



PART ONE ENGINEERING PRINCIPLES

Chapter 1

Keystones of Design: Materials

Selection and Geometry Determination

1.1	Some Background Philosophy	1
1.2	The Product Design Team	2
1.3	Function and Form; Aesthetics and Ergonomics	5
1.4	Concepts and Definitions of Mechanical Design	6
1.5	Design Safety Factor	7
1.6	Stages of Design	7
1.7	Steps in the Design Process	7
1.8	Fail Safe and Safe Life Design Concepts	9
1.9	The Virtues of Simplicity	10
1.10	Lessons Learned Strategy	12
1.11	Machine Elements, Subassemblies, and the Whole Machine	12
1.12	The Role of Codes and Standards in the Design Process	13
1.13	Ethics in Engineering Design	13
1.14	Units	14

Chapter 2

The Failure Prevention Perspective

2.1	Role of Failure Prevention Analysis in Mechanical Design	22
2.2	Failure Criteria	22
2.3	Modes of Mechanical Failure	23
2.4	Elastic Deformation, Yielding, and Ductile Rupture	28
2.5	Brittle Fracture and Crack Propagation: Linear Elastic Fracture Mechanics	34

2.6 Fluctuating Loads, Cumulative Damage, and Fatigue Life

43

Fluctuating Loads and Stresses	44
Fatigue Strength and Fatigue Limit	46
Estimating S-N Curves	48
Stress-Life (S-N) Approach to Fatigue	50
Factors That May Affect S-N Curves	50
Nonzero-Mean Stress	59
Cumulative Damage Concepts and Cycle Counting	66
Multiaxial Cyclic Stresses	72
Fracture Mechanics (F-M) Approach to Fatigue	73
Crack Initiation Phase	73
Crack Propagation and Final Fracture Phases	76
Design Issues in Fatigue Life Prediction	81

2.7 Elastic Instability and Buckling

81

Buckling of a Simple Pin-Jointed Mechanism	82
Buckling of a Pinned-End Column	83
Columns With Other End Constraints	85
Inelastic Behavior and Initially Crooked Columns	86
Column Failure Prediction and Design Considerations	87
Buckling of Elements Other Than Columns	90

2.8 Shock and Impact

92

Stress Wave Propagation Under Impact Loading Conditions	93
Energy Method of Approximating Stress and Deflection Under Impact Loading Conditions	93

2.9 Creep and Stress Rupture	98	<i>Torsional Shear; Noncircular Cross Section</i>	181
Predictions of Long-Term Creep Behavior	100	<i>Torsional Shear; Shear Center in Bending</i>	185
Creep under Uniaxial State of Stress	101	<i>Surface Contact Stress</i>	188
Cumulative Creep Prediction	104	Deflection; Common Types of Loading	188
2.10 Wear and Corrosion	105	Stored Strain Energy	189
Wear	106	Castigliano's Theorem	191
Corrosion	111	4.5 Multiaxial States of Stress and Strain	194
2.11 Fretting, Fretting-Fatigue, and Fretting Wear	113	Principal Stresses	195
Fretting Fatigue	114	Stress Cubic Equation	195
Fretting Wear	116	Mohr's Circle Analogy for Stress	198
Minimizing or Preventing Fretting Damage	116	Strain Cubic Equation and Principal Strains	201
2.12 Failure Data and the Design Task	117	Mohr's Circle Analogy for Strain	202
2.13 Failure Assessment and Retrospective Design	117	Elastic Stress-Strain Relationships (Hooke's Law)	202
		4.6 Combined Stress Theories of Failure	204
		Maximum Normal Stress Theory (Rankine's Theory)	204
		Maximum Shearing Stress Theory (Tresca-Guest Theory)	205
		Distortion Energy Theory (Huber-Von Mises-Hencky Theory)	205
		Failure Theory Selection	207
		4.7 Multiaxial States of Cyclic Stress and Multiaxial Fatigue Failure Theories	208
		4.8 Stress Concentration	212
		Stress Concentration Effects	212
		Multiple Notches	214
		Fatigue Stress Concentration Factors and Notch Sensitivity Index	220
		4.9 Bending of Initially Curved Beams	227
		4.10 Stresses Caused by Curved Surfaces in Contact	232
		4.11 Load Sharing in Redundant Assemblies and Structures	237
		Machine Elements as Springs	238
		4.12 Preloading Concepts	243
		4.13 Residual Stresses	247
		Estimating Residual Stresses	248
		4.14 Environmental Effects	254
Chapter 3		Chapter 5	
Materials Selection	130	The Role of Safety Factor; Reliability Concepts	267
3.1 Steps in Materials Selection	130	5.1 Purpose of Safety Factors in Design Calculations	267
3.2 Analyzing Requirements of the Application	130	5.2 Selection and Use of a Design Safety Factor	267
3.3 Assembling Lists of Responsive Materials	141		
3.4 Matching Responsive Materials to Application Requirements; Rank Ordered Data Table Method	142		
3.5 Matching Responsive Materials to Application Requirements; Ashby Chart Method	151		
Chapter 4			
Response of Machine Elements to Loads and Environments; Stress, Strain, and Energy Parameters	160		
4.1 Loads and Geometry	160		
4.2 Equilibrium Concepts and Free Body Diagrams	160		
4.3 Force Analysis	161		
4.4 Stress and Deflection Analysis; Common Stress Patterns	163		
States of Stress; Common Types of Loading	163		
<i>Direct Axial Stress</i>	164		
<i>Bending; Load, Shear, and Moment Diagrams</i>	164		
<i>Bending; Straight Beam with Pure Moment</i>	169		
<i>Bending; Straight Beam with Transverse Forces</i>	172		
<i>Direct Shear and Transverse Shear Stress</i>	172		
<i>Torsional Shear; Circular Cross Section</i>	179		

