Table of Contents

Preface	e v	CHAPTER 3
		Block Diagrams and Signal-Flow Graphs 44
	APTER 1	3-1 Block Diagrams 44
Introdu	uction 1	3-1-1 Block Diagrams of Control Systems 45
1-1	Introduction 1	3-1-2 Block Diagrams and Transfer Functions of
	1-1-1 Basic Components of a Control System 2	Multivariable Systems 46
	1-1-2 Examples of Control-System	3-2 Signal-Flow Graphs (SFGs) 48
	Applications 2	3-2-1 Basic Elements of an SFG 49
	1-1-3 Open-Loop Control Systems (Nonfeedback Systems) 6	3-2-2 Summary of the Basic Properties of SFG 50
	1-1-4 Closed-loop Control Systems (Feedback	3-2-3 Definitions of SFG Terms 51
	Control Systems) 7	3-2-4 SFG Algebra 53
1-2	What is Feedback and What are its Effects? 8	3-2-5 SFG of a Feedback Control System 54
12	1-2-1 Effect of Feedback on Overall Gain 8	3-2-6 Gain Formula for SFG 54
	1-2-2 Effect of Feedback on Stability 9	3-2-7 Application of the Gain Formula between
	1-2-3 Effect of Feedback on External	Output Nodes and Noninput Nodes 56
	Disturbance or Noise 10	3-2-8 Application of the Gain Formula to Block
1-3	Types of Feedback Control Systems 11	Diagrams 57
	1-3-1 Linear versus Nonlinear Control	3-3 State Diagram 58
	Systems 11	3-3-1 From Differential Equations to State
	1-3-2 Time-Invariant versus Time-Varying	Diagram 59
	Systems 12	3-3-2 From State Diagram to Transfer
1-4	Summary 15	Function 61
		3-3-3 From State Diagram to State and Output
► CHA	APTER 2	Equations 61
Mathe	matical Foundation 16	3-4 MATLAB Tools and Case Studies 63
2-1	Introduction 16	3-5 Summary 65
2-1	Laplace Transform 17	,
2-2	2-2-1 Definition of the Laplace Transform 17	▶ CHAPTER 4
	2-2-2 Inverse Laplace Transformation 18	Modeling of Physical Systems 77
	2-2-3 Important Theorems of the Laplace	
	Transform 19	4-1 Introduction 77
2-3	Inverse Laplace Transform by Partial-Fraction	4-2 Modeling of Electrical Networks 77
2-3	Expansion 21	4-3 Modeling of Mechanical Systems Elements 80 4-3-1 Translational Motion 80
	2-3-1 Partial-Fraction Expansion 22	
2-4	Application of the Laplace Transform to the Solution	4-3-2 Rotational Motion 83 4-3-3 Conversion Between Translational and
2 7	of Linear Ordinary Differential Equations 25	****
2-5	Impulse Response and Transfer Functions of Linear	Rotational Motions 85
	Systems 27	4-3-4 Gear Trains 86 4-3-5 Backlash and Dead Zone (Nonlinear
	2-5-1 Impulse Response 27	(
	2-5-2 Transfer Function (Single-Input, Single-	Characteristics) 88
	Output Systems) 27	4-4 Equations of Mechanical Systems 89
	2-5-3 Transfer Function (Multivariable	4-5 Sensors and Encoders in Control Systems 94
	Systems) 29	4-5-1 Potentiometer 94 4-5-2 Tachometers 99
2-6	MATLAB Tools and Case Studies 30	
2.0	2-6-1 Description and Use of Transfer Function	4-5-3 Incremental Encoder 100
	Tool 30	4-6 DC Motors in Control Systems 103
2-7	Summary 41	4-6-1 Basic Operational Principles of DC
	government for the first of the contract of the second property and the first of the first of the second property and the seco	Motors 104

