Contents

Acknowledgments xxii 1 **Background Matters** PART 1 3 Manufacturing Management Chapter 1 1.1 Mechanical Production 3 1.2 Industrial and Production Engineering 12 Industrial Engineering: Production Planning and Control 14 1.3 1.4 Group Technology 20 Process Planning: Computer-Aided Process Planning 24 1.5 Manufacturing Resources Planning 33 1.6 1.7 Production Scheduling, Monitoring, and Control 37 1.8 Just in Time 38 1.9 Conclusion References Questions 43 45 Chapter 2 Engineering Materials and Their Properties 2.1 Introduction 45 2.2 Mechanical Properties 46 2.2.1 The Tensile Test 2.2.2 Hardness Testing 50 Table 2.1 Comparison of Hardness Numbers 51 2.2.3 Notched Bar Impact Tests 51 2.2.4 High Temperature Tests 52 Fatigue Testing 52 2.2.5 Structures and Transformations in Metals and Alloys 53 2.3 Crystal Structures 53 2.3.1 Table 2.2 Interatomic Distances of Selected Crystals 54 Crystal Imperfections: Dislocations 2.3.2 Grain Boundaries and Deformation 56 2.3.3 Alloys: Phase Diagrams 56 2.4

Preface xix

2.4.1

2.4.2

General 56

The Fe-C Phase Diagram 60

2.5	Heat Treatment of Metals 63 2.5.1 Allotropic Metals: Steels 63 2.5.2 Phase Diagram for Al Alloys: Precipitation Hardening 67 2.5.3 Solid Solution Treatment 69 2.5.4 Summarizing Methods of Strengthening Metals 70	
2.6	Engineering Metals 71 2.6.1 Steels 71 Table 2.3 Specifications of Selected SAE-AISI Low-Alloy Steels 73 Table 2.4 Properties of the 4340 Steel 74 Table 2.5 Stainless Steels 75 Table 2.6 Tool Steels 76	
	 2.6.2 Cast Irons 76 2.6.3 Aluminum Alloys and Magnesium Alloys 78 Table 2.7 Aluminum Casting Alloys 78 Table 2.8 Wrought Aluminum Alloys 80 	
	2.6.4 Copper, Nickel, Zinc, and Their Alloys 80 Table 2.9 Selected Copper and Nickel Alloys 81 Table 2.10 Zinc Die-Casting Alloys 81	
	2.6.5 Titanium Alloys 82	
	Table 2.11 Titanium Alloys 82	
	2.6.6 Superalloys 83 Table 2.12 Superalloys 84 Table 2.13 Refractory Metals 85	
	2.6.7 Refractory Metals 84	
2.7	Plastics 85	
	2.7.1 Polymerization Methods, Bonding, and Structures 86	
	2.7.2 Additives 88	
	2.7.4 Thermoplastics 89	
	2.7.4 Thermosets 90 2.7.5 Elastomers 92	
	2.7.6 Special Applications of Polymers 92 Table 2.14 Room-Temperature, Short-Time Parameters of Selected Plastics 96	
2.8	Ceramics 96	
	Table 2.15 Hardness of Some Ceramics 97	
2.9	Composite Materials 99 Table 2.16 Mechanical Properties of GRP and CRP in Comparison with Metals 101	
	References 102	
	Questions 103	
Prima	ary Metalworking	05
3.1	Introduction: Iron and Steel Industries 105	
3.2	Blast Furnace Operations 111 3.2.1 Design of the Furnace: Inputs and Outputs 111 3.2.2 Chemistry of the Blast Furnace Reactions Table 3.1 Pig Iron Compositions 116	
	Table 3.2 Utilities Requirements of a Self-Contained Blast Furnace Plant with Two Furnaces Producing 8400 Tons of Iron Per Day 118	

PART 2

3.3

3.3.2

3.3.3

		3.3.4 Summary of Steel Production 126	
	3.4	Ingots: Continuous Casting of Slabs 127	
	3.5	Hot Forming: Open-Die Forging and Rolling 130 3.5.1 Primary Hot Rolling 131 3.5.2 Rolling Mill Configurations 134	
		Example 3.1 Specific Power in Rough Hot Rolling 138 3.5.3 Hot Forming of Tubes and Pipes 139	
	3.6	Cold Rolling of Sheet Metal 142	
	3.7	Casting 142	
		 3.7.1 Expendable Mold Processes 146 3.7.2 Permanent-Mold Casting 152 3.7.3 Casting Materials 156 	
	3.8	Aluminum: Manufacture, Use, and Processing 157 3.8.1 Manufacture and Use 157 3.8.2 Processing 160	
	3.9	Other Metals 164	
	3.10	Powder Metallurgy 165 3.10.1 The Powder 166 3.10.2 Compacting 167 3.10.3 Sintering 168	
		References 171	
		Questions 172	
Traditional I	Proce	sses	175
Chapter 4	Meta	l Forming Technology	177
•	4.1	General Operating Conditions, Machines, and Tools 177 4.1.1 Hot Forming 178 4.1.2 Cold Work and Anneal Cycle 181 Example 4.1 Combining Cold Work and Annealing for Desired Material Properties 184	
	4.2	Basic Machines for Metal Forming 185 Table 4.1 Ratings of Forging Hammers 190 Table 4.2 Parameters of Presses 193 Example 4.2 Kinematics of a Crank Mechanism 194 Example 4.3 The Crank and Toggle Mechanism 196 Example 4.4 Work Done in a Forging Hammer 197 Example 4.5 Energy of a Hammer Strike Lost in the Motion of the Anvil 198 Example 4.6 Slowdown of the Flywheel in a Punching Operation	199
	4.3	Forging 201 4.3.1 Open-Die Forging (ODF) 201	

