Contents

Preface **ix**

1 Overview **1**
1.1 Introduction . . . 1
1.2 Basic Concepts . . . 5
1.3 Basic Structures of Feedback Systems . . . 7
1.4 About This Book . . . 9
Problems . . . 11
Notes and References . . . 11

2 Modeling and Simulation **13**
2.1 Modeling Based on First Principles . . . 14
2.1.1 Electrical systems . . . 14
2.1.2 Mechanical systems . . . 17
2.1.3 Electromechanical systems . . . 18
2.2 State Space Model and Linearization . . . 21
2.3 Transfer Functions and Impulse Responses . . . 27
2.4 Simplifying Block Diagrams . . . 31
2.5 Transfer Function Modeling . . . 34
2.6 MATLAB Manipulation of LTI Systems . . . 36
2.7 Simulation and Implementation of Systems . . . 39
2.7.1 Hardware simulation and implementation . . . 39
2.7.2 Software simulation and implementation . . . 42
2.8 MISO and SIMO Systems . . . 44
2.9 Modeling of Closed-Loop Systems . . . 47

2.10 Case Studies . . . 53
2.10.1 Ball and beam system . . . 53
2.10.2 Inverted pendulum system . . . 55
Problems . . . 57
Notes and References . . . 62

3 Stability and Stabilization 63
3.1 Concept of Stability . . . 64
3.2 Routh Criterion . . . 68
3.3 Other Stability Criteria . . . 76
3.4 Robust Stability . . . 82
3.5 Stability of Closed-Loop Systems . . . 86
3.6 Pole Placement Design . . . 95
3.7 All Stabilizing Controllers* . . . 101
3.8 All Stabilizing 2DOF Controllers* . . . 106
3.9 Case Studies . . . 111
3.9.1 Ball and beam system . . . 111
3.9.2 Inverted pendulum system . . . 114
Problems . . . 120
Notes and References . . . 123

4 Time-Domain Analysis 127
4.1 Responses to Typical Input Signals . . . 128
4.2 Step Response Analysis . . . 133
4.3 Dominant Poles and Zeros . . . 143
4.4 Steady-State Response and System Type . . . 146
4.5 Internal Model Principle . . . 153
4.6 Undershoot . . . 156
4.7 Overshoot . . . 160
4.8 Time-Domain Signal and System Norms . . . 166
4.9 Computation of the Time-Domain 2-Norm . . . 170
Problems . . . 175
Notes and References . . . 182

5 Root-Locus Method 185
5.1 Root-Locus Techniques . . . 186
5.2 Derivations of Root-Locus Rules* . . . 195
5.3 Effects of Adding Poles and Zeros . . . 198
5.4 Phase-Lag Controller . . . 199
5.5 PI Controller . . . 204
5.6 Phase-Lead Controller . . . 205
5.7 PD Controller . . . 211
5.8 Lead-Lag or PID Controller . . . 215
5.9 2DOF Controllers . . . 218
5.10 General Guidelines in Root-Locus Design . . . 219

5.11 Complementary Root-Locus . . . 219
5.12 Strong Stabilization . . . 222
5.13 Case Study – Ball and Beam System . . . 226
Problems . . . 230
Notes and References . . . 233

6 Frequency-Domain Analysis 234
6.1 Frequency Response . . . 235
6.2 Bode Diagrams . . . 244
6.3 Nyquist Stability Criterion . . . 252
6.4 Gain Margin and Phase Margin . . . 260
6.5 Closed-Loop Frequency Response . . . 265
6.6 Nichols Chart . . . 268
6.7 Riemann Plot . . . 271
Problems . . . 275
Notes and References . . . 278

7 Classical Design in Frequency Domain 279
7.1 Phase-Lag Controller . . . 280
7.2 PI Controller . . . 284
7.3 Phase-Lead Controller . . . 286
7.4 PD Controller . . . 292
7.5 Lead-Lag or PID Controller . . . 295
7.6 Ziegler and Nichols Tuning Rules . . . 298
7.6.1 Ziegler and Nichols first method . . . 298
7.6.2 Frequency-response analysis of the Ziegler and Nichols tuning rules . . . 299
7.6.3 Ziegler and Nichols second method . . . 303
7.7 Derivative Control . . . 304
7.8 Alternative PID Implementation . . . 308
7.9 Integral Control and Antiwindup . . . 309
7.10 Design by Loopshaping . . . 312
7.11 Bode's Gain and Phase Relation . . . 314
7.12 Bode's Sensitivity Integral . . . 319
Problems . . . 321
Notes and References . . . 323

8 Performance and Robustness 325
8.1 Frequency-Domain 2-Norm of Signals and Systems . . . 325
8.2 Frequency-Domain ∞-Norm of Systems . . . 333
8.3 Model Uncertainties and Robust Stability . . . 337
8.4 Chordal and Spherical Distances . . . 345
8.5 Distance between Systems . . . 348

8.6 Uncertainty and Robustness . . . 354
Problems . . . 361
Notes and References . . . 364

9 Optimal and Robust Control 365
9.1 Controller with Optimal Transient . . . 365
9.2 Controller with Weighted Optimal Transient . . . 372
9.3 Minimum-Energy Stabilization . . . 378
9.4 Derivation of the Optimal Controller* . . . 380
9.5 Optimal Robust Stabilization . . . 385
9.6 Stabilization with Guaranteed Robustness . . . 394
Problems . . . 398
Notes and References . . . 400

A Laplace Transform 401
A.1 Definition . . . 401
A.2 Properties . . . 402
A.3 Inverse Laplace Transform . . . 405
Problems . . . 410
Notes and References . . . 410

B Matrices and Polynomials 412
B.1 Matrices . . . 412
B.2 Polynomials . . . 414
Problems . . . 418
Notes and References . . . 418

C Answers to Selected Problems 419
C.1 Chapter 1 . . . 419
C.2 Chapter 2 . . . 419
C.3 Chapter 3 . . . 422
C.4 Chapter 4 . . . 423
C.5 Chapter 5 . . . 425
C.6 Chapter 6 . . . 426
C.7 Chapter 7 . . . 427
C.8 Chapter 8 . . . 428
C.9 Chapter 9 . . . 428

Bibliography 430

Index 437