Contents

PREFACE XVII

1 INTRODUCTION 1

1.1 Systems and System Models 1

1.2 System Elements, Their Characteristics, and the Role of Integration 3

1.3 Linearization 5

1.4 Synopsis 10

Problems 11

2 MECHANICAL SYSTEMS 14

2.1 Introduction 14

2.2 Translational Mechanical Systems 16

2.2.1 Translational Masses 16

2.2.2 Translational Springs 19

2.2.3 Translational Dampers 23

2.2.4 Elementary Systems—Combinations of Translational Elements 24

2.3 Rotational Mechanical Systems 31

2.3.1 Rotational Inertias 31

2.3.2 Rotational Springs 32

2.3.3 Rotational Dampers 33

2.4 Simulation Block Diagrams 37

2.4.1 Coefficient Blocks 38

2.4.2 Summation Blocks 38

2.4.3 Integration and Differentiation Blocks 39

2.4.4 Drawing Complete Diagrams from Describing Equations 39

2.5 Synopsis 41

Problems 42

3 MATHEMATICAL MODELS 49

3.1 Introduction 49

3.2 Input-Output Models 50

3.3 State Models 56

3.4 Transition Between Input-Output and State Models 64

3.5 Nonlinearities in Input-Output and State Models 67

3.6 Synopsis 69

Problems 69

4 ANALYTICAL SOLUTIONS OF SYSTEM INPUT-OUTPUT EQUATIONS 73

4.1 Introduction 73

4.2 Analytical Solutions of Linear Differential Equations 74

4.3 First-Order Models 76

4.4 Second-Order Models 85

4.4.1 Free Response 85

4.4.2 Step Response 91

4.5 Third- and Higher-Order Models 98

4.6 Synopsis 99

Problems 101

5 NUMERICAL SOLUTIONS OF ORDINARY DIFFERENTIAL EQUATIONS 107

5.1 Introduction 107

5.2 Euler's Method 108

5.3 More Accurate Methods 112

5.4 Integration Step Size 117

5.5 Systems of Differential Equations 121

5.6 Synopsis 125

Problems 125

6 SIMULATION OF DYNAMIC SYSTEMS 127

6.1 Introduction 127

6.2 Block-Diagram-Oriented Packages 129

6.3 Building a Simulation 129
- 6.3.1 Structure of the Simulation: The Block Diagram 129
- 6.3.2 Model Parameters 131
- 6.3.3 Initial Conditions 131
- 6.3.4 Inputs 131
- 6.3.5 Outputs 131
- 6.3.6 Simulation Run-Time Control 132

6.4 Studying a System with a Simulation 133
- 6.4.1 Monitoring Indices of Performance 134
- 6.4.2 Parametric Studies: Engineering Design 135
- 6.4.3 Nonlinear Systems 136

6.5 Simulation Case Study: Mechanical Snubber 140
- 6.5.1 Modeling the System 140
- 6.5.2 Block Diagram Approach to Simulation Structure 141
- 6.5.3 Alternative Approach to Configuration Dependence 143
- 6.5.4 Parametric Study 145

6.6 Synopsis 147

Problems 148

7 ELECTRICAL SYSTEMS 150

7.1 Introduction 150

7.2 Diagrams, Symbols, and Circuit Laws 151

7.3 Elemental Diagrams, Equations, and Energy Storage 153
- 7.3.1 Capacitors 153
- 7.3.2 Inductors 154
- 7.3.3 Transformers 155
- 7.3.4 Resistors 155

7.4 Analysis of Systems of Interacting Electrical Elements 156

7.5 Linear Time-Varying Electrical Elements 162

7.6 Synopsis 164

Problems 165

8 THERMAL SYSTEMS 172

8.1 Introduction 172

8.2 Basic Mechanisms of Heat Transfer 173
8.2.1 Conduction 173
8.2.2 Convection 174
8.2.3 Radiation 175

8.3 Lumped Models of Thermal Systems 176

8.4 Synopsis 182

Problems 182

9 FLUID SYSTEMS 187

9.1 Introduction 187

9.2 Fluid System Elements 188
9.2.1 Fluid Capacitors 188
9.2.2 Fluid Inertors 189
9.2.3 Fluid Resistors 190
9.2.4 Fluid Sources 192
9.2.5 Interconnection Laws 192

