Contents

PART I Principles of Design and Stress Analysis 1

1 The Nature of Mechanical Design 2

The Big Picture 3

You Are the Designer 9

1–1 Objectives of This Chapter 9

1–2 The Mechanical Design Process 9

1–3 Skills Needed in Mechanical Design 11

1–4 Functions, Design Requirements, and Evaluation Criteria 11

1–5 Example of the Integration of Machine Elements into a Mechanical Design 14

1–6 Computational Aids in This Book 17

1–7 Design Calculations 17

1–8 Preferred Basic Sizes, Screw Threads, and Standard Shapes 18

1–9 Unit Systems 24

1–10 Distinction among Weight, Force, and Mass 26

References 27

Internet Sites 27

Problems 28

2 Materials in Mechanical Design 29

The Big Picture 30

You Are the Designer 31

2–1 Objectives of This Chapter 32

2–2 Properties of Materials 32

2–3 Classification of Metals and Alloys 44

2–4 Variability of Material Properties Data 45

2–5 Carbon and Alloy Steel 46

2–6 Conditions for Steels and Heat Treatment 49

2–7 Stainless Steels 53

2–8 Structural Steel 54

2–9 Tool Steels 54

2–10 Cast Iron 54

2–11 Powdered Metals 56

2–12 Aluminum 57

2–13 Zinc Alloys 59

2–14 Titanium 60

2–15 Copper, Brass, and Bronze 60

2–16 Nickel-Based Alloys 61

2–17 Plastics 61

2–18 Composite Materials 65

2–19 Materials Selection 77

References 78

Internet Sites 79

Problems 80

3 Stress and Deformation Analysis 83

The Big Picture 84

You Are the Designer 85

3–1 Objectives of This Chapter 89

3–2 Philosophy of a Safe Design 89

3–3 Representing Stresses on a Stress Element 89

3–4 Direct Stresses: Tension and Compression 90

3–5 Deformation under Direct Axial Loading 92

3–6 Direct Shear Stress 92

3–7 Relationship among Torque, Power, and Rotational Speed 94

3–8 Torsional Shear Stress 95

3–9 Torsional Deformation 97

3–10 Torsion in Members Having Noncircular Cross Sections 98

3–11 Torsion in Closed, Thin-Walled Tubes 100

3–12 Open Tubes and a Comparison with Closed Tubes 100

3–13 Vertical Shearing Stress 102

3–14 Special Shearing Stress Formulas 104

3–15 Stress Due to Bending 105
3–16 Flexural Center for Beams 107
3–17 Beam Deflections 108
3–18 Equations for Deflected Beam Shape 110
3–19 Beams with Concentrated Bending Moments 112
3–20 Combined Normal Stresses: Superposition Principle 117
3–21 Stress Concentrations 119
3–22 Notch Sensitivity and Strength Reduction Factor 122
References 123
Internet Sites 123
Problems 123

4 Combined Stresses and Mohr's Circle 135

The Big Picture 136
You Are the Designer 136
4–1 Objectives of This Chapter 138
4–2 General Case of Combined Stress 138
4–3 Mohr's Circle 145
4–4 Mohr's Circle Practice Problems 151
4–5 Case When Both Principal Stresses Have the Same Sign 155
4–6 Mohr's Circle for Special Stress Conditions 158
4–7 Analysis of Complex Loading Conditions 161
References 162
Internet Site 162
Problems 162

5 Design for Different Types of Loading 163

The Big Picture 164
You Are the Designer 166
5–1 Objectives of This Chapter 166
5–2 Types of Loading and Stress Ratio 166
5–3 Endurance Strength 172
5–4 Estimated Actual Endurance Strength, s'_n 173
5–5 Example Problems for Estimating Actual Endurance Strength 181
5–6 Design Philosophy 182
5–7 Design Factors 185
5–8 Predictions of Failure 186
5–9 Design Analysis Methods 193
5–10 General Design Procedure 197
5–11 Design Examples 200
5–12 Statistical Approaches to Design 213
5–13 Finite Life and Damage Accumulation Method 214
References 218
Problems 219

