

Contents

N° 1396

Chapter 1	INTRODUCTION	1
1.1	Control Systems: What They Are	1
1.2	Examples of Control Systems	2
1.3	Open-Loop and Closed-Loop Control Systems	3
1.4	Feedback	4
1.5	Characteristics of Feedback	4
1.6	Analog and Digital Control Systems	4
1.7	The Control Systems Engineering Problem	6
1.8	Control System Models or Representations	6
Chapter 2	CONTROL SYSTEMS TERMINOLOGY	15
2.1	Block Diagrams: Fundamentals	15
2.2	Block Diagrams of Continuous (Analog) Feedback Control Systems	16
2.3	Terminology of the Closed-Loop Block Diagram	17
2.4	Block Diagrams of Discrete-Time (Sampled-Data, Digital) Components, Control Systems, and Computer-Controlled Systems	18
2.5	Supplementary Terminology	20
2.6	Servomechanisms	22
2.7	Regulators	23
Chapter 3	DIFFERENTIAL EQUATIONS, DIFFERENCE EQUATIONS, AND LINEAR SYSTEMS	39
3.1	System Equations	39
3.2	Differential Equations and Difference Equations	39
3.3	Partial and Ordinary Differential Equations	40
3.4	Time Variability and Time Invariance	40
3.5	Linear and Nonlinear Differential and Difference Equations	41
3.6	The Differential Operator D and the Characteristic Equation	41
3.7	Linear Independence and Fundamental Sets	42
3.8	Solution of Linear Constant-Coefficient Ordinary Differential Equations	44
3.9	The Free Response	44
3.10	The Forced Response	45
3.11	The Total Response	46
3.12	The Steady State and Transient Responses	46
3.13	Singularity Functions: Steps, Ramps, and Impulses	47
3.14	Second-Order Systems	48
3.15	State Variable Representation of Systems Described by Linear Differential Equations	49
3.16	Solution of Linear Constant-Coefficient Difference Equations	51
3.17	State Variable Representation of Systems Described by Linear Difference Equations	54
3.18	Linearity and Superposition	56
3.19	Causality and Physically Realizable Systems	57

CONTENTS

Chapter 4	THE LAPLACE TRANSFORM AND THE z-TRANSFORM	74
4.1	Introduction	74
4.2	The Laplace Transform	74
4.3	The Inverse Laplace Transform	75
4.4	Some Properties of the Laplace Transform and Its Inverse	75
4.5	Short Table of Laplace Transforms	78
4.6	Application of Laplace Transforms to the Solution of Linear Constant-Coefficient Differential Equations	79
4.7	Partial Fraction Expansions	83
4.8	Inverse Laplace Transforms Using Partial Fraction Expansions	85
4.9	The z -Transform	86
4.10	Determining Roots of Polynomials	93
4.11	Complex Plane: Pole-Zero Maps	95
4.12	Graphical Evaluation of Residues	96
4.13	Second-Order Systems	98
<hr/>		
Chapter 5	STABILITY	114
5.1	Stability Definitions	114
5.2	Characteristic Root Locations for Continuous Systems	114
5.3	Routh Stability Criterion	115
5.4	Hurwitz Stability Criterion	116
5.5	Continued Fraction Stability Criterion	117
5.6	Stability Criteria for Discrete-Time Systems	117
<hr/>		
Chapter 6	TRANSFER FUNCTIONS	128
6.1	Definition of a Continuous System Transfer Function	128
6.2	Properties of a Continuous System Transfer Function	129
6.3	Transfer Functions of Continuous Control System Compensators and Controllers	129
6.4	Continuous System Time Response	130
6.5	Continuous System Frequency Response	130
6.6	Discrete-Time System Transfer Functions, Compensators and Time Responses	132
6.7	Discrete-Time System Frequency Response	133
6.8	Combining Continuous-Time and Discrete-Time Elements	134
<hr/>		
Chapter 7	BLOCK DIAGRAM ALGEBRA AND TRANSFER FUNCTIONS OF SYSTEMS	154
7.1	Introduction	154
7.2	Review of Fundamentals	154
7.3	Blocks in Cascade	155
7.4	Canonical Form of a Feedback Control System	156
7.5	Block Diagram Transformation Theorems	156
7.6	Unity Feedback Systems	158
7.7	Superposition of Multiple Inputs	159
7.8	Reduction of Complicated Block Diagrams	160
<hr/>		
Chapter 8	SIGNAL FLOW GRAPHS	179
8.1	Introduction	179
8.2	Fundamentals of Signal Flow Graphs	179

CONTENTS

8.3	Signal Flow Graph Algebra	180
8.4	Definitions	181
8.5	Construction of Signal Flow Graphs	182
8.6	The General Input-Output Gain Formula	184
8.7	Transfer Function Computation of Cascaded Components	186
8.8	Block Diagram Reduction Using Signal Flow Graphs and the General Input-Output Gain Formula	187

Chapter 9	SYSTEM SENSITIVITY MEASURES AND CLASSIFICATION OF FEEDBACK SYSTEMS	208
9.1	Introduction	208
9.2	Sensitivity of Transfer Functions and Frequency Response Functions to System Parameters	208
9.3	Output Sensitivity to Parameters for Differential and Difference Equation Models	213
9.4	Classification of Continuous Feedback Systems by Type	214
9.5	Position Error Constants for Continuous Unity Feedback Systems	215
9.6	Velocity Error Constants for Continuous Unity Feedback Systems	216
9.7	Acceleration Error Constants for Continuous Unity Feedback Systems	217
9.8	Error Constants for Discrete Unity Feedback Systems	217
9.9	Summary Table for Continuous and Discrete-Time Unity Feedback Systems	217
9.10	Error Constants for More General Systems	218
Chapter 10	ANALYSIS AND DESIGN OF FEEDBACK CONTROL SYSTEMS: OBJECTIVES AND METHODS	230
10.1	Introduction	230
10.2	Objectives of Analysis	230
10.3	Methods of Analysis	230
10.4	Design Objectives	231
10.5	System Compensation	235
10.6	Design Methods	236
10.7	The w -Transform for Discrete-Time Systems Analysis and Design Using Continuous System Methods	236
10.8	Algebraic Design of Digital Systems, Including Deadbeat Systems	238