Steel-Making Furnace Operations 119
3.3.1 The Open-Hearth (OH) Process 119

Electric Furnaces 124

Basic Oxygen Furnace (BOF) 122

		4.3.6	Forgeability of Metals 217	
	4.4	Sheet I	Metal Forming 218	
		4.4.1	Basic Operations and Presses 218	
		4.4.2	Automation of Presswork 223	
		4.4.3	Press Brake Work 229	
		4.4.4	Cold Roll Forming 230	
		4.4.5	Formability of Sheet Metals 232	
	4.5	Numer	ical Control (NC) in Metal Forming 236	
		4.5.1	Numerically Controlled (NC) Bending on a Press Brake 236	
		4.5.2	NC Turret Punch Presses 237	
		Refere	nces 240	
		Questio	ons 241	
Chapter 5	Meta	l Formir	ng Mechanics	2.42
onapter c	5.1			242
	J.1	5.1.1	ntary Concepts 242 The Stress-Strain Diagram 243	
		5.1.2		
		5.1.3		
		5.1.4	Special Cases of Yielding 251	
	5.2		orming: Basic Approach—Forces, Pressures 253	
	J.2	5.2.1	Wire Drawing: Work, Force, and Maximum Reduction Without Friction 253	
		5.2.2	W' D ' D	254
		5.2.3	Wire Drawing with Friction 255	231
			Example 5.1 Wire Drawing with Friction: Solution by	
			Discrete Integration 255	
		5.2.4	Extruding a Round Bar 258	
		5.2.5	Rolling with Back and Forward Tension: Plane-Strain Yielding	258
	5.3		orming: Effects of Redundant Work and of Friction 260	
		5.3.1	Nonhomogeneous Deformation: Redundant Work 260	
		5.3.2	The Effect of Friction in Plane Strain 266	
			Example 5.2 Determine p_{max} and p_{av} for Plane-Strain Compression U	
			the Combined Conditions of Dry Friction and of Friction	n
		500	Shear Flow 270	
		5.3.3	Effect of Friction in Upsetting a Cylindrical Workpiece 273 Example 5.3 Using a Gravity Hammer for Cold Upsetting of a Cylindrical Workpiece 276	
		5.3.4	Summary of the Effects of Friction and Redundant Work 280	
		5.3.5	Force and Neutral Point in Cold Rolling 282	
			Example 5.4 Compute the Pressures and Forces in Rolling 286	
		5.3.6	Material Failure in Bulk Forming 288	

4.3.2

4.3.3

4.3.4

4.3.5

Roll Forging 204

Extrusion 215

Closed-Die Forging (CDF) 205 Hot and Cold Upsetting 209

 Table 4.3
 Principal Parameters of Hot Upsetting Machines
 211

5.4	-	s of Plate- and Sheet-Metal Forming 290
	5.4.1	
	5.4.2	Control of the contro
		Example 5.5 Determine the Shape of the Deformation of a Plate Loaded in
		the Middle Between Supports 297
	5 1 2	Table 5.1 The Coordinates of the Deflection Curve 298
	5.4.3	Residual Stresses 299
	5.4.4	Failures and Limitations in Bending 302
	5.4.6	Table 5.2 Smallest Radii in Bending (ρ_{min}/h) 303 Drawing of a Non-Strain-Hardening Material 306
	5.4.7	Radial Drawing of a Strain-Hardening Material 308
	3.4.7	Example 5.6 Compute the Variation of the Radial Drawing Stress for a
		Strain-Hardening Material 311
5.5	Chatter	in Cold Rolling 312
5.5	5.5.1	A Simple Rolling Chatter Theory 312
		ices 317
	_	ns 317
	Problen	ns 318
Proce	essing of	Polymers 32-
6.1	Introdu	ction: Properties Used in Processing 324
6.2		ry of Selected Polymers 325
0.2		Table 6.1 U.S. Sales of Most Common Polymers 326
	6.2.1	Thermoplastics 330
	6.2.2	Thermosets 332
	6.2.3	Elastomers 332
6.3	Therma	ll Properties: Viscosity 333
		Table 6.2 Processing Parameters of Thermoplastics 335
		Table 6.3 Thermal Properties of Polymers 336
	6.3.1	Newtonian Flow in a Rectangular Channel (Slit) 337
	6.3.2	Non-Newtonian, Power-Law Flow in a Flat Channel 340
		Example 6.1 Newtonian and Non-Newtonian Flow in a Flat Channel 341
		Example 6.2 Viscous Heat Generation 345
	6.3.3	Example 6.3 Is the Flow in Example 6.1 (b2) Laminar? 345 Flow in a Tube 345
6.1		
6.4	6.4.1	sing Methods and Operations 347 General Considerations 347
	6.4.2	Casting 348
	6.4.3	Compression (CM) and Transfer Molding (TM) 349
	6.4.4	Extrusion 349
	6.4.5	Injection Molding (IM) 356
	6.4.6	Thermoforming 364
6.5		is of the Plasticating Screw 366
6.6		
0.0	6.6.1	sing of Polymer-Based Composites 368 Preforms 368
	6.6.2	Hand Lay-Up and Spray-Up Molding 370
	6.6.2	