6 Columns 229

The Big Picture 230
You Are the Designer 231
6–1 Objectives of This Chapter 231
6–2 Properties of the Cross Section of a Column 232
6–3 End Fixity and Effective Length 232
6–4 Slenderness Ratio 234
6–5 Transition Slenderness Ratio 234
6–6 Long Column Analysis: The Euler Formula 235
6–7 Short Column Analysis: The J. B. Johnson Formula 239
6–8 Column Analysis Spreadsheet 241
6–9 Efficient Shapes for Column Cross Sections 244
6–10 The Design of Columns 245
6–11 Crooked Columns 250
6–12 Eccentrically Loaded Columns 251
References 257
Problems 257

PART II Design of a Mechanical Drive 261

7 Belt Drives and Chain Drives 264

The Big Picture 265
You Are the Designer 267
7–1 Objectives of This Chapter 267
7–2 Types of Belt Drives 268

Contents

PART I Principles of Design and Stress Analysis 1

1 The Nature of Mechanical Design 2

The Big Picture 3

You Are the Designer 9

1–1 Objectives of This Chapter 9

1–2 The Mechanical Design Process 9

1–3 Skills Needed in Mechanical Design 11

1–4 Functions, Design Requirements, and Evaluation Criteria 11

1–5 Example of the Integration of Machine Elements into a Mechanical Design 14

1–6 Computational Aids in This Book 17

1–7 Design Calculations 17

1–8 Preferred Basic Sizes, Screw Threads, and Standard Shapes 18

1–9 Unit Systems 24

1–10 Distinction among Weight, Force, and Mass 26

References 27

Internet Sites 27

Problems 28

2 Materials in Mechanical Design 29

The Big Picture 30

You Are the Designer 31

2–1 Objectives of This Chapter 32

2–2 Properties of Materials 32

2–3 Classification of Metals and Alloys 44

2–4 Variability of Material Properties Data 45

2–5 Carbon and Alloy Steel 46

2–6 Conditions for Steels and Heat Treatment 49

2–7 Stainless Steels 53

2–8 Structural Steel 54

2–9 Tool Steels 54

2–10 Cast Iron 54

2–11 Powdered Metals 56

2–12 Aluminum 57

2–13 Zinc Alloys 59

2–14 Titanium 60

2–15 Copper, Brass, and Bronze 60

2–16 Nickel-Based Alloys 61

2–17 Plastics 61

2–18 Composite Materials 65

2–19 Materials Selection 77

References 78

Internet Sites 79

Problems 80

3 Stress and Deformation Analysis 83

The Big Picture 84

You Are the Designer 85

3–1 Objectives of This Chapter 89

3–2 Philosophy of a Safe Design 89

3–3 Representing Stresses on a Stress Element 89

3–4 Direct Stresses: Tension and Compression 90

3–5 Deformation under Direct Axial Loading 92

3–6 Direct Shear Stress 92

3–7 Relationship among Torque, Power, and Rotational Speed 94

3–8 Torsional Shear Stress 95

3–9 Torsional Deformation 97

3–10 Torsion in Members Having Noncircular Cross Sections 98

3–11 Torsion in Closed, Thin-Walled Tubes 100

3–12 Open Tubes and a Comparison with Closed Tubes 100

3–13 Vertical Shearing Stress 102

3–14 Special Shearing Stress Formulas 104

3–15 Stress Due to Bending 105
3–16 Flexural Center for Beams 107
3–17 Beam Deflections 108
3–18 Equations for Deflected Beam Shape 110
3–19 Beams with Concentrated Bending Moments 112
3–20 Combined Normal Stresses: Superposition Principle 117
3–21 Stress Concentrations 119
3–22 Notch Sensitivity and Strength Reduction Factor 122
References 123
Internet Sites 123
Problems 123

4 Combined Stresses and Mohr's Circle 135

The Big Picture 136
You Are the Designer 136
4–1 Objectives of This Chapter 138
4–2 General Case of Combined Stress 138
4–3 Mohr's Circle 145
4–4 Mohr's Circle Practice Problems 151
4–5 Case When Both Principal Stresses Have the Same Sign 155
4–6 Mohr's Circle for Special Stress Conditions 158
4–7 Analysis of Complex Loading Conditions 161
References 162
Internet Site 162
Problems 162

