

Contents

Preface xv

1 Introduction 1

- 1.1 Dynamic Systems 1
 - 1.1.2 Control Systems 3
 - 1.2 Dimensions and Units 3
 - 1.3 Mathematical Modeling of Dynamic Systems 9
 - 1.4 System Response 12
 - 1.5 Linearization of Differential Equations 15
 - 1.6 Unit Impulse Function and Unit Step Function 20
 - 1.6.1 Unit Impulse Function 21
 - 1.6.2 Unit Step Function 23
 - 1.7 Stability 25
 - 1.8 MATLAB 27
 - 1.9 Scope of Study 43
 - 1.9.1 Model Formulation 43
 - 1.9.2 Mathematical Solutions 44
 - 1.9.3 System Response 44
 - 1.9.4 Introduction to Control Systems 44
 - 1.10 Summary 45
 - 1.10.1 Chapter Highlights 45
 - 1.10.2 Important Equations 45
- Problems 46

2 Mechanical Systems 50

- 2.1 Inertia Elements 51
 - 2.1.1 Particles 51
 - 2.1.2 Rigid Bodies 52

Contents

	2.1.3	Deformable Bodies	58
	2.1.4	Degrees of Freedom	59
2.2		Springs	61
	2.2.1	Force-Displacement Relations	62
	2.2.2	Combinations of Springs	64
	2.2.3	Static Deflections	67
2.3		Friction Elements	68
	2.3.1	Viscous Damping	68
	2.3.2	Coulomb Damping	72
	2.3.3	Hysteretic Damping	74
2.4		Mechanical System Input	74
	2.4.1	External Forces and Torques	75
	2.4.2	Impulsive Forces	78
	2.4.3	Step Forces	78
	2.4.4	Periodic Forces	79
	2.4.5	Motion Input	80
2.5		Free-Body Diagrams	81
2.6		Newton's Laws	87
	2.6.1	Particles	87
	2.6.2	Rigid Body Motion	90
	2.6.3	Pure Rotational Motion about a Fixed Axis of Rotation	91
	2.6.4	Planar Motion of a Rigid Body	93
	2.6.5	Three-Dimensional Motion of Rigid Bodies	95
	2.6.6	D'Alembert's Principle	95
	2.6.6.1	Particles	95
	2.6.6.2	Rigid Bodies Undergoing Planar Motion	95
2.7		Single-Degree-of-Freedom Systems	101
2.8		Multidegree-of-Freedom Systems	103
2.9		Energy Methods	104
	2.9.1	Principle of Work and Energy	104
	2.9.2	Equivalent Systems	105
	2.9.3	Energy Storage	110
	2.9.4	Lagrange's Equations for Multidegree-of-Freedom Systems	111
	2.9.5	States and Order	112
2.10		Further Examples	114
2.11		Summary	123
	2.11.1	Modeling Methods	123
	2.11.2	Chapter Highlights	124

2.11.3 Important Equations	125
Problems	127

3 Electrical Systems 133

3.1	Charge, Current, Voltage, and Power	134
3.2	Circuit Components	136
3.2.1	Resistors	136
3.2.2	Capacitors	138
3.2.3	Inductors	141
3.2.4	Voltage and Current Sources	143
3.2.5	Operational Amplifiers	143
3.2.6	Electric Circuits and Mechanical Systems	143
3.3	Kirchoff's Laws	144
3.4	Circuit Reduction	146
3.4.1	Series and Parallel Components	147
3.4.2	Series Combinations	147
3.4.3	Parallel Combinations	148
3.5	Modeling of Electric Circuits	151
3.6	Mechanical Systems Analogies	156
3.6.1	Energy Principles	156
3.6.2	Single-Loop Circuits with Voltage Sources	157
3.6.3	Single-Loop Circuits with Current Sources	159
3.6.4	Multiple-Loop Circuits	161
3.6.5	Mechanical Systems with Motion Input	163
3.6.6	States	165
3.7	Operational Amplifiers	166
3.8	Electromechanical Systems	172
3.8.1	Magnetic Fields	172
3.8.2	General Theory	173
3.8.3	Direct Current (dc) Servomotors	176
3.8.4	Microelectromechanical Systems (MEMSs) and Nanoelectromechanical Systems (NEMSs)	179
3.9	Further Examples	182
3.10	Summary	189
3.10.1	Mathematical Modeling of Electrical Systems	189
3.10.2	Other Chapter Highlights	190
3.10.3	Important Equations	190
	Problems	191