Chapter 7	Cutti	ing Technology	377
	7.1	Introduction 377	
	7.2	Single-Point Tool Operations 378	
		7.2.1 Metal Removal Rate: Cutting Force 379	
		Example 7.1 Metal Removal Rate in Turning 379	
		Table 7.1 Specific Force and Power for Selected Workpiece Materials	380
		7.2.2 The Tools 381	
	7.0	7.2.3 The Machine Tools 386	
	7.3	Drilling and Allied Operations 390	
		7.3.1 Metal Removal Rate: Force, Torque, and Power 393 7.3.2 Drilling Machines 394	
	7.4	8	
	7.4	Multipoint Tool Operations: Milling 396	
		7.4.1 Mean Chip Thickness, MRR, and Power 398	
		Example 7.2 Mean Chip Thickness in Milling 401 Example 7.3 Power in Face Milling 402	
		7.4.2 Design of Milling Cutters 402	
		7.4.3 Milling Machines 405	
	7.5	Broaching 408	
		References 412	
		Questions 413	
		Problems 413	
		1100101115 415	
Chapter 8	Cutti	ing Mechanics	415
	8.1	The Cutting Force 416	413
	0.1	8.1.1 Chip Generation 418	
		Example 8.1 Shearing and Friction Power in Chip Formation 424	
		Example 8.2 Strain and Strain Rate in Chip Formation 425	
		8.1.2 Simplified Formulations 425	
	8.2	Temperature Field in the Chip and in the Tool 427	
		8.2.1 Shear Plane Temperature 427	
		Table 8.1 Mechanical and Thermal Properties of Selected	
		Workpiece Materials 428	
		8.2.2 Computing the Temperature Field 431	
		Example 8.3 Compute Temperature Fields for a Particular Case 436 Example 8.4 Compute Temperature Fields for Four	
		Different Materials 440	
	8.3	Cutting-Tool Materials 443	
		Table 8.2 Usage of Different Tool Materials (1997) 445	
		Table 8.3 Hardness and Melting Temperature of	
		Tool-Material Constituents 447	
		8.3.1 High-Speed Steels 447	

6.6.4

References 375
Questions 375
Problems 376

Pultrusion 374

PART 3

8.3.2

Sintered Carbides 450

		8.3.3 Ceramic Tools 455	
	0 1	8.3.4 Borazon and Polycrystalline Diamond 456	50
	8.4	Tool Wear: Choice of Cutting Conditions, Machinability of Materials 45 8.4.1 Tool Wear 458	10
		8.4.2 Tool Wear Rate and Tool Life 462	
		Example 8.5 Determine the Parameters of the Tool Life Equation 46.	3
		8.4.3 Optimizing Cutting Speed and Feed in a Single Cut Operation:	
		Taylor-Type Tool Life Equation 465	
		8.4.4 Optimizing Cutting Speed and Feed in a Single Cut Operation: T Life Equation Non-Taylor-Type 468	lool
		8.4.5 Optimizing Speeds and Feeds for a Multi-Tool Operation: Tool I	Life
		Equation of the Taylor Type 469 Example 8.6 Optimize Speeds and Feeds for a Multitool Operation	
		According To Figure 8.44 471	
		Example 8.7 How Does the Number of Tools Cutting Simultaneously Affect Optimum Speed and Optimum Tool Life? 473	
		8.4.6 General Conclusions for the Choice of Cutting Speeds and Feeds Table 8.6 Parameters Used in Cutting Data Banks 476	475
	8.5	Tool Breakage: Wear and Breakage in Milling 477	
		8.5.1 Breakage in Continuous Cutting 477	
		8.5.2 Tool Wear and Breakage in Interrupted Cutting 481 8.5.3 Flank Wear in Milling 483	
		2	
		References 486	
		Questions 486	
		Problems 488	
Machine To	ols		493
Chapter 9	Desi	gn of Machine Tools: Drives and Structures	495
	9.1	General Description of Machine-Tool Design 495	
	9.2	Specifying the Characteristics of Main Drives 501 Example 9.1 Drive Characteristics 504	
	9.3	Accuracy of Machine Tools 506	
		9.3.1 Geometric Accuracy: Machine Tool Metrology 507 Example 9.2 Determining Errors at Offsets 513	
		9.3.2 Weight Deformations 516	
		9.3.3 Deformations Under Cutting Forces 519 Example 9.3 Copying of Form Error of Workpiece 523	
	9.4	Review of Fundamentals of Mechanical Vibrations 525	
		9.4.1 Vibrations: Natural, Forced, Self-Excited 525	
		9.4.2 Harmonic Variables 527	
		9.4.3 Basics of Vibrations: Transfer Function of a System with a Singl	le
		Degree of Freedom 529	