5 Design for Different Types of Loading 163

The Big Picture 164
You Are the Designer 166
5–1 Objectives of This Chapter 166
5–2 Types of Loading and Stress Ratio 166
5–3 Endurance Strength 172
5–4 Estimated Actual Endurance Strength, s'_n 173
5–5 Example Problems for Estimating Actual Endurance Strength 181
5–6 Design Philosophy 182
5–7 Design Factors 185
5–8 Predictions of Failure 186
5–9 Design Analysis Methods 193
5–10 General Design Procedure 197
5–11 Design Examples 200
5–12 Statistical Approaches to Design 213
5–13 Finite Life and Damage Accumulation Method 214
References 218
Problems 219

6 Columns 229

The Big Picture 230
You Are the Designer 231
6–1 Objectives of This Chapter 231
6–2 Properties of the Cross Section of a Column 232
6–3 End Fixity and Effective Length 232
6–4 Slenderness Ratio 234
6–5 Transition Slenderness Ratio 234
6–6 Long Column Analysis: The Euler Formula 235
6–7 Short Column Analysis: The J. B. Johnson Formula 239
6–8 Column Analysis Spreadsheet 241
6–9 Efficient Shapes for Column Cross Sections 244
6–10 The Design of Columns 245
6–11 Crooked Columns 250
6–12 Eccentrically Loaded Columns 251
References 257
Problems 257

PART II Design of a Mechanical Drive 261

7 Belt Drives and Chain Drives 264

The Big Picture 265
You Are the Designer 267
7–1 Objectives of This Chapter 267
7–2 Types of Belt Drives 268

7–3 V-Belt Drives 269
7–4 V-Belt Drive Design 272
7–5 Chain Drives 283
7–6 Design of Chain Drives 285
References 296
Internet Sites 298
Problems 298

8 Kinematics of Gears 300

The Big Picture 301
You Are the Designer 305
8–1 Objectives of This Chapter 306
8–2 Spur Gear Styles 306
8–3 Spur Gear Geometry: Involute-Tooth Form 307
8–4 Spur Gear Nomenclature and Gear-Tooth Features 308
8–5 Interference between Mating Spur Gear Teeth 320
8–6 Velocity Ratio and Gear Trains 322
8–7 Helical Gear Geometry 329
8–8 Bevel Gear Geometry 333
8–9 Types of Wormgearing 339
8–10 Geometry of Worms and Wormgears 341
8–11 Typical Geometry of Wormgear Sets 344
8–12 Train Value for Complex Gear Trains 347
8–13 Devising Gear Trains 350
References 357
Internet Sites 357
Problems 358

9 Spur Gear Design 363

The Big Picture 364
You Are the Designer 365
9–1 Objectives of This Chapter 365
9–2 Concepts from Previous Chapters 366
9–3 Forces, Torque, and Power in Gearing 367
9–4 Gear Manufacture 370
9–5 Gear Quality 372
9–6 Allowable Stress Numbers 378
9–7 Metallic Gear Materials 379
9–8 Stresses in Gear Teeth 385
9–9 Selection of Gear Material Based on Bending Stress 394
9–10 Pitting Resistance of Gear Teeth 399
9–11 Selection of Gear Material Based on Contact Stress 402
9–12 Design of Spur Gears 407
9–13 Gear Design for the Metric Module System 413
9–14 Computer-Aided Spur Gear Design and Analysis 415
9–15 Use of the Spur Gear Design Spreadsheet 419
9–16 Power-Transmitting Capacity 428
9–17 Practical Considerations for Gears and Interfaces with Other Elements 430
9–18 Plastics Gearing 434
References 442
Internet Sites 443
Problems 444

10 Helical Gears, Bevel Gears, and Wormgearing 449

The Big Picture 450
You Are the Designer 452
10–1 Objectives of This Chapter 452
10–2 Forces on Helical Gear Teeth 452
10–3 Stresses in Helical Gear Teeth 455
10–4 Pitting Resistance for Helical Gear Teeth 459
10–5 Design of Helical Gears 460
10–6 Forces on Straight Bevel Gears 463
10–7 Bearing Forces on Shafts Carrying Bevel Gears 465
10–8 Bending Moments on Shafts Carrying Bevel Gears 470
10–9 Stresses in Straight Bevel Gear Teeth 470
10–10 Design of Bevel Gears for Pitting Resistance 473
10–11 Forces, Friction, and Efficiency in Wormgear Sets 475
10–12 Stress in Wormgear Teeth 481
10–13 Surface Durability of Wormgear Drives 482
References 488
Internet Sites 488
Problems 489