9.3 Analysis of Fluid Systems 193

9.4 Pneumatic Systems 195

9.5 Synopsis 203

Problems 204

10 MIXED SYSTEMS 209

10.1 Introduction 209

10.2 Energy-Converting Transducers and Devices 209
10.2.1 Translational Mechanical to Rotational Mechanical Transducers 210
10.2.2 Electromechanical Energy Converters 210
10.2.3 Fluidomechanical Energy Converters 212

10.3 Signal-Converting Transducers 213

10.4 Application Examples 214

10.5 Synopsis 219

Problems 219

11 SYSTEM TRANSFER FUNCTIONS 229

11.1 Introduction 229

11.2 Examples of Exponential Inputs 230

11.3 System Response to an Exponential Input 231

11.4 Use of Block Diagrams in System Modeling 232

11.4.1 Elementary Block Diagrams 232

11.4.2 Combining Elementary "Building Block" Diagrams 233

11.4.3 Illustrative Example 233

11.5 Transfer Functions and Performance Characteristics 236

11.6 Synopsis 237

Problems 238

12 FREQUENCY ANALYSIS 240

12.1 Introduction 240

12.2 Frequency Response Transfer Functions 240

12.3 Bode Diagrams 241

12.4 Polar Plot Diagrams 249

12.5 Synopsis 251

Problems 252

13 CLOSED-LOOP SYSTEMS AND SYSTEM STABILITY 255

13.1 Introduction 255

13.2 Basic Definitions and Terminology 257

13.3 Algebraic Stability Criteria 259

13.3.1 Hurwitz Criterion 260

13.3.2 Routh Criterion 263

13.4 Nyquist Stability Criterion 264

13.5 Quantitative Measures of Stability 267

13.6 Root Locus Method 270

13.7 Synopsis 273

Problems 275

14 CONTROL SYSTEMS 279

14.1 Introduction 279

14.2 Steady-State Control Error 280
14.2.1 Unit Step Input, $u(t) = U_s(t)$ 282
14.2.2 Unit Ramp Input, $u(t) = t$ 283

14.3 Steady-State Disturbance Sensitivity 284

14.4 Interrelation of Steady-State and Transient Considerations 288

14.5 Industrial Controllers 289
14.5.1 Two-Position or On-Off Control 290
14.5.2 Proportional Control 290
14.5.3 Proportional-Integral Control 291
14.5.4 Proportional-Derivative Control 291
14.5.5 Proportional-Integral-Derivative Control 292

14.6 System Compensation 294

14.7 Synopsis 297

Problems 298

15 ANALYSIS OF DISCRETE-TIME SYSTEMS 303

15.1 Introduction 303

15.2 Mathematical Modeling 304
15.2.1 Input-Output Models 304
15.2.2 State Models 308

15.3 Sampling and Holding Devices 310

15.4 The z Transform 314
15.4.1 Definition and Basic z Transforms 315
15.4.2 z Transform Theorems 316
15.4.3 Inverse z Transform 317

15.5 Pulse Transfer Function 319

15.6 Synopsis 322

Problems 322

16 DIGITAL CONTROL SYSTEMS 325

16.1 Introduction 325

16.2 Single-Loop Control Systems 325

16.3 Transient Performance 327

16.4 Steady-State Performance 333

16.4.1 Unit Step Input 334

16.4.2 Unit Ramp Input 334

16.5 Digital Controllers 336

16.6 Synopsis 338

Problems 339

APPENDIX 1 FOURIER SERIES AND THE FOURIER TRANSFORM 343

APPENDIX 2 LAPLACE TRANSFORMS 349

APPENDIX 3 SIMULINK TUTORIAL 355

GLOSSARY 365

INDEX 369