

Contents

1	Introduction — 1
1.1	System and System Analysis — 1
1.2	Modeling the System — 2
1.3	Solving the Model — 4
1.4	Principle of Automatic Control Systems — 5
1.4.1	Control and Control Systems — 5
1.4.2	How Does an Automatic Control System Work? — 6
1.5	Structure of Control Systems — 8
1.5.1	Schematic Diagram for a Typical Automatic Control System — 8
1.5.2	Terminologies — 9
1.6	Characteristics of Control Systems — 10
1.6.1	Stability — 10
1.6.2	Accuracy — 11
1.6.3	Dynamic Properties — 11
1.6.4	Robustness — 12
1.7	Classification of Control Systems (to Broadest Sense) — 13
1.7.1	Open-Loop Control System — 13
1.7.2	Closed-Loop Control System — 14
1.8	Application of Control Theory in Mechanical Engineering Systems — 16
1.9	Brief History of Automatic Control — 16
1.10	Organization of Book — 18
1.11	Problems — 18
2	Laplace Transform Solution — 20
2.1	Definition — 20
2.2	Laplace Transforms of Common Functions — 21
2.2.1	Step Function — 21
2.2.2	Ramp Function — 21
2.2.3	Pulse Function — 23
2.2.4	Exponential Function — 23
2.2.5	Trigonometric Function — 24
2.2.6	Power Function — 25
2.2.7	Summary — 25
2.3	Laplace Transform Properties — 25
2.3.1	Multiplication by a Constant — 27
2.3.2	Superposition — 27
2.3.3	Differential Theorem — 27
2.3.4	Integral Theorem — 29
2.3.5	Initial Value Theorem — 29

2.3.6	Final Value Theorem —	30
2.3.7	Shifting Theorem in Time Domain (Delay Theorem) —	31
2.3.8	Shifting Theorem in Complex Domain —	31
2.3.9	Partial Fraction Method —	32
2.4	Laplace Transform Inversion —	33
2.4.1	Distinct Poles —	35
2.4.2	Repeated Poles —	37
2.4.3	Complex Poles —	39
2.5	Problems —	41

3 Formulation and Dynamic Behavior of Translational Mechanical Systems — 42

3.1	Introduction —	42
3.1.1	Concepts of Mathematical Models —	42
3.1.2	Types of Mathematical Models —	42
3.2	Variables —	43
3.3	Element Laws —	44
3.3.1	Mass —	45
3.3.2	Friction —	46
3.3.3	Stiffness —	47
3.4	Interconnection Laws —	48
3.4.1	D'Alembert's Law —	48
3.4.2	The Law of Reaction Forces —	49
3.5	Obtaining the System Model —	50
3.5.1	Free-Body Diagrams —	50
3.5.2	Parallel Combinations —	54
3.5.3	Series Combinations —	56
3.6	Summary —	58
3.7	Problems —	58

4 Formulation and Dynamic Behavior of Electrical Systems — 61

4.1	Element Laws —	61
4.1.1	Resistor —	61
4.1.2	Capacitor —	62
4.1.3	Inductor —	63
4.2	Interconnection Laws —	63
4.2.1	Kirchhoff's Voltage Law —	64
4.2.2	Kirchhoff's Current Law —	64
4.2.3	The Nodal Method of Electrical Network Analysis —	65
4.3	Analogue relationships among different systems —	66
4.4	Examples —	68
4.5	Problems —	69

5	Fundamentals of Control Systems — 71
5.1	Representation of Control Systems — 71
5.2	The Transfer Function — 71
5.2.1	Definition of the TF — 71
5.2.2	Properties of the TF — 73
5.2.3	The Rational Polynomial Form of a TF — 74
5.2.4	TF of Elements in Series Connection — 76
5.2.5	TF of Elements in Parallel Connection — 77
5.2.6	Remarks — 78
5.3	The TF for Typical Links — 79
5.3.1	Proportional Link — 80
5.3.2	Integral Link — 80
5.3.3	Inertial Link — 82
5.3.4	Differential Link — 84
5.3.5	Oscillation Link — 85
5.4	Block Diagrams — 86
5.4.1	Introduction — 86
5.4.2	Summing Point and Tie Point — 87
5.4.3	Terminologies — 87
5.4.4	Simplification of the Block Diagram — 90
5.4.4.1	Moving Tie Points — 90
5.4.4.2	Moving Summing Points — 91
5.4.4.3	General Feedback Case — 93
5.4.4.4	Multiple Inputs — 95
5.5	Plot the Block Diagrams — 99
5.6	Signal Flow Diagrams — 103
5.6.1	Introduction to Signal Flow Diagrams — 103
5.6.2	Draw the Signal Flow Diagram — 103
5.6.3	Mason's Gain Formula — 105
5.7	Problems — 107
6	Time Response Analysis of Control Systems — 110
6.1	Introduction — 110
6.2	Time Response from TF — 110
6.2.1	Response of First-Order System — 110
6.2.1.1	Unit Step Response — 112
6.2.1.2	Unit Ramp Response — 113
6.2.1.3	Unit Impulse Response — 114
6.2.1.4	Remarks — 114
6.2.2	Response of Second-Order System — 116
6.2.2.1	$\zeta = 0$ — 118
6.2.2.2	$0 < \zeta < 1$ — 119

