

Contents

CHAPTER 1 *Introduction to Control Systems* 1

- 1.1 Introduction 2
- 1.2 History of Automatic Control 4
- 1.3 Two Examples of the Use of Feedback 7
- 1.4 Control Engineering Practice 8
- 1.5 Examples of Modern Control Systems 9
- 1.6 Automatic Assembly and Robots 16
- 1.7 The Future Evolution of Control Systems 16
- 1.8 Engineering Design 18
- 1.9 Control System Design 19
- 1.10 Design Example: Turntable Speed Control 21
- 1.11 Design Example: Insulin Delivery Control System 22
- 1.12 Sequential Design Example: Disk Drive Read System 23
 - Exercises 24
 - Problems 25
 - Design Problems 30
 - Terms and Concepts 31

CHAPTER 2 *Mathematical Models of Systems* 32

- 2.1 Introduction 33
- 2.2 Differential Equations of Physical Systems 33
- 2.3 Linear Approximations of Physical Systems 38
- 2.4 The Laplace Transform 41
- 2.5 The Transfer Function of Linear Systems 47
- 2.6 Block Diagram Models 62
- 2.7 Signal-Flow Graph Models 66
- 2.8 Computer Analysis of Control Systems 71
- 2.9 Design Examples 72
- 2.10 The Simulation of Systems Using MATLAB 80
- 2.11 Sequential Design Example: Disk Drive Read System 94
- 2.12 Summary 97
 - Exercises 98
 - Problems 104
 - Advanced Problems 115
 - Design Problems 115
 - MATLAB Problems 116
 - Terms and Concepts 118

CHAPTER 3 *State Variable Models* **119**

- 3.1 Introduction 120
- 3.2 The State Variables of a Dynamic System 121
- 3.3 The State Differential Equation 123
- 3.4 Signal-Flow Graph State Models 126
- 3.5 Alternative Signal-Flow Graph State Models 132
- 3.6 The Transfer Function from the State Equation 136
- 3.7 The Time Response and the State Transition Matrix 138
- 3.8 A Discrete-Time Evaluation of the Time Response 142
- 3.9 Design Example: Printer Belt Drive 147
- 3.10 Analysis of State Variable Models Using MATLAB 152
- 3.11 Sequential Design Example: Disk Drive Read System 155
- 3.12 Summary 159
 - Exercises 159
 - Problems 161
 - Advanced Problems 168
 - Design Problems 170
 - MATLAB Problems 171
 - Terms and Concepts 172

CHAPTER 4 *Feedback Control System Characteristics* **173**

- 4.1 Open- and Closed-Loop Control Systems 174
- 4.2 Sensitivity of Control Systems to Parameter Variations 176
- 4.3 Control of the Transient Response of Control Systems 179
- 4.4 Disturbance Signals in a Feedback Control System 183
- 4.5 Steady-State Error 187
- 4.6 The Cost of Feedback 190
- 4.7 Design Example: English Channel Boring Machines 191
- 4.8 Design Example: Mars Rover Vehicle 194
- 4.9 Control System Characteristics Using MATLAB 196
- 4.10 Sequential Design Example: Disk Drive Read System 202
- 4.11 Summary 205
 - Exercises 207
 - Problems 209
 - Advanced Problems 215
 - Design Problems 218
 - MATLAB Problems 220
 - Terms and Concepts 222

CHAPTER 5 *The Performance of Feedback Control Systems* **223**

- 5.1 Introduction 224
- 5.2 Test Input Signals 225
- 5.3 Performance of a Second-Order System 227
- 5.4 Effects of a Third Pole and a Zero on the Second-Order System Response 233
- 5.5 Estimation of the Damping Ratio 238
- 5.6 The s -Plane Root Location and the Transient Response 239
- 5.7 The Steady-State Error of Feedback Control Systems 240
- 5.8 The Steady-State Error of Nonunity Feedback Systems 245
- 5.9 Performance Indices 247
- 5.10 The Simplification of Linear Systems 256
- 5.11 Design Example: Hubble Telescope Pointing Control 259
- 5.12 System Performance Using MATLAB 262
- 5.13 Sequential Design Example: Disk Drive Read System 271
- 5.14 Summary 277
 - Exercises 275
 - Problems 279
 - Advanced Problems 284
 - Design Problems 285
 - MATLAB Problems 287
 - Terms and Concepts 289