5.3 Determination of Existing Safety Factor in a Completed Design: A Conceptual Contrast	270	Strain Matching Guideline	291
5.4 Reliability: Concepts, Definitions, and Data	271	Load Spreading Guideline	291
System Reliability, Reliability Goals, and Reliability Allocation	276	6.3 Critical Sections and Critical Points	293
Reliability Data	279	6.4 Transforming Combined Stress Failure Theories into Combined Stress Design Equations	295
5.5 The Dilemma of Reliability Specification Versus Design Safety Factor	279	6.5 Simplifying Assumptions: The Need and the Risk	296
		6.6 Iteration Revisited	297
		6.7 Fits, Tolerances, and Finishes	303
Chapter 6			
Geometry Determination	283	Chapter 7	
6.1 The Contrast in Objectives Between Analysis and Design	283	Design-Stage Integration of Manufacturing and Maintenance Requirements	313
6.2 Basic Principles and Guidelines for Creating Shape and Size	284	7.1 Concurrent Engineering	313
Direct Load Path Guideline	284	7.2 Design for Function, Performance, and Reliability	314
Tailored-Shape Guideline	285	7.3 Selection of the Manufacturing Process	314
Triangle-Tetrahedron Guideline	286	7.4 Design for Manufacturing (DFM)	317
Buckling Avoidance Guideline	287	7.5 Design for Assembly (DFA)	317
Hollow Cylinder and I-Beam Guideline	288	7.6 Design for Critical Point Accessibility, Inspectability, Disassembly, Maintenance, and Recycling	319
Conforming Surface Guideline	288		
Lazy-Material Removal Guideline	289		
Merging Shape Guideline	290		

PART TWO DESIGN APPLICATIONS

Chapter 8		Chapter 9	
Power Transmission Shafting; Couplings, Keys, and Splines	321	Pressurized Cylinders; Interference Fits	362
8.1 Uses and Characteristics of Shafting	321	9.1 Uses and Characteristics of Pressurized Cylinders	362
8.2 Potential Failure Modes	323	9.2 Interference Fit Applications	362
8.3 Shaft Materials	324	9.3 Potential Failure Modes	363
8.4 Design Equations—Strength Based	325	9.4 Materials for Pressure Vessels	363
8.5 Design Equations—Deflection Based	331	9.5 Principles from Elasticity Theory	364
8.6 Shaft Vibration and Critical Speed	338	9.6 Thin-Walled Cylinders	365
8.7 Summary of Suggested Shaft Design Procedure; General Guidelines for Shaft Design	340	9.7 Thick-Walled Cylinders	366
8.8 Couplings, Keys, and Splines	341	9.8 Interference Fits: Pressure and Stress	372
Rigid Couplings	341	9.9 Design for Proper Interference	376
Flexible Couplings	343		
Keys, Splines, and Tapered Fits	345	Chapter 10	
		Plain Bearings and Lubrication	383
		10.1 Types of Bearings	383
		10.2 Uses and Characteristics of Plain Bearings	383