11 Keys, Couplings, and Seals 491

The Big Picture 492

You Are the Designer 493

11–1 Objectives of This Chapter 493

11–2 Keys 494

11–3 Materials for Keys 498

11–4 Stress Analysis to Determine Key Length 499

11–5 Splines 503

11–6 Other Methods of Fastening Elements to Shafts 508

11–7 Couplings 513

11–8 Universal Joints 516

11–9 Retaining Rings and Other Means of Axial Location 518

11–10 Types of Seals 521

11–11 Seal Materials 525

References 526

Internet Sites 527

Problems 528

12 Shaft Design 530

The Big Picture 531

You Are the Designer 532

12–1 Objectives of This Chapter 532

12–2 Shaft Design Procedure 532

12–3 Forces Exerted on Shafts by Machine Elements 535

12–4 Stress Concentrations in Shafts 540

12–5 Design Stresses for Shafts 543

12–6 Shafts in Bending and Torsion Only 546

12–7 Shaft Design Example 548

12–8 Recommended Basic Sizes for Shafts 552

12–9 Additional Design Examples 553

12–10 Spreadsheet Aid for Shaft Design 561

12–11 Shaft Rigidity and Dynamic Considerations 562

12–12 Flexible Shafts 563

References 564

Internet Sites 564

Problems 565

13 Tolerances and Fits 575

The Big Picture 576

You Are the Designer 577

13–1 Objectives of This Chapter 577

13–2 Factors Affecting Tolerances and Fits 578

13–3 Tolerances, Production Processes, and Cost 578

13–4 Preferred Basic Sizes 581

13–5 Clearance Fits 581

13–6 Interference Fits 585

13–7 Transition Fits 586

13–8 Stresses for Force Fits 587

13–9 General Tolerancing Methods 591

13–10 Robust Product Design 592

References 594

Internet Sites 594

Problems 595

14 Rolling Contact Bearings 597

The Big Picture 598

You Are the Designer 599

14–1 Objectives of This Chapter 600

14–2 Types of Rolling Contact Bearings 600

14–3 Thrust Bearings 604

14–4 Mounted Bearings 604

14–5 Bearing Materials 606

14–6 Load/Life Relationship 606

14–7 Bearing Manufacturers' Data 606

14–8 Design Life 611

14–9 Bearing Selection: Radial Loads Only 613

14–10 Bearing Selection: Radial and Thrust Loads Combined 614

14–11 Mounting of Bearings 616

14–12 Tapered Roller Bearings 618

14–13 Practical Considerations in the Application of Bearings 621

14–14 Importance of Oil Film Thickness in Bearings 624

14–15 Life Prediction under Varying Loads 625

References 627

Internet Sites 627

Problems 628

15 Completion of the Design of a Power Transmission 630

The Big Picture 631

15–1 Objectives of This Chapter 631

15–2 Description of the Power Transmission to Be Designed 631

15–3 Design Alternatives and Selection of the Design Approach 633

15–4 Design Alternatives for the Gear-Type Reducer 635

15–5 General Layout and Design Details of the Reducer 635

15–6 Final Design Details for the Shafts 652

15–7 Assembly Drawing 655

References 657

Internet Sites 657

PART III Design Details and Other Machine Elements 659

16 Plain Surface Bearings 660

The Big Picture 661

You Are the Designer 663

16–1 Objectives of This Chapter 663

16–2 The Bearing Design Task 663

16–3 Bearing Parameter, $\mu n/p$ 665

16–4 Bearing Materials 666

16–5 Design of Boundary-Lubricated Bearings 668

16–6 Full-Film Hydrodynamic Bearings 674

16–7 Design of Full-Film Hydrodynamically Lubricated Bearings 675

16–8 Practical Considerations for Plain Surface Bearings 682

16–9 Hydrostatic Bearings 683

16–10 Tribology: Friction, Lubrication, and Wear 687

References 691

Internet Sites 692

Problems 693

17 Linear Motion Elements 694

The Big Picture 695

You Are the Designer 698

17–1 Objectives of This Chapter 698

17–2 Power Screws 699

17–3 Ball Screws 704

17–4 Application Considerations for Power Screws and Ball Screws 707

References 709

Internet Sites 709

Problems 709

18 Fasteners 711

The Big Picture 713

You Are the Designer 714