 Table 8.4
 Compositions and Properties of Selected High-Speed Steels
 449

 Table 8.5
 Classification of Sintered Carbides
 454

	9.4.4	Transfer Functions of a Selected System with Two Degrees of
		Freedom: Uncoupled Modes in Two Directions 532
		Example 9.4 Forced Vibration of a System with Two Uncoupled Modes in a Plane 533
		Example 9.5 Determine the Transfer Function (Y/F) for a System with Two Uncoupled Modes in a Plane 534
9.5	Forces	and Forced Vibrations in Milling 537
	9.5.1	Accuracy of End Milling: Straight Teeth, Static Deflection 537
	9.5.2	The Dynamics: Forced Vibrations, Straight Teeth 538
		Example 9.6 Variation of Fx and Fy Forces on Cutters with Straight Teeth 539
	9.5.3	Forced Vibrations and Their Imprint as Error of Location of the
		Machined Surface 542
		Example 9.7 Slotting with a Two-Fluted Cutter: Resonant Vibration 542
		Example 9.8 Slotting with a Two-Fluted Cutter, Nonresonant Conditions 544
		Example 9.9 Up-Milling with a Four-Fluted Cutter with Straight Teeth:
	0 7 4	Only One Tooth in Cut; Forces and Deflections 545
	9.5.4	Forces on End Mills with Helical Teeth 548
		Example 9.10 Forces in Milling with Helical Teeth 551
		Example 9.11 Prove that the Cutting Force on a Four-Fluted Cutter in
		Slotting Is Constant 553 Example 9.12 Show that at Certain Axial Depths of Cut the Milling Force
		Example 9.12 Show that at Certain Axial Depths of Cut the Milling Force Is Constant 555
	9.5.5	Errors of Surface Produced by End Mills with Helical Teeth:
		Static Deflections 556
9.6	Chatte	in Metal Cutting 559
	9.6.1	General Features 559
	9.6.2	Mechanisms of Self-Excitation in Metal Cutting 560
	9.6.3	The Condition for the Limit of Stability of Chatter 563
	9.6.4	Analyzing Stability of a Boring Bar 565
	9.6.5	Another Way of Deriving the Limit of Stability, Using the
		Nyquist Criterion 568
	9.6.6	Time Domain Simulation of Chatter in Turning 570
		Example 9.13 Simulation of Chatter in Turning 573
	9.6.7	Chatter in Milling 575
9.7	Design	ing Machine-Tool Structures for High Stability 579
9.8		of Cutting Conditions on Stability 586
9.9		udy: High-Speed Milling (HSM) Machine for Aluminum
	Aircraf	t Parts 594
	9.9.1	High Speed Milling in General: Operations with a Lack
		of Stiffness 594
	9.9.2	Developing HSM Machine for Aluminum Aircraft Parts 598
	Referen	
	Questic	ns 605
	Probler	ns 606