10.3	Potential Failure Modes	384	13.4	Threaded Fasteners	465
10.4	Plain Bearing Materials	385		Screw Thread Standards and Terminology	466
10.5	Lubrication Concepts	385		Threaded Fastener Materials	469
10.6	Boundary Lubricated Bearing Design	386		Critical Points and Thread Stresses	471
10.7	Hydrodynamic Bearing Design	389		Preloading Effects; Joint Stiffness and Gasketed Joints	473
	Lubricant Properties	390		Tightening Torque; Fastener Loosening	482
	Loading, Friction, and Lubricant Flow Relationships	391		Multiply Bolted Joints; Symmetric and Eccentric Loading	486
	Thermal Equilibrium and Oil Film Temperature Rise	396	13.5	Rivets	491
	Design Criteria and Assumptions	399		Rivet Materials	491
	Suggested Design Procedure	400		Critical Points and Stress Analysis	492
10.8	Hydrostatic Bearing Design	405	13.6	Welds	494
				Base Metals, Filler Materials, and Weldability	497
				Butt Welds	498
				Fillet Welds	500
			13.7	Adhesive Bonding	506
				Joint Design	506
				Structural Adhesive Materials	508
Chapter 11			Chapter 14		
Rolling Element Bearings	409		Springs	515	
11.1	Uses and Characteristics of Rolling Element Bearings	409	14.1	Uses and Characteristics of Springs	515
11.2	Types of Rolling Element Bearings	410	14.2	Types of Springs	515
11.3	Potential Failure Modes	413	14.3	Potential Failure Modes	517
11.4	Bearing Materials	413	14.4	Spring Materials	518
11.5	Bearing Selection	414	14.5	Axially Loaded Helical Coil Springs; Stress, Deflection, and Spring Rate	521
	Basic Load Ratings	415		Deflection and Spring Rate	525
	Reliability Specifications	415		Buckling and Surging	527
	Suggested Selection Procedure for Steady Loads	416	14.6	Summary of Suggested Helical Coil Spring Design Procedure, and General Guidelines for Spring Design	529
	Suggested Selection Procedure for Spectrum Loading	427	14.7	Beam Springs (Leaf Springs)	535
	Lubrication	431	14.8	Summary of Suggested Leaf Spring Design Procedure	540
11.6	Preloading and Bearing Stiffness	432	14.9	Torsion Bars and Other Torsion Springs	544
11.7	Bearing Mounting and Enclosure	436	14.10	Belleville (Coned Disk) Springs	547
			14.11	Energy Storage in Springs	548
Chapter 12			Chapter 15		
Power Screw Assemblies	440		Gears and Systems of Gears	557	
12.1	Uses and Characteristics of Power Screws	440	15.1	Uses and Characteristics of Gears	557
12.2	Potential Failure Modes	443	15.2	Types of Gears; Factors in Selection	558
12.3	Materials	444	15.3	Gear Trains; Reduction Ratios	563
12.4	Power Screw Torque and Efficiency	444	15.4	Potential Failure Modes	567
12.5	Suggested Power Screw Design Procedure	450	15.5	Gear Materials	568
12.6	Critical Points and Thread Stresses	451	15.6	Spur Gears; Tooth Profile and Mesh Geometry	570
Chapter 13					
Machine Joints and Fastening Methods	462				
13.1	Uses and Characteristics of Joints in Machine Assemblies	462			
13.2	Selection of Joint Type and Fastening Method	462			
13.3	Potential Failure Modes	464			