	4-6-2	Basic Classifications of PM DC Motors 104	5-11	Observability of Linear Systems 173 5-11-1 Definition of Observability 173
	4-6-3	Mathematical Modeling of PM DC		5-11-2 Alternate Tests on Observability 174
4.7		Motors 107	5-12	Relationship Among Controllability, Observability,
4-7		tion of Nonlinear Systems 110	~ 10	and Transfer Functions 175
4-8		with Transportation Lags (Time Delays) 114	5-13	Invariant Theorems on Controllability and
	4-8-1	Approximation of the Time-Delay Function		Observability 177
		by Rational Functions 115	5-14	A Final Illustrative Example: Magnetic-Ball
4-9	A Sun-Se	eker System 116		Suspension System 178
	4-9-1	Coordinate System 117	5-15	MATLAB Tools and Case Studies 181
	4-9-2	Error Discriminator 117		5-15-1 Description and Use of the State-Space
	4-9-3	Op-Amp 118		Analysis Tool 182
	4-9-4	Servoamplifier 118		5-15-2 Description and Use of tfsym for State-
	4-9-5	Tachometer 118		Space Applications 189
	4-9-6	DC Motor 118		5-15-3 Another Example 189
4-10	MATLAE	3 Tools and Case Studies 120	5-16	Summary 195
4-11	Summary		2 10	Summary 170
			» CH	APTER 6
	APTER 5			ty of Linear Control Systems 211
State \	Variable A	analysis 138	6-1	Introduction 211
5-1	Introduct	ion 138	6-2	Bounded-Input, Bounded-Output (BIBO) Stability—
5-2		atrix Representation of State		Continuous-Data Systems 212
And)		ons 138		6-2-1 Relationship between Characteristic
5-3		nsition Matrix 140		Equation Roots and Stability 212
5-5	5-3-1	Significance of the State-Transition	6-3	Zero-Input and Asymptotic Stability of Continuous-
	J=J=1			Data Systems 213
	5-3-2	Matrix 141	6-4	Methods of Determining Stability 215
	3-3-2	Properties of the State-Transition	6-5	Routh-Hurwitz Criterion 216
<i>-</i> 1	O	Matrix 142	. 0,3	6-5-1 Routh's Tabulation (1) 217
5-4		nsition Equation 143		6-5-2 Special Cases When Routh's Tabulation
	5-4-1	State-Transition Equation Determined from		Terminates Prematurely 219
		the State Diagram 145	6-6	MATLAB Tools and Case Studies 222
5-5		hip between State Equations and High-	6-7	
		Differential Equations 147	0-7	Summary 226
5-6		hip between State Equations and Transfer	» OU	ADTED
		ons 149		APTER 7 Domain Analysis of Control
5-7		ristic Equations, Eigenvalues, and		ns 233
	_	ectors 151	than to serious	
	5-7-1	Eigenvalues 152	7-1	Time Response of Continuous-Data Systems:
		Eigenvectors 153		Introduction 233
5-8	Similarity	y Transformation 155	7-2	Typical Test Signals for the Time Response of
	5-8-1	Invariance Properties of the Similarity		Control Systems 234
		Transformations 156	7-3	The Unit-Step Response and Time-Domain
	5-8-2	Controllability Canonical Form (CCF) 156		Specifications 236
	5-8-3	Observability Canonical Form (OCF) 158	7-4	Steady-State Error 237
	5-8-4	Diagonal Canonical Form (DCF) 159		7-4-1 Steady-State Error of Linear Continuous-
	5-8-5	Jordan Canonical Form (JCF) 160		Data Control Systems 237
5-9	Decompo	ositions of Transfer Functions 161		7-4-2 Steady-State Error Caused by Nonlinear
	5-9-1	Direct Decomposition 162		System Elements 249
	5-9-2	Cascade Decomposition 166	7-5	Time Response of a First-Order System 251
	5-9-3	Parallel Decomposition 167	, ,	7-5-1 Speed Control of a DC Motor 251
5-10		ability of Control Systems 169	7-6	Transient Response of a Prototype Second-Order
2 10	5-10-1	General Concept of Controllability 170	, -0	System 253
	5-10-2	Definition of State Controllability 171		7-6-1 Damping Ratio and Damping Factor 253
	5-10-2	Alternate Tests on Controllability 171		7-6-2 Natural Undamped Frequency 255
	2 20 2	I		. 0 2 . I ratarar Originipou i requericy 255