CHAPTER 6 *The Stability of Linear Feedback Systems* **290**

- 6.1 The Concept of Stability 291
- 6.2 The Routh-Hurwitz Stability Criterion 295
- 6.3 The Relative Stability of Feedback Control Systems 303
- 6.4 The Stability of State Variable Systems 304
- 6.5 Design Example: Tracked Vehicle Turning Control 307
- 6.6 System Stability Using MATLAB 309
- 6.7 Sequential Design Example: Disk Drive Read System 317
- 6.8 Summary 320
 - Exercises 321
 - Problems 322
 - Advanced Problems 326
 - Design Problems 328
 - MATLAB Problems 329
 - Terms and Concepts 330

CHAPTER 7 *The Root Locus Method* 331

- 7.1 Introduction 332
- 7.2 The Root Locus Concept 332
- 7.3 The Root Locus Procedure 339
- 7.4 An Example of a Control System Analysis and Design Utilizing the Root Locus Method 351
- 7.5 Parameter Design by the Root Locus Method 354
- 7.6 Sensitivity and the Root Locus 359
- 7.7 Three-Term (PID) Controllers 366
- 7.8 Design Example: Laser Manipulator Control System 368
- 7.9 The Design of a Robot Control System 371
- 7.10 The Root Locus Using MATLAB 373
- 7.11 Sequential Design Example: Disk Drive Read System 379
- 7.12 Summary 380
 - Exercises 384
 - Problems 386
 - Advanced Problems 396
 - Design Problems 398
 - MATLAB Problems 404
 - Terms and Concepts 405

CHAPTER 8 *Frequency Response Methods* 406

- 8.1 Introduction 407
- 8.2 Frequency Response Plots 409
- 8.3 An Example of Drawing the Bode Diagram 426
- 8.4 Frequency Response Measurements 430
- 8.5 Performance Specifications in the Frequency Domain 432
- 8.6 Log Magnitude and Phase Diagrams 435
- 8.7 Design Example: Engraving Machine Control System 435
- 8.8 Frequency Response Methods Using MATLAB 439
- 8.9 Sequential Design Example: Disk Drive Read System 444
- 8.10 Summary 446
 - Exercises 451
 - Problems 454
 - Advanced Problems 462
 - Design Problems 464
 - MATLAB Problems 466
 - Terms and Concepts 468

CHAPTER 9 *Stability in the Frequency Domain* 469

- 9.1 Introduction 470
- 9.2 Mapping Contours in the s -Plane 471

- 9.3 The Nyquist Criterion 476
- 9.4 Relative Stability and the Nyquist Criterion 487
- 9.5 Time-Domain Performance Criteria Specified in the Frequency Domain 493
- 9.6 System Bandwidth 500
- 9.7 The Stability of Control Systems with Time Delays 501
- 9.8 Design Example: Remotely Controlled Reconnaissance Vehicle 505
- 9.9 PID Controllers in the Frequency Domain 508
- 9.10 Stability in the Frequency Domain Using MATLAB 509
- 9.11 Sequential Design Example: Disk Drive Read System 519
- 9.12 Summary 521
 - Exercises 528
 - Problems 534
 - Advanced Problems 544
 - Design Problems 546
 - MATLAB Problems 551
 - Terms and Concepts 552

CHAPTER 10 *The Design of Feedback Control Systems* 553

- 10.1 Introduction 554
- 10.2 Approaches to System Design 555
- 10.3 Cascade Compensation Networks 557
- 10.4 Phase-Lead Design Using the Bode Diagram 561
- 10.5 Phase-Lead Design Using the Root Locus 567
- 10.6 System Design Using Integration Networks 573
- 10.7 Phase-Lag Design Using the Root Locus 576
- 10.8 Phase-Lag Design Using the Bode Diagram 580
- 10.9 System Design on the Bode Diagram Using Analytical and Computer Methods 585
- 10.10 Systems with a Prefilter 586
- 10.11 Design for Deadbeat Response 589
- 10.12 Design Example: Rotor Winder Control System 592
- 10.13 Design Example: The X-Y Plotter 595
- 10.14 System Design Using MATLAB 598
- 10.15 Sequential Design Example: Disk Drive Read System 605
- 10.16 Summary 606
 - Exercises 608
 - Problems 610
 - Advanced Problems 621
 - Design Problems 624
 - MATLAB Problems 628
 - Terms and Concepts 630

CHAPTER 11 *The Design of State Variable Feedback Systems* **631**

- 11.1 Introduction 631
- 11.2 Controllability 632
- 11.3 Observability 634
- 11.4 Optimal Control Systems 636
- 11.5 Pole Placement Using State Feedback 645
- 11.6 Ackermann's Formula 651
- 11.7 Limitations of State Variable