Where the possibility of accident cannot be eliminated, the design should be geared to limiting personnel accident-imposed loads to values minimizing the severity of injury.

2. *Communication*. Engineers must communicate to others the rationale and operation of the safety provisions incorporated in their designs, and in many situations they must involve themselves in "*selling*" the proper use of these safety provisions. What good does it do, for example, to develop an effective motorcycle helmet if it is not used? Or to provide a punch

press with safety switches for both hands if the operator blocks one of the switches closed in order to have a hand free for smoking? Unfortunately, even the most effective communication does not always guarantee intelligent use by the operator. This unresponsiveness may cause controversies, such as that surrounding the requirement that air bags be installed in cars, because a significant segment of the public cannot be persuaded to use seat belts voluntarily. Resolution of such controversies requires intelligent input from many quarters, one of which is certainly the engineering profession.

3. *Cooperation*. The controversy just mentioned illustrates the need for engineers to cooperate effectively with members of other disciplines—government, management, sales, service, legal, and so on—in order that joint safety-directed efforts may prove effective.

1.3 Ecological Considerations

People inherently depend on their environment for air, water, food, and materials for clothing and shelter. In primitive society, human-made wastes were naturally recycled for repeated use. When open sewers and dumps were introduced, nature became unable to reclaim and recycle these wastes within normal time periods, thus interrupting natural ecological cycles. Traditional economic systems enable products to be mass-produced and sold at prices that often do not reflect the true cost to society in terms of resource consumption and ecological damage. Now that society is becoming more generally aware of this problem, legislative requirements and more realistic “total” cost provisions are having increasing impact upon engineering design. Certainly, it is important that the best available engineering input go into societal decisions involving these matters.

We can perhaps state the basic ecological objectives of mechanical engineering design rather simply: (1) to utilize materials so that they are economically recyclable within reasonable time periods without causing objectionable air, ground, and water pollution and (2) to minimize the rate of consumption of nonrecycled energy sources (such as fossil fuels) both to conserve these resources and to minimize thermal pollution. In some instances, the minimization of noise pollution is also a factor to be considered.

As with safety considerations, ecological factors are much more difficult for the engineer to tie down than are such matters as stress and deflection. The following is a suggested list of points to be considered.

1. Consider all aspects of the *basic design objective* involved, to be sure that it is sound. For example, questions are raised about the overall merits of some major dam constructions. Are there ecological side effects that might make it preferable to follow an alternative approach? Before undertaking the design of an expanded highway system or a specific mass-transit system, the engineer must determine whether the best available knowledge and judgment indicate that the proposed project represents the best alternative.

2. After accepting the basic design objective, the next step is a review of the *overall concepts* to be embodied into the proposed design. For example, a modular concept may be appropriate, wherein specific components or modules most likely to wear out or become obsolete can be replaced with updated modules that are interchangeable with the originals. The motor and transmission assembly of a domestic automatic washing machine might be an example for which this approach would be appropriate. Another example is the provision of replaceable exterior trim panels on major kitchen appliances that permit the exterior surfaces to be changed to match a new decorating scheme without replacing the entire appliance.

3. An important consideration is *designing for recycling*. At the outset of a new design, it is becoming increasingly important that the engineer consider the full ecological cycle

including the disposal and reuse of the entire device and its components. Consider an automobile. Parts appropriate for reuse (either with or without rebuilding) should be made so that they can be easily removed from a "junk" car. Dismantling and sorting of parts by material should be made as easy and economical as possible. It has been somewhat facetiously suggested that cars be made so that all fasteners break when dropping a junk car from, say, a height of 30 feet. Automatic devices would then sort the pieces by material for reprocessing. A more realistic proposal is that of attaching the wiring harness so that it can be quickly ripped out in one piece for easy salvaging of the copper.

In developing recycling procedures along these lines it is obviously desirable that the costs to a company for recycling versus costs for abandoning the old parts and using virgin materials reflect total real costs to society. No individual company could stay in business if it magnanimously undertook a costly recycling program in order to conserve virgin materials and reduce processing pollution if its competitors could utilize inexpensive new materials obtained at a price that did not reflect these total costs.

4. Select *materials* with ecological factors in mind. Of importance here are the known availability in nature of the required raw materials, processing energy requirements, processing pollution problems (air, water, land, thermal, and noise), and recyclability. Ideally, all these factors would be appropriately reflected within the pricing structure, and this will more likely happen in the future than it has in the past.