	7-6-3	Maximum Overshoot 257	8-4	Design Aspects of the Root Loci 330
	7-6-4	Delay Time and Rise Time 259		8-4-1 Effects of Adding Poles and Zeros to
7.7	7-6-5	Settling Time 261		G(s)H(s). 330
7-7	Time-Domain Analysis of a Position-Control System 265		8-5	Root Contours (RC): Multiple-Parameter Variation 336
	7-7-1	Unit-Step Transient Response 268	8-6	Root Locus with the MATLAB Toolbox 342
	7-7-2	The Steady-State Response 271	8-7	Summary 345
	7-7-3	Time Response to a Unit-Ramp Input 271	» CH	APTER 9
	7-7-4	Time Response of a Third-Order System 273		ency-Domain Analysis 352
7-8	Effects of Adding Poles and Zeros to Transfer		9-1	Introduction 352
	Functions 276			9-1-1 Frequency Response of Closed-Loop
	7-8-1	Addition of a Pole to the Forward-Path		Systems 353
		Transfer Function: Unity-Feedback Systems 276	9-2	9-1-2 Frequency-Domain Specifications 355 M_r , ω_r , and Bandwidth of the Prototype Second-
	7-8-2	Addition of a Pole to the Closed-Loop		Order System 356
		Transfer Function 277		9-2-1 Resonant Peak and Resonant
	7-8-3	Addition of a Zero to the Closed-Loop		Frequency 356
		Transfer Function 279		9-2-2 Bandwidth 358
	7-8-4	Addition of a Zero to the Forward-Path	9-3	Effects of Adding a Zero to the Forward-Path
		Transfer Function: Unity-Feedback	0.4	Transfer Function 360
		Systems 280	9-4	Effects of Adding a Pole to the Forward-Path
7-9		t Poles of Transfer Functions 281	0.5	Transfer Function 364
	7-9-1	The Relative Damping Ratio 282	9-5	Nyquist Stability Criterion: Fundamentals 365 9-5-1 Stability Problem 366
	7-9-2	The Proper Way of Neglecting the		9-5-1 Stability Problem 366 9-5-2 Definition of Encircled and
		Insignificant Poles with Consideration		Enclosed 366
	FF1 4	of the Steady-State Response 282		9-5-3 Number of Encirclements and
7-10		roximation of High-Order Systems by Low-		Enclosures 367
		System the Formal Approach 283		9-5-4 Principle of the Argument 368
7 11	7-10-1	Approximation Criterion 284		9-5-5 Nyquist Path 372
7-11 7-12		B Tools and Case Studies 293		9-5-6 Nyquist Criterion and the $L(s)$ or the
7-12	Summary	307	9-6	G(s)H(s) plot 373
Root-Locus Technique 318				Nyquist Criterion for Systems with Minimum-Phase Transfer Functions 374
11001-1	ocus iec	milique 318		9-6-1 Application of the Nyquist Criterion to
8-1	Introduct			Minimum-Phase Transfer Functions tha
8-2	Basic Properties of the Root Loci (RL) 319			Are Not Strictly Proper 375
8-3		s of the Root Loci 323	9-7	Relation Between the Root Loci and the Nyquist
	8-3-1	$K = 0$ and $K = \pm \infty$ Points 323		Plot 376
	8-3-2	Number of Branches on the Root Loci 324	9-8	Illustrative Examples: Nyquist Criterion for Minimum-Phase Transfer Functions 378
	8-3-3	Symmetry of the RL 324	9-9	Effects of Addition of Poles and Zeros to $L(s)$ on the
	8-3-4	Angles of Asymptotes of the RL: Behavior		Shape of the Nyquist Plot 382
		of the RL at $ s = \infty$ 324	9-10	Relative Stability: Gain Margin and Phase
	8-3-5	Intersect of the Asymptotes (Centroid) 325		Margin 386
	8-3-6	Root Loci on the Real Axis 325		9-10-1 Gain Margin (GM) 388
	8-3-7	Angles of Departure and Angles of Arrival		9-10-2 Phase Margin (PM) 389
	0.00	of the RL 325	9-11	Stability Analysis with the Bode Plot 392
	8-3-8	Intersection of the RL with the Imaginary Axis 326		9-11-1 Bode Plots of Systems with Pure Time Delays 394
	8-3-9	Breakaway Points (Saddle Points) on the	9-12	
		RL 326		Magnitude Curve of the Bode Plot 396

8-3-10 The Root Sensitivity [17, 18, 19] **326** 9-12-1 Conditionally Stable System **396**