10.1 Automation of Machine Tools 613 Table 10.1 Actions to Automate and Devices to Use 613 10.1.1 Rigid and Flexible Automation 616 10.2 Machine Tools with Rigid Automation 618 10.2.1 Single-Spindle Automatic Lathes 618 10.2.2 Multispindle Automatic Lathes 622 10.2.3 Dial-Index Machines and Transfer Lines 625 10.3 Numerically Controlled Machine Tools 628 10.3.1 Basic Operation 628 10.3.2 Adaptive Control 633 10.3.3 Turning Centers 634 10.3.4 Machining Centers 635 10.5 Positional Servomechanism: Review 647 10.5.1 Characteristics of the Servomotor 648 10.5.2 Step Input Response of the Servomotor 650 10.5.3 Time-Domain Simulation of the Servomotor 653 10.5.4 The Positional Servomechanism 654 10.5.5 Step Input Response of the Positional Servo 656 10.5.6 Time-Domain Simulation of the Positional Servo 657 Example 10.1 Performance of Positional Servo 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.5 Response to a Ramp Input of the Positional Servo 659 10.5 Response to a Ramp Input of the Positional Servo 659 10.5 Response to a Ramp Input of the Positional Servo 659 10.5 Response to a Ramp Input of the Positional Servo 659 10.5 Response to a Ramp Input of the Positional Servo 659 10.5 Response to a Ramp Input of the Positional Servo 659 10.5 Response to a Ramp Input of the Positional Servo 659 10.5 Response to a Ramp Input of the Positional Servo 659 10.5 Response to a Ramp Input of the Positional Servo 659 10.5 Response to a Ramp Input of the Adaptive Control 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The *Machine Tool* Case with SMD System in the Feedback Loop: MT/A 683	Autor	nation	611
10.2 Machine Tools with Rigid Automation 618 10.2.1 Single-Spindle Automatic Lathes 618 10.2.2 Multispindle Automatic Lathes 622 10.2.3 Dial-Index Machines and Transfer Lines 625 10.3.1 Basic Operation 628 10.3.2 Adaptive Control 633 10.3.3 Turning Centers 634 10.3.4 Machining Centers 635 10.5 Computerized, Flexible Manufacturing Systems 639 10.5.1 Characteristics of the Servomotor 648 10.5.2 Step Input Response of the Servomotor 650 10.5.3 Time-Domain Simulation of the Servomotor 653 10.5.4 The Positional Servomechanism 654 10.5.5 Step Input Response of the Positional Servo 656 10.5.6 Time-Domain Simulation of the Positional Servo 657 Example 10.1 Performance of Positional Servo 658 Table 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.5 Errors of Two-Dimensional Tool Path 661 Example 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.3 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8 Positional Servo Driving a Spring-Mass System 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683	10.1		tion of Machine Tools 613 Table 10.1 Actions to Automate and Devices to Use 613
10.2.1 Single-Spindle Automatic Lathes 618 10.2.2 Multispindle Automatic Lathes 622 10.2.3 Dial-Index Machines and Transfer Lines 625 10.3 Numerically Controlled Machine Tools 628 10.3.1 Basic Operation 628 10.3.2 Adaptive Control 633 10.3.3 Turning Centers 634 10.3.4 Machining Centers 635 10.4 Computerized, Flexible Manufacturing Systems 639 10.5 Positional Servomechanism: Review 647 10.5.1 Characteristics of the Servomotor 648 10.5.2 Step Input Response of the Servomotor 650 10.5.3 Time-Domain Simulation of the Servomotor 653 10.5.4 The Positional Servomechanism 654 10.5.5 Step Input Response of the Positional Servo 656 10.5.6 Time-Domain Simulation of the Positional Servo 657 Example 10.1 Performance of Positional Servo 658 Table 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.5.8 Table 10.2 Parameters of the Four Test Cases 659 10.5.9 Response to a Ramp Input of the Positional Servo 659 10.5.1 Characteristics of the Central Servo 659 10.5.2 Response to a Ramp Input of the Positional Servo 659 10.5.3 Time-Domain Simulation of the Positional Servo 659 10.5.4 The Velocity Lag 661 Example 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.5 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8 Positional Servo Driving a Spring-Mass System 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683		10.1.1	Rigid and Flexible Automation 616
10.2.2 Multispindle Automatic Lathes 622 10.2.3 Dial-Index Machines and Transfer Lines 625 10.3.1 Numerically Controlled Machine Tools 628 10.3.2 Adaptive Control 633 10.3.3 Turning Centers 634 10.3.4 Machining Centers 635 10.4 Computerized, Flexible Manufacturing Systems 639 10.5 Positional Servomechanism: Review 647 10.5.1 Characteristics of the Servomotor 648 10.5.2 Step Input Response of the Servomotor 650 10.5.3 Time-Domain Simulation of the Servomotor 653 10.5.4 The Positional Servomechanism 654 10.5.5 Step Input Response of the Positional Servo 656 10.5.6 Time-Domain Simulation of the Positional Servo 657 Example 10.1 Performance of Positional Servos 658 Table 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.5.8 Table 10.2 Parameters of the Four Test Cases 659 10.5.9 Response to a Ramp Input of the Positional Servo 659 10.6 Errors of Two-Dimensional Tool Path 661 Example 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.7 Limit of Stability of the Adaptive Control System 677 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Specifications: MT and ROB 681 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683	10.2	Machin	e Tools with Rigid Automation 618
10.2.3 Dial-Index Machines and Transfer Lines 625 10.3 Numerically Controlled Machine Tools 628 10.3.1 Basic Operation 628 10.3.2 Adaptive Control 633 10.3.3 Turning Centers 634 10.3.4 Machining Centers 635 10.4 Computerized, Flexible Manufacturing Systems 639 10.5 Positional Servomechanism: Review 647 10.5.1 Characteristics of the Servomotor 648 10.5.2 Step Input Response of the Servomotor 650 10.5.3 Time-Domain Simulation of the Servomotor 653 10.5.4 The Positional Servomechanism 654 10.5.5 Step Input Response of the Positional Servo 656 10.5.6 Time-Domain Simulation of the Positional Servo 657 Example 10.1 Performance of Positional Servo 657 Example 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.6 Errors of Two-Dimensional Tool Path 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control System 677 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683		10.2.1	Single-Spindle Automatic Lathes 618