18–1 Objectives of This Chapter 714

18–2 Bolt Materials and Strength 714

18–3 Thread Designations and Stress Area 717

18–4 Clamping Load and Tightening of Bolted Joints 719

18–5 Externally Applied Force on a Bolted Joint 722

18–6 Thread Stripping Strength 723

18–7 Other Types of Fasteners and Accessories 724

18–8 Other Means of Fastening and Joining 726

References 727

Internet Sites 727

Problems 728

19 Springs 729

The Big Picture 730

You Are the Designer 731

19–1 Objectives of This Chapter 732

19–2 Kinds of Springs 732

19–3 Helical Compression Springs 735

19–4 Stresses and Deflection for Helical Compression Springs 744

19–5 Analysis of Spring Characteristics 746

19–6 Design of Helical Compression Springs 749

19–7 Extension Springs 757

19–8 Helical Torsion Springs 762

19–9 Improving Spring Performance by Shot Peening 769

19–10 Spring Manufacturing 770

References 770

Internet Sites 770

Problems 771

20 Machine Frames, Bolted Connections, and Welded Joints 773

The Big Picture 774

You Are the Designer 775

20–1 Objectives of This Chapter 775

20–2 Machine Frames and Structures 776

20–3 Eccentrically Loaded Bolted Joints 780

20–4 Welded Joints 783

References 792

Internet Sites 792

Problems 793

21 Electric Motors and Controls 795

The Big Picture 796

You Are the Designer 797

21–1 Objectives of This Chapter 797

21–2 Motor Selection Factors 798

21–3 AC Power and General Information about AC Motors 799

21–4 Principles of Operation of AC Induction Motors 800

21–5 AC Motor Performance 802

21–6 Three-Phase, Squirrel-Cage Induction Motors 803

21–7 Single-Phase Motors 806

21–8 AC Motor Frame Types and Enclosures 808

21–9 Controls for AC Motors 811

21–10 DC Power 820

21–11 DC Motors 821

21–12 DC Motor Control 824

21–13 Other Types of Motors 824

References 826

Internet Sites 827

Problems 827

22 Motion Control: Clutches and Brakes 830

The Big Picture 831

You Are the Designer 833

22–1 Objectives of This Chapter 833

22–2 Descriptions of Clutches and Brakes 833

22–3 Types of Friction Clutches and Brakes 835

22–4 Performance Parameters 840

22–5 Time Required to Accelerate a Load 841

22–6 Inertia of a System Referred to the Clutch Shaft Speed 844

22–7 Effective Inertia for Bodies Moving Linearly 845

22–8 Energy Absorption: Heat-Dissipation Requirements 846

22–9 Response Time 847

22–10 Friction Materials and Coefficient of Friction 849

22–11 Plate-Type Clutch or Brake 851

22–12 Caliper Disc Brakes 854

22–13 Cone Clutch or Brake 854

22–14 Drum Brakes 855

22–15 Band Brakes 860

22–16 Other Types of Clutches and Brakes 862

References 864

Internet Sites 864

Problems 865

23 Design Projects 867

23–1 Objectives of This Chapter 868

23–2 Design Projects 868

Appendices A–1

Appendix 1 Properties of Areas A–1

Appendix 2 Preferred Basic Sizes and Screw Threads A–3

Appendix 3 Design Properties of Carbon and Alloy Steels A–6

Appendix 4 Properties of Heat-Treated Steels A–8

Appendix 5 Properties of Carburized Steels A–11

Appendix 6 Properties of Stainless Steels A–12

Appendix 7 Properties of Structural Steels A–13

Appendix 8 Design Properties of Cast Iron A–14

Appendix 9 Typical Properties of Aluminum A–15

Appendix 10 Typical Properties of Zinc Casting Alloys A–16

Appendix 11 Properties of Titanium Alloys A–16

Appendix 12 Properties of Bronzes A–17
Appendix 13 Typical Properties of Selected Plastics A–17
Appendix 14 Beam-Deflection Formulas A–18
Appendix 15 Stress Concentration Factors A–27
Appendix 16 Steel Structural Shapes A–31
Appendix 17 Aluminum Structural Shapes A–37
Appendix 18 Conversion Factors A–39
Appendix 19 Hardness Conversion Table A–40
Appendix 20 Geometry Factor *I* for Pitting for Spur Gears A–41

Answers to Selected Problems A–44

Index I–1