9-13	Stability Analysis with the Magnitude-Phase Plot 399	10-11-1 Rate-Feedback or Tachometer-Feedback Control 531
9-14	Constant- <i>M</i> Loci in the Magnitude-Phase Plane: The Nichols Chart 400	10-11-2 Minor-Loop Feedback Control with Active
9-15	Nichols Chart Applied to Nonunity-Feedback Systems 406	10-12 State-Feedback Control 534 10-13 Pole-Placement Design through State
9-16	Sensitivity Studies in the Frequency Domain 407	Feedback 535
	MATLAB Tools and Case Studies 409	10-14 State Feedback with Integral Control 540
9-18	Summary 421	10-15 MATLAB Tools and Case Studies 545
9-10	Summary 421	10-16 Summary 558
» OIIA	NATED 40	10-10 Summary 330
	of Control Systems 433	CHAPTER 11 The Virtual Lab 578
10-1	Introduction 433	
10 1	10-1-1 Design Specifications 433	11-1 Introduction 578
	10-1-2 Controller Configurations 435	11-2 Important Aspects in the Response of a DC
	10-1-3 Fundamental Principles of Design 437	Motor 579
10-2	Design with the PD Controller 438	11-2-1 Speed Response and the Effects of
10-2	10-2-1 Time-Domain Interpretation of PD	Inductance and Disturbance-Open Loop
	Control 440	Response 579
		11-2-2 Speed Control of DC Motors: Closed-Loc
	10-2-2 Frequency-Domain Interpretation of PD Control 442	Response 581
		11-2-3 Position Control 582
10.2	10-2-3 Summary of Effects of PD Control 442	11-3 Description of the Virtual Experimental
10-3	Design with the PI Controller 454	System 583
	10-3-1 Time-Domain Interpretation and Design of	11-3-1 Motor 584
	PI Control 456	11-3-2 Position Sensor or Speed Sensor 584
	10-3-2 Frequency-Domain Interpretation and	11-3-3 Power Amplifier 584
10.4	Design of PI Control 456	11-3-4 Interface 584
10-4	Design with the PID Controller 468	11-4 Description of SIMLab and Virtual Lab
10-5	Design with Phase-Lead Controller 471	Software 585
	10-5-1 Time-Domain Interpretation and Design of	11-5 Simulation and Virtual Experiments 589
	Phase-Lead Control 473	11-5-1 Open-Loop Speed 589
	10-5-2 Frequency-Domain Interpretation and	11-5-2 Open-Loop Sine Input 591
	Design of Phase-Lead Control 474	11-5-3 Speed Control 593
	10-5-3 Effects of Phase-Lead	11-5-4 Position Control 596
	Compensation 489	11-6 Design Project 598
	10-5-4 Limitations of Single-Stage Phase-Lead	11-7 Summary 603
	Control 489	
	10-5-5 Multistage Phase-Lead Controller 489	▶ INDEX 606
	10-5-6 Sensitivity Considerations 493	
10-6	Design with Phase-Lag Controller 494	
	10-6-1 Time-Domain Interpretation and Design of	APPENDIX A
	Phase-Lag Control 494	Complex Variable Theory CD-ROM
	10-6-2 Frequency-Domain Interpretation and	
	Design of Phase-Lag Control 496	APPENDIX B
	10-6-3 Effects and Limitations of Phase-Lag	Differential and Difference Equations CD-ROM
	Control 506	
10-7	Design with Lead-Lag Controller 507	▶ APPENDIX C
10-8	Pole-Zero Cancellation Design: Notch Filter 508	Elementary Matrix Theory and Algebra CD-ROM
	10-8-1 Second-Order Active Filter 511	
	10-8-2 Frequency-Domain Interpretation and	APPENDIX D
	Design 512	Laplace Transform Table CD-ROM
10-9	Forward and Feedforward Controllers 520	
10-10	Design of Robust Control Systems 521	» APPENDIX E
10-11	Minor-Loop Feedback Control 530	Operational Amplifiers CD-ROM
~~ ~ .	. = : = = = = = = = = = :	

APPENDIX F

Properties and Construction of the Root Loci CD-ROM

APPENDIX G

Frequency-Domain Plots CD-ROM

APPENDIX H

General Nyquist Criterion CD-ROM

> APPENDIX I

Discrete-Data Control Systems CD-ROM

MAPPENDIX J

z-Transform Table CD-ROM

APPENDIX K

ACSYS 2002: Description of the Software CD-ROM

» ANSWERS TO SELECTED PROBLEMS CD-ROM