Chapter 11	NYQUIST ANALYSIS	246
11.1	Introduction	246
11.2	Plotting Complex Functions of a Complex Variable	246
11.3	Definitions	247
11.4	Properties of the Mapping $P(s)$ or $P(z)$	249
11.5	Polar Plots	250
11.6	Properties of Polar Plots	252
11.7	The Nyquist Path	253
11.8	The Nyquist Stability Plot	256
11.9	Nyquist Stability Plots of Practical Feedback Control Systems	256
11.10	The Nyquist Stability Criterion	260
11.11	Relative Stability	262
11.12	M- and N-Circles	263

CONTENTS

Chapter 12	NYQUIST DESIGN	299
12.1	Design Philosophy	299
12.2	Gain Factor Compensation	299
12.3	Gain Factor Compensation Using M-Circles	301
12.4	Lead Compensation	302
12.5	Lag Compensation	304
12.6	Lag-Lead Compensation	306
12.7	Other Compensation Schemes and Combinations of Compensators	308
Chapter 13	ROOT-LOCUS ANALYSIS	319
13.1	Introduction	319
13.2	Variation of Closed-Loop System Poles: The Root-Locus	319
13.3	Angle and Magnitude Criteria	320
13.4	Number of Loci	321
13.5	Real Axis Loci	321
13.6	Asymptotes	322
13.7	Breakaway Points	322
13.8	Departure and Arrival Angles	323
13.9	Construction of the Root-Locus	324
13.10	The Closed-Loop Transfer Function and the Time-Domain Response	326
13.11	Gain and Phase Margins from the Root-Locus	328
13.12	Damping Ratio from the Root-Locus for Continuous Systems	329
Chapter 14	ROOT-LOCUS DESIGN	343
14.1	The Design Problem	343
14.2	Cancellation Compensation	344
14.3	Phase Compensation: Lead and Lag Networks	344
14.4	Magnitude Compensation and Combinations of Compensators	345
14.5	Dominant Pole-Zero Approximations	348
14.6	Point Design	352
14.7	Feedback Compensation	353
Chapter 15	BODE ANALYSIS	364
15.1	Introduction	364
15.2	Logarithmic Scales and Bode Plots	364
15.3	The Bode Form and the Bode Gain for Continuous-Time Systems	365
15.4	Bode Plots of Simple Continuous-Time Frequency Response Functions and Their Asymptotic Approximations	365
15.5	Construction of Bode Plots for Continuous-Time Systems	371
15.6	Bode Plots of Discrete-Time Frequency Response Functions	373
15.7	Relative Stability	375
15.8	Closed-Loop Frequency Response	376
15.9	Bode Analysis of Discrete-Time Systems Using the w-Transform	377
Chapter 16	BODE DESIGN	387
16.1	Design Philosophy	387
16.2	Gain Factor Compensation	387
16.3	Lead Compensation for Continuous-Time Systems	388
16.4	Lag Compensation for Continuous-Time Systems	392
16.5	Lag-Lead Compensation for Continuous-Time Systems	393
16.6	Bode Design of Discrete-Time Systems	395

CONTENTS

Chapter 17 NICHOLS CHART ANALYSIS	411
17.1 Introduction	411
17.2 db Magnitude-Phase Angle Plots	411
17.3 Construction of db Magnitude-Phase Angle Plots	411
17.4 Relative Stability	416
17.5 The Nichols Chart	417
17.6 Closed-Loop Frequency Response Functions	419
<hr/>	
Chapter 18 NICHOLS CHART DESIGN	433
18.1 Design Philosophy	433
18.2 Gain Factor Compensation	433
18.3 Gain Factor Compensation Using Constant Amplitude Curves	434
18.4 Lead Compensation for Continuous-Time Systems	435
18.5 Lag Compensation for Continuous-Time Systems	438
18.6 Lag-Lead Compensation	440
18.7 Nichols Chart Design of Discrete-Time Systems	443
<hr/>	
Chapter 19 INTRODUCTION TO NONLINEAR CONTROL SYSTEMS	453
19.1 Introduction	453
19.2 Linearized and Piecewise-Linear Approximations of Nonlinear Systems	454
19.3 Phase Plane Methods	458
19.4 Lyapunov's Stability Criterion	463
19.5 Frequency Response Methods	466
<hr/>	
Chapter 20 INTRODUCTION TO ADVANCED TOPICS IN CONTROL SYSTEMS ANALYSIS AND DESIGN	480
20.1 Introduction	480
20.2 Controllability and Observability	480
20.3 Time-Domain Design of Feedback Systems (State Feedback)	481
20.4 Control Systems with Random Inputs	483
20.5 Optimal Control Systems	484
20.6 Adaptive Control Systems	485
<hr/>	
APPENDIX A	486
Some Laplace Transform Pairs Useful for Control Systems Analysis	
<hr/>	
APPENDIX B	488
Some z-Transform Pairs Useful for Control Systems Analysis	
<hr/>	
REFERENCES AND BIBLIOGRAPHY	489
<hr/>	
INDEX	491