4 Fluid, Thermal, and Chemical Systems 198

- 4.1** Introduction 198
- 4.2** Control Volume Analysis 200
 - 4.2.1** Conservation of Mass 201
 - 4.2.2** Energy Equation 202
 - 4.2.3** Bernoulli's Equation 204
- 4.3** Pipe Flow 207
 - 4.3.1** Losses 208
 - 4.3.2** Orifices 213
 - 4.3.3** Compressible Flows 214
- 4.4** Modeling of Liquid-Level Systems 215
- 4.5** Pneumatic and Hydraulic Systems 222
 - 4.5.1** Pneumatic Systems 223
 - 4.5.2** Hydraulic Systems 226
- 4.6** Thermal Systems 232
- 4.7** Chemical and Biological Systems 240
 - 4.7.1** Continuous Stirred Tank Reactors (CSTRs) 240
 - 4.7.2** Biological Systems 244
- 4.8** Further Examples 245
- 4.9** Summary 261
 - 4.9.1** Mathematical Modeling of Transport Systems 261
 - 4.9.2** Chapter Highlights 261
 - 4.9.3** Important Equations 262
- Problems 264

5 Laplace Transforms 269

- 5.1** Definition and Existence 271
- 5.2** Determination of Transform Pairs 272
 - 5.2.1** Direct Integration 272
 - 5.2.2** Use of MATLAB 276
- 5.3** Laplace Transform Properties 278
- 5.4** Inversion of Transforms 289
 - 5.4.1** Use of Tables and Properties 290
 - 5.4.2** Partial Fraction Decompositions 292
 - 5.4.2.1** Real Distinct Poles 294
 - 5.4.2.2** Complex Poles 295
 - 5.4.2.3** Repeated Poles 297
 - 5.4.2.4** Brute Force Methods 299

5.4.3	Inversion of Transforms of Periodic Functions	300
5.4.4	Use of MATLAB	301
5.5	Laplace Transform Solution of Differential Equations	307
5.5.1	Systems with One Dependent Variable	307
5.5.2	Systems of Differential Equations	310
5.5.3	Integrodifferential Equations	313
5.5.4	Use of MATLAB	315
5.6	Further Examples	317
5.7	Summary	331
5.7.1	Mathematical Solutions for Response of Dynamic Systems	331
5.7.2	Important Equations	332
	Problems	332

6 Transient Analysis and Time Domain Response 336

6.1	Transfer Functions	336
6.1.1	Definition and Determination	336
6.1.2	Multiple Inputs and Multiple Outputs	340
6.1.3	System Order	342
6.2	Transient Response Specification	342
6.2.1	Free Response	343
6.2.2	Impulsive Response	343
6.2.3	Step Response	343
6.2.4	Ramp Response	345
6.2.5	Convolution Integral	345
6.2.6	Transient System Response Using MATLAB	346
6.3	Stability Analysis	349
6.3.1	General Theory	349
6.3.2	Routh's Method	353
6.3.3	Relative Stability	355
6.3.4	An Introduction to Root-Locus Analysis	357
6.4	First-Order Systems	361
6.4.1	Free Response	362
6.4.2	Impulsive Response	365
6.4.3	Step Response	366
6.4.4	Ramp Response	367
6.5	Second-Order Systems	368
6.5.1	Free Response	370
6.5.2	Impulsive Response	379

6.5.3	Step Response	383
6.5.4	General Transient Response	391
6.6	Higher-Order Systems	394
6.6.1	General Case	394
6.6.2	Multidegree-of-Freedom Mechanical Systems	399
6.6.2.1	Transfer Functions	399
6.6.2.2	Undamped Systems	400
6.7	Systems with Time Delay	403
6.8	Further Examples	408
6.9	Summary	426
6.9.1	Chapter Highlights	426
6.9.2	Important equations	428
	Problems	430