6.2.2.3	$\zeta = 1$ —	121
6.2.2.4	$\zeta > 0$ —	122
6.2.3	Approximate Analysis of High-Order System —	124
6.2.3.1	Pole and Zero —	124
6.2.3.2	Dominant Pole —	125
6.2.3.3	Closed-Loop Dominant Poles —	126
6.3	Performance Specifications in Time Domain —	129
6.3.1	Performance Specifications of First-Order System —	129
6.3.1.1	Time constant τ —	130
6.3.1.2	Rise Time T_r —	130
6.3.1.3	Settling Time T_s —	130
6.3.2	Performance Specifications of Second-Order System —	131
6.3.2.1	Rise Time T_r —	132
6.3.2.2	Peak Time T_p —	133
6.3.2.3	Percentage Overshoot PO —	133
6.3.2.4	Settling Time T_s —	134
6.4	Problems —	138
7	Frequency Response Analysis of Control Systems —	140
7.1	Concepts —	140
7.2	Graphical Description: Nyquist Diagram and Bode Diagram —	145
7.2.1	Simple Rules for Plotting a Nyquist Diagram —	145
7.2.2	The Nyquist Diagrams for Typical Links —	146
7.2.2.1	Proportion Link —	146
7.2.2.2	Integral Link —	146
7.2.2.3	Ideal Differential Link —	147
7.2.2.4	Inertial Link —	147
7.2.2.5	First-Order Differential Link —	148
7.2.2.6	Second-Order Oscillation Link —	150
7.2.2.7	Second-Order Differential Link —	152
7.2.3	Simple Rules for Plotting Bode Diagrams —	154
7.2.3.1	Coordinate Dividing —	155
7.2.3.2	Slope of the Asymptote —	155
7.2.3.3	The Asymptote of the Logarithm Amplitude Characteristic Curve —	157
7.2.3.4	Break Frequency —	158
7.2.3.5	Amplitude Crossing Frequency —	158
7.2.3.6	Phase Crossing Frequency —	158
7.2.4	The Bode Diagrams for Typical Links —	159
7.2.4.1	Proportion Link —	159
7.2.4.2	Integral Link —	160

7.2.4.3	Ideal Differential Link — 164
7.2.4.4	Inertial Link — 165
7.2.4.5	First-Order Differential Link — 167
7.2.4.6	Second-Order Oscillation Link — 168
7.2.4.7	Second-Order Differential Link — 171
7.2.4.8	Summary — 172
7.3	The Open-Loop Bode Diagram of Control System — 172
7.4	Minimum Phase Systems — 177
7.5	Nyquist Stability Criterion — 180
7.5.1	An Explanation for the Nyquist Stability Criterion — 180
7.5.2	Some Tips for the Nyquist Stability Criterion — 182
7.5.3	The Nyquist Stability Criterion for a Minimum Phase System — 183
7.5.4	Stability Margin — 184
7.5.4.1	Introduction to Stability Margin — 184
7.5.4.2	The Nyquist Diagram Representation for Stability Margin — 185
7.5.4.3	The Bode diagram representation for a stable margin — 187
7.6	Problems — 189

8 Stability Analysis of Control Systems — 191

8.1	Stability — 191
8.2	Conditions for the System Stability — 191
8.3	Routh–Hurwitz Stability Criterion — 194
8.3.1	The Preconditions for Routh–Hurwitz Stability Criterion — 194
8.3.2	Full Condition for Routh–Hurwitz Stability Criterion — 194
8.3.3	Special Cases for the Routh–Hurwitz Stability Criterion — 199
8.3.3.1	Case 1: The first-column element in some row is zero but others in the same row are not all zero — 199
8.3.3.2	Case 2: All elements in some row are zero — 200
8.4	Problems — 205

9 Error Analysis and Calculation of Control Systems — 206

9.1	Terminologies — 206
9.1.1	Deviation — 206
9.1.2	Steady-State Deviation — 206
9.1.3	Desired Output Value — 207
9.1.4	Error — 207
9.1.5	Steady-State Error — 209
9.2	Static Error Coefficients — 210
9.2.1	Two Impact Factors of the Steady-State Error — 210
9.2.1.1	System Type — 210
9.2.1.2	Input Signal Type — 210

9.2.2	The Static Error Coefficients and the Steady-State Error —	211
9.2.2.1	Step Input Signal —	211
9.2.2.2	Ramp Input Signal —	212
9.2.2.3	Acceleration Input Signal —	214
9.3	Steady-State Error Calculation —	216
9.3.1	Steady-State Deviation Calculation —	217
9.3.1.1	Determination of $E_x(s)$ —	217
9.3.1.2	Determination of $E_N(s)$ —	218
9.3.1.3	Determination of $E(s)$ —	218
9.3.2	Steady-State Error Calculation —	218
9.4	Methods for Reducing Steady-State Error —	220
9.4.1	Increase Open-Loop Gain —	220
9.4.2	Increasing System Types —	221
9.4.3	Feed Forward Control —	222
9.4.4	Compound Control —	223
9.5	Problems —	224

References — 227

Index — 229