Another factor to be considered is the relative durability of alternative materials for use in a perishable part. For example, consider the great reduction in the number of razor blades required (and in the number of scrap razor blades) made by changing the material to stainless steel. (But would it be better, overall, to devise a convenient and effective way to resharpen the blades rather than throwing them away?)

The engineer should also consider the *compatibility* of materials with respect to recycling. For example, zinc die castings deteriorate the quality of the scrap obtained when present junked cars are melted.

5. Consider ecological factors when specifying *processing*. Important here are pollution of all kinds, energy consumption, and efficiency of material usage. For example, forming operations such as rolling and forging use less material (and generate less scrap) than cutting operations. There may also be important differences in energy consumption.

6. *Packaging* is an important area for resource conservation and pollution reduction. Reusable cartons, and the use of recycled materials for packaging, are two areas receiving increasing attention. Perhaps the ultimate in ecologically desirable packaging is that commonly used ice cream container, the cone.

The matter of protecting our environment is a deadly serious one. As the late Adlai Stevenson once said, "We travel together, passengers on a little space ship, dependent on its vulnerable supplies of air and soil … preserved from annihilation only by the care, the work, and I will say the love, we give our fragile craft."

1.4 Societal Considerations

As the reader well knows, the solution to any engineering problem begins with its clear definition. Accordingly, let us define, in the broadest terms, the problem to be addressed when undertaking mechanical engineering design. The opening sentence in this chapter suggests a definition: The basic objective of any engineering design is to provide a machine or device that will benefit humanity. In order to apply this definition, it is necessary to think in more specific terms. Just how does an individual benefit humanity? What "yardstick" (meterstick?) can be used to measure such benefits? The formulation of precise definitions of problem objectives, and the devising of means for measuring results, *fall within the special province of the engineer*.

The writer has suggested [2] that the basic objective of engineering design as well as other human pursuits is to improve the quality of life within our society, and that this might be measured in terms of a life quality index (LQI). This index is in some ways similar to the familiar "gross national product," but very much broader. Judgments about the proper composition of the LQI would, of course, vary somewhat in the many segments of society and also with time.

To illustrate the LQI concept, Table 1.1 lists some of the important factors most people would agree should be included. Perhaps we might arbitrarily assign a value of 100 to the factor deemed most important, with other factors being weighed accordingly. Each factor might then be multiplied by the same fraction so that the total would add up to 100.

The list in the table is admittedly a very rough and oversimplified indication of the direction of thought that would be involved in arriving at an LQI for a given segment of society at a given time. But this *kind* of thinking must be done in order to provide a sound basis for judgment with respect to the fulfillment of the engineering mission of service to humanity.

The professional contribution of engineers engaged in the broad area of engineering design and development plays a major role in determining the LQI of a population. Figure 1.1 depicts the societal relationships involving engineered products. A major segment of the population works within organizations whose function is to do one or more of the following: research, design, develop, manufacture, market, and service engineered products. The efforts of these people, together with appropriate natural resources, go into production systems that yield useful products, waste materials, and experience. The experience is of two kinds: (1) direct working experience of the individuals, which is hopefully constructive and satisfying, and (2) empirical knowledge gained about the effectiveness of the overall system, with implications for its future improvement.

Table 1.1 Preliminary List of Factors Constituting the Life Quality Index (LQI)

1. *Physical health*
2. *Material well-being*
3. *Safety* (crime and accident rates)
4. *Environment* (air, water, land, and natural resource management)
5. *Cultural–educational* (literacy rate, public school quality, college attendance among those qualified, adult educational opportunities, library and museum facilities, etc.)
6. *Treatment of disadvantaged groups* (physically and mentally handicapped, aged, etc.)
7. *Equality of opportunity* (and stimulation of initiative to use opportunities)
8. *Personal freedom*
9. *Population control*

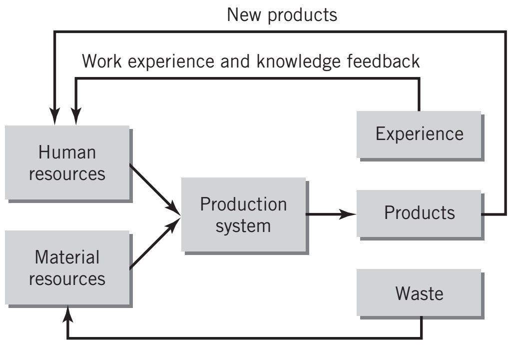

FIGURE 1.1 Societal relationships involving engineered products.