7 Frequency Response 435

7.1	Undamped Second-Order Systems	436
7.2	Sinusoidal Transfer Function	440
7.3	Graphical Representation of the Frequency Response	448
7.3.1	Frequency Response Curves	448
7.3.2	Bode Diagrams	450
7.3.2.1	Construction and Asymptotes	450
7.3.2.2	Products of Transfer Functions	451
7.3.2.3	Bode Diagrams for Common Transfer Functions	453
7.3.2.4	Bode Diagram Parameters	461
7.3.3	Nyquist Diagrams	462
7.3.4	Use of MATLAB to Develop Bode Plots and Nyquist Diagrams	463
7.4	First-Order Systems	467
7.5	Second-Order Systems	472
7.5.1	One-Degree-of-Freedom Mechanical System	472
7.5.2	Motion Input	478
7.5.3	Filters	482
7.6	Higher-Order Systems	485
7.6.1	Dynamic Vibration Absorbers	486
7.6.2	Higher-Order Filters	489
7.7	Response Due to Periodic Input	493
7.8	Further Examples	497
7.9	Summary	510

7.9.1	Chapter Highlights	510
7.9.2	Important Equations	511
	Problems	512

8 Feedback Control Systems 515

8.1	Block Diagrams	515
8.1.1	Block Diagram Algebra	516
8.1.2	Block Diagram Modeling of Dynamic Systems	522
8.2	Using SIMULINK in Block Diagram Modeling	525
8.3	Feedback Control	533
8.3.1	Proportional Control	534
8.3.2	Integral Control and Proportional Plus Integral (PI) Control	535
8.3.4	Derivative Control and Proportional Plus Derivative (PD) Control	536
8.3.5	Proportional Plus Integral Plus Derivative (PID) Control	536
8.3.6	Error and Offset	538
8.3.7	Response Due to Unit Step Input	538
8.4	Feedback Control of First-Order Plants	539
8.5	Control of Second-Order Plants	551
8.6	Control System Design	562
8.6.1	Design Using Root-Locus Diagrams	563
8.6.2	Ziegler-Nichols Tuning Rules	573
8.7	Further Examples	576
8.8	Summary	594
8.8.1	Chapter Highlights	594
8.8.2	Important Equations	595
	Problems	597

9 State-Space Methods 601

9.1	An Example in the State Space	601
9.2	General State-Space Modeling	607
9.2.1	Basic Concepts	607
9.2.2	Multidegree-of-Freedom Mechanical Systems	615
9.3	State-Space Solutions for Free Response	620
9.3.1	Laplace Transform Solution	620
9.3.2	Exponential Solution	621

Contents

	9.3.3 General Description of Free Response	624
9.4	State-Space Analysis of Response Due to Inputs	627
	9.4.1 Laplace Transform Solution	627
	9.4.2 Numerical Solutions	631
	9.4.3 Use of MATLAB Program ode45.m	636
9.5	Relationship Between Transfer Functions and State-Space Models	638
9.6	MATLAB and SIMULINK Modeling in the State-Space	641
	9.6.1 MATLAB	641
	9.6.2 SIMULINK	649
9.7	Nonlinear Systems and Systems with Variable Coefficients	656
9.8	Further Examples	663
9.9	Summary	669
	9.9.1 Chapter Highlights	669
	9.9.2 Important Equations	670
	Problems	670

A Complex Algebra 673

B Matrix Algebra 676

B.1	Definitions	676
B.2	Matrix Arithmetic	677
B.3	Determinants	677
B.4	Matrix Inverse	678
B.5	Systems of Equations	679
B.6	Cramer's Rule	680
B.7	Eigenvalues and Eigenvectors	680

C MATLAB 683

C.1	MATLAB Basics	684
C.2	Plotting and Annotating Graphs	688
C.3	Programming commands	690
	C.3.1 Input and Output	691
	C.3.2 Conditional Statements	692
	C.3.3 Looping	694
	C.3.4 User-Defined Functions	695

C.4	Symbolic Math Toolbox	696
C.6	Control System Toolbox	696

D Construction of Root-Locus Diagrams 698

D.1	Definitions	698
D.2	Angle and Magnitude Criteria	799
D.3	Construction Guidelines	700
D.4	Summary of Construction Steps	703
D.5	Examples	704

References 709

Index 711