10.3 Numerically Controlled Machine Tools 628 10.3.1 Basic Operation 628 10.3.2 Adaptive Control 633 10.3.3 Turning Centers 634 10.3.4 Machining Centers 635 10.4 Computerized, Flexible Manufacturing Systems 639 10.5 Positional Servomechanism: Review 647 10.5.1 Characteristics of the Servomotor 648 10.5.2 Step Input Response of the Servomotor 650 10.5.3 Time-Domain Simulation of the Servomotor 653 10.5.4 The Positional Servomechanism 654 10.5.5 Step Input Response of the Positional Servo 656 10.5.6 Time-Domain Simulation of the Positional Servo 657 Example 10.1 Performance of Positional Servos 658 Table 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.5.8 Table 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7.1 Analysis of Stability 674 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683		10.2.2	Multispindle Automatic Lathes 622
10.3.1 Basic Operation 628 10.3.2 Adaptive Control 633 10.3.3 Turning Centers 634 10.3.4 Machining Centers 635 10.4 Computerized, Flexible Manufacturing Systems 639 10.5 Positional Servomechanism: Review 647 10.5.1 Characteristics of the Servomotor 648 10.5.2 Step Input Response of the Servomotor 650 10.5.3 Time-Domain Simulation of the Servomotor 653 10.5.4 The Positional Servomechanism 654 10.5.5 Step Input Response of the Positional Servo 656 10.5.6 Time-Domain Simulation of the Positional Servo 657 Example 10.1 Performance of Positional Servo 658 Table 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.5.8 Ramp Input 661 Example 10.1 The Velocity Lag 661 Example 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683		10.2.3	Dial-Index Machines and Transfer Lines 625
10.3.1 Basic Operation 628 10.3.2 Adaptive Control 633 10.3.3 Turning Centers 634 10.3.4 Machining Centers 635 10.4 Computerized, Flexible Manufacturing Systems 639 10.5 Positional Servomechanism: Review 647 10.5.1 Characteristics of the Servomotor 648 10.5.2 Step Input Response of the Servomotor 650 10.5.3 Time-Domain Simulation of the Servomotor 653 10.5.4 The Positional Servomechanism 654 10.5.5 Step Input Response of the Positional Servo 656 10.5.6 Time-Domain Simulation of the Positional Servo 657 Example 10.1 Performance of Positional Servo 658 Table 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.5.8 Rample 10.1 The Velocity Lag 661 Example 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8 Positional Servo Driving a Spring-Mass System 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683	10.3	Numeri	cally Controlled Machine Tools 628
10.3.3 Turning Centers 634 10.3.4 Machining Centers 635 10.4 Computerized, Flexible Manufacturing Systems 639 10.5 Positional Servomechanism: Review 647 10.5.1 Characteristics of the Servomotor 648 10.5.2 Step Input Response of the Servomotor 650 10.5.3 Time-Domain Simulation of the Servomotor 653 10.5.4 The Positional Servomechanism 654 10.5.5 Step Input Response of the Positional Servo 656 10.5.6 Time-Domain Simulation of the Positional Servo 657 Example 10.1 Performance of Positional Servo 658 Table 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 Errors of Two-Dimensional Tool Path 661 Example 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683			
10.3.4 Machining Centers 635 10.4 Computerized, Flexible Manufacturing Systems 639 10.5 Positional Servomechanism: Review 647 10.5.1 Characteristics of the Servomotor 648 10.5.2 Step Input Response of the Servomotor 650 10.5.3 Time-Domain Simulation of the Servomotor 653 10.5.4 The Positional Servomechanism 654 10.5.5 Step Input Response of the Positional Servo 656 10.5.6 Time-Domain Simulation of the Positional Servo 657 Example 10.1 Performance of Positional Servos 658 Table 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.6 Errors of Two-Dimensional Tool Path 661 Example 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8 Positional Servo Driving a Spring-Mass System 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683		10.3.2	Adaptive Control 633
10.4 Computerized, Flexible Manufacturing Systems 639 10.5 Positional Servomechanism: Review 647 10.5.1 Characteristics of the Servomotor 648 10.5.2 Step Input Response of the Servomotor 650 10.5.3 Time-Domain Simulation of the Servomotor 653 10.5.4 The Positional Servomechanism 654 10.5.5 Step Input Response of the Positional Servo 656 10.5.6 Time-Domain Simulation of the Positional Servo 657 Example 10.1 Performance of Positional Servo 658 Table 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.6 Errors of Two-Dimensional Tool Path 661 Example 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683		10.3.3	Turning Centers 634
10.5 Positional Servomechanism: Review 647 10.5.1 Characteristics of the Servomotor 648 10.5.2 Step Input Response of the Servomotor 650 10.5.3 Time-Domain Simulation of the Servomotor 653 10.5.4 The Positional Servomechanism 654 10.5.5 Step Input Response of the Positional Servo 656 10.5.6 Time-Domain Simulation of the Positional Servo 657 Example 10.1 Performance of Positional Servo 658 Table 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.6 Errors of Two-Dimensional Tool Path 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8 Positional Servo Driving a Spring-Mass System 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683		10.3.4	Machining Centers 635
10.5.1 Characteristics of the Servomotor 648 10.5.2 Step Input Response of the Servomotor 650 10.5.3 Time-Domain Simulation of the Servomotor 653 10.5.4 The Positional Servomechanism 654 10.5.5 Step Input Response of the Positional Servo 656 10.5.6 Time-Domain Simulation of the Positional Servo 657 Example 10.1 Performance of Positional Servo 658 Table 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.6 Errors of Two-Dimensional Tool Path 661 Example 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8 Positional Servo Driving a Spring-Mass System 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683	10.4	Comput	terized, Flexible Manufacturing Systems 639
10.5.2 Step Input Response of the Servomotor 650 10.5.3 Time-Domain Simulation of the Servomotor 653 10.5.4 The Positional Servomechanism 654 10.5.5 Step Input Response of the Positional Servo 656 10.5.6 Time-Domain Simulation of the Positional Servo 657 Example 10.1 Performance of Positional Servo 658 Table 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.6 Errors of Two-Dimensional Tool Path 661 Example 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7.1 Analysis of Stability 674 Example 10.7 Limit of Stability 674 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683	10.5	Position	nal Servomechanism: Review 647
10.5.3 Time-Domain Simulation of the Servomotor 653 10.5.4 The Positional Servomechanism 654 10.5.5 Step Input Response of the Positional Servo 656 10.5.6 Time-Domain Simulation of the Positional Servo 657 Example 10.1 Performance of Positional Servo 658 Table 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.6 Errors of Two-Dimensional Tool Path 661 Example 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7.1 Analysis of Stability 674 Example 10.7 Limit of Stability of the Adaptive Control System 677 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683		10.5.1	Characteristics of the Servomotor 648