Involute Profiles and Conjugate Action	570	16.3 Potential Failure Modes	661
Gearing Nomenclature; Tooth Shape and Size	572	16.4 Brake and Clutch Materials	661
Gear Tooth Systems	574	16.5 Basic Concepts for Design of Brakes and Clutches	663
Mesh Interactions	576	16.6 Rim (Drum) Brakes With Short Shoes	665
15.7 Gear Manufacturing; Methods, Quality, and Cost	579	16.7 Rim (Drum) Brakes With Long Shoes	675
Gear Cutting	580	16.8 Band Brakes	680
Gear Finishing	581	16.9 Disk Brakes and Clutches	685
Cutter Path Simulation, Mesh Deflection, and Profile Modification	582	Uniform Wear Assumption	686
Accuracy Requirements, Measurement Factors, and Manufacturing Cost Trends	584	Uniform Pressure Assumption	687
15.8 Spur Gears; Force Analysis	586	16.10 Cone Clutches and Brakes	690
15.9 Spur Gears; Stress Analysis and Design	587	Chapter 17	
Tooth Bending: Simplified Approach	588	Belts, Chains, Wire Rope, and Flexible Shafts	697
Tooth Bending: Synopsis of AGMA Refined Approach	592	17.1 Uses and Characteristics of Flexible Power Transmission Elements	697
Surface Durability: Hertz Contact Stresses and Surface Fatigue Wear	599	17.2 Belt Drives; Potential Failure Modes	701
Surface Durability: Synopsis of AGMA Refined Approach	601	17.3 Belts; Materials	703
15.10 Lubrication and Heat Dissipation	605	17.4 Belt Drives; Flat Belts	703
15.11 Spur Gears; Summary of Suggested Design Procedure	607	17.5 Belt Drives; V-Belts	707
15.12 Helical Gears; Nomenclature, Tooth Geometry, and Mesh Interaction	608	17.6 Belt Drives; Synchronous Belts	718
15.13 Helical Gears; Force Analysis	613	17.7 Chain Drives; Potential Failure Modes	719
15.14 Helical Gears; Stress Analysis and Design	614	17.8 Chain Drives; Materials	720
15.15 Helical Gears; Summary of Suggested Design Procedure	615	17.9 Chain Drives; Precision Roller Chain	721
15.16 Bevel Gears; Nomenclature, Tooth Geometry, and Mesh Interaction	621	17.10 Roller Chain Drives; Suggested Selection Procedure	723
15.17 Bevel Gears; Force Analysis	624	17.11 Chain Drives; Inverted Tooth Chain	728
15.18 Bevel Gears; Stress Analysis and Design	625	17.12 Wire Rope; Potential Failure Modes	728
15.19 Bevel Gears; Summary of Suggested Design Procedure	627	17.13 Wire Rope; Materials	731
15.20 Worm Gears and Worms; Nomenclature, Tooth Geometry, and Mesh Interaction	634	17.14 Wire Rope; Stresses and Strains	731
15.21 Worm Gears and Worms; Force Analysis and Efficiency	638	17.15 Wire Rope; Suggested Selection Procedure	734
15.22 Worm Gears and Worms; Stress Analysis and Design	640	17.16 Flexible Shafts	739
15.23 Worm Gears and Worms; Suggested Design Procedure	642	Chapter 18	
Chapter 16		Flywheels and High-Speed Rotors	746
Brakes and Clutches	658	18.1 Uses and Characteristics of Flywheels	746
16.1 Uses and Characteristics of Brakes and Clutches	658	18.2 Fluctuating Duty Cycles, Energy Management, and Flywheel Inertia	747
16.2 Types of Brakes and Clutches	659	18.3 Types of Flywheels	752
		18.4 Potential Failure Modes	753
		18.5 Flywheel Materials	753
		18.6 Spoke- and Rim-Flywheels	753
		Stresses in a Rotating Free Ring	754
		Bending Stresses in Flywheel Rim	755
		Spoke-Axial Tensile Stresses	756
		18.7 Disk Flywheels of Constant Thickness	757
		18.8 Disk Flywheels of Uniform Strength	761

xvi / Contents

18.9	Uniform-Strength Disk Flywheel with a Rim	763	19.5	Summary of Suggested Crankshaft Design Procedure	772
18.10	Flywheel-to-Shaft Connections	766			
Chapter 19			Chapter 20		
Cranks and Crankshafts		770	Completing the Machine		788
19.1	Uses and Characteristics of Crankshafts	770	20.1	Integrating the Components; Bases, Frames, and Housings	788
19.2	Types of Crankshafts	771	20.2	Safety Issues; Guards, Devices, and Warnings	795
19.3	Potential Failure Modes	772	20.3	Design Reviews; Releasing the Final Design	800
19.4	Crankshaft Materials	772			

APPENDIX

NSPE Code of Ethics for Engineers

Table A-1	Table A-4
Coefficients of Friction	Section Properties of Selected S (Standard I) Shapes
809	815
Table A-2	Table A-5
Mass Moments of Inertia <i>J</i> and Radii of Gyration <i>k</i> for Selected Homogeneous Solid Bodies Rotating About Selected Axes, as Sketched	Section Properties of Selected C (Channel) Shapes
812	816
Table A-3	Table A-6
Section Properties of Selected W (Wide Flange) Shapes	Section Properties of Selected Equal-Leg L (Angle) Shapes
813	817

INDEX

819