10.5.4 The Positional Servomechanism 654 10.5.5 Step Input Response of the Positional Servo 656 10.5.6 Time-Domain Simulation of the Positional Servo 657 Example 10.1 Performance of Positional Servos 658 Table 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.6 Errors of Two-Dimensional Tool Path 661 Example 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8 Positional Servo Driving a Spring-Mass System 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683		10.5.2	Step Input Response of the Servomotor 650
10.5.5 Step Input Response of the Positional Servo 656 10.5.6 Time-Domain Simulation of the Positional Servo 657 Example 10.1 Performance of Positional Servos 658 Table 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.6 Errors of Two-Dimensional Tool Path 661 Example 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.7 Limit of Stability of the Adaptive Control System 677 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8 Positional Servo Driving a Spring-Mass System 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683		10.5.3	Time-Domain Simulation of the Servomotor 653
10.5.6 Time-Domain Simulation of the Positional Servo 657 Example 10.1 Performance of Positional Servos 658 Table 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.6 Errors of Two-Dimensional Tool Path 661 Example 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8 Positional Servo Driving a Spring-Mass System 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683		10.5.4	The Positional Servomechanism 654
Example 10.1 Performance of Positional Servos 658 Table 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.6 Errors of Two-Dimensional Tool Path 661 Example 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683		10.5.5	Step Input Response of the Positional Servo 656
Table 10.2 Parameters of the Four Test Cases 659 10.5.7 Response to a Ramp Input of the Positional Servo 659 10.6 Errors of Two-Dimensional Tool Path 661 Example 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.7 Limit of Stability of the Adaptive Control System 677 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8 Positional Servo Driving a Spring-Mass System 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683		10.5.6	Time-Domain Simulation of the Positional Servo 657
10.5.7 Response to a Ramp Input of the Positional Servo 659 10.6 Errors of Two-Dimensional Tool Path 661			Example 10.1 Performance of Positional Servos 658
10.6 Errors of Two-Dimensional Tool Path 661 Example 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.7 Limit of Stability of the Adaptive Control System 677 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683			
Example 10.2 The Velocity Lag 661 Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.7 Limit of Stability of the Adaptive Control System 677 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683		10.5.7	Response to a Ramp Input of the Positional Servo 659
Example 10.3 Ramp Input Response: Overshoot on Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.7 Limit of Stability of the Adaptive Control System 677 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683	10.6	Errors o	
Stopping a Motion 662 Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.7 Limit of Stability of the Adaptive Control System 677 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683			
Example 10.4 Two-Coordinate Motions: Corner Motion 664 Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.7 Limit of Stability of the Adaptive Control System 677 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683			1 1
Example 10.5 Effect of the Dead Zone 666 Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.7 Limit of Stability of the Adaptive Control System 677 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8 Positional Servo Driving a Spring-Mass System 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683			11 0
Example 10.6 Distortions of a Continuous Path 667 10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.7 Limit of Stability of the Adaptive Control System 677 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8 Positional Servo Driving a Spring-Mass System 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683			
10.7 Adaptive Control for Constant Force in Milling 674 10.7.1 Analysis of Stability 674 Example 10.7 Limit of Stability of the Adaptive Control System 677 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8 Positional Servo Driving a Spring-Mass System 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683			
10.7.1 Analysis of Stability 674 Example 10.7 Limit of Stability of the Adaptive Control System 677 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8 Positional Servo Driving a Spring-Mass System 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683	10.7	Adaptiv	
Example 10.7 Limit of Stability of the Adaptive Control System 677 Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8 Positional Servo Driving a Spring-Mass System 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683	10.7		
Example 10.8 Simulation of a Stable and an Unstable A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8 Positional Servo Driving a Spring-Mass System 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683		10.7.1	
A/C System 678 10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8 Positional Servo Driving a Spring-Mass System 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683			
10.7.2 Summary of Analyses of Numerical and Adaptive Control 681 10.8 Positional Servo Driving a Spring-Mass System 681 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683			
 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683 		10.7.2	
 10.8.1 Two Basic Specifications: MT and ROB 681 10.8.2 The Two Basic Alternatives, A and B 682 10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683 	10.8	Position	al Servo Driving a Spring-Mass System 681
10.8.3 The "Machine Tool" Case with SMD System in the Feedback Loop: MT/A 683			
MT/A 683		10.8.2	The Two Basic Alternatives, A and B 682
		10.8.3	The "Machine Tool" Case with SMD System in the Feedback Loop:
Example 10.9 Limit of Stability: The "Machine Tool" Case: MT/A 685			
Example 10.10 Response To a Ramp Command of the Case MT/A (SMD System in the Loop) 687			
10.8.4 Flexibility Outside of the Loop: Case MT/B 687		10.8.4	
10.8.5 The "Robot" Case with SMD System within the Loop: ROB/A 689			

Example 10.11 Limit of Stability of the Robot Case: ROB/A 689

		Example 10.12 Using Accelerometer Feedback 692 Example 10.13 The "Robot Arm": Configuration B 693	1
	10.9	Feedforward Compensation 694	
		10.9.1 Ideal Servodrive 694	
		10.9.2 Real Servodrive 697	
		Example 10.14 Feedforward Compensation in One Coordinate 700	
		10.9.3 Numerical Derivation of the Feedforward Compensation 701 Example 10.15 Using Numerical Derivation of the Feedforward Com	
		Motion in One Coordinate 703	manu.
		Example 10.16 Feedforward Compensation for Constant Jerk Motion	704
	10.10	Simplified Robot Kinematics and Dynamics 709	
		10.10.1 Introduction: Types of Robots and Their Uses 709	
		10.10.2 Simplified Kinematics 715	
		10.10.3 Dynamics of the 2D Polar Case 717	0
	10.11	Example 10.17 Feedforward Compensation in Two Dimensions 716	8
	10.11		
		References 724	
		Questions 724	
		Problems 725	
PART 4 Assembly a	and No	ntraditional Processes	733
Chanton 11	Accor	nhly Matarial Handling and Walding	72
Chapter 11		mbly: Material Handling and Welding	73:
	11.1	Introduction 735	
	11.2	Material Handling 737	
	11.3	Mechanical Joining 743	
	11.4	Assembly 746	
	11.5	Design for Assembly 756	
	11.6	Welding Processes 757	
		11.6.1 Introduction 757	
		11.6.2 Oxyacetylene Welding 762	
		11.6.3 Arc Welding Processes 764 11.6.4 Other Welding Processes 775	
	11.7		
	11.7	Control of the Arc 784 11.7.1 Melting Rates 784	
		Table 11.1 Melting Rate Coefficients 785	
		11.7.2 Self Regulation of the Arc in SMAW and GMAW 787	
		Example 11.1 SMAW, GMAW, SAW. Step Change Δh 791	
		Example 11.2 Step Change Δf : GMAW, Const $e = 792$	
		11.7.3 Servo Control in SAW 793	
		Example 11.3 Servo Control of SAW 795	
		Example 11.4 Servo Control of SAW: Effect of a Change of the	
		Gap Δh 799 11.7.4 Time Domain Simulation 799	
		Example 11.5 Servo Control of SAW 800	

11.8	Heat Transfer in Arc Welding 803 11.8.1 Continuous Field Solution: Thick Plate Formulation 803 Example 11.6 Temperature Profile Along the <i>Y</i> -Axis 805
	Example 11.7 Temperature Profiles for Three Different Materials 806
	Table 11.2 Thermal Parameters of Three Materials 806 Example 11.8 Heat Input Versus Welding Speed for Three Materials 808
	11.8.2 Gradients: Cooling Rates 809
	11.8.3 The 2D Case: The "Thin Plate" Line Heat Source q" 810 Example 11.9 Temperature Profiles for the Thin Plate 811
	Example 11.10 Heat Energy per Unit Length Versus Welding Speed for the Thin Plate 812
	11.8.4 The Finite Difference Approach: Thin Plate (2D) 813 Example 11.11 Using the Finite-Difference Method to Compute Temperature Fields 816
11.9	Residual Stresses and Distortions 822
	References 828
	Questions 829 Problems 830
	Problems 830
Nontra	aditional Processes 833
12.1	Introduction 833
12.2	Ultrasonic Machining (USM) 836
12.3	Water Jet Cutting (WJC) 838 Table 424 Performance of WJC for Various Meterials 820
12.4	Table 12.1 Performance of WJC for Various Materials 839 Electrochemical Machining (ECM) 839
12.7	12.4.1 Metal Removal Rate: Working Gap 841
	Table 12.2 Specific Volume V_s for Selected Materials 842
	Example 12.1 Transient Gap in ECM 844 Example 12.2 Electrolyte Flow 845
12.5	Chemical Machining (CHM), Photochemical Machining (PCM) 853 Table 12.3 Maskants and Etchants 854
12.6	Electro-Discharge Machining (EDM) 859
	Table 12.4 Comparison of Dielectric Fluids for Brass Electrodes and Tool-Steel Workpieces 861
10.7	Table 12.5 Comparison of Tool Materials 861
12.7	Laser Beam Machining (LBM) 864 Table 12.6 Operational Comparison of CO ₂ , Nd:YAG, and Excimer Lasers 868
	Example 12.3 Power in Laser Drilling 868
	Table 12.7 Physical and Thermal Properties of Selected Metals 869Table 12.8 High-Power Laser Cutting 875
12.8	Electron Beam Machining (EBM) 875
	Table 12.9 Holes Drilled by EBM in Various Materials 877 Table 12.10 Slot Cutting by EBM in Various Materials 877
	Example 12.4 Power in EBM Cutting 877
12.9	Oxygen Cutting (OC) 879
12.10	Plasma Arc Cutting (PAC) 881

- 12.11 Electronics Manufacturing 882
- 12.12 Additive CNC Manufacturing (Rapid Prototyping) 889
 12.12.1 Rapid Modeling 890
 12.12.2 Rapid Tooling 897
- 12.13 Conclusion 903
 References 904
 Questions 905
 Problems 907
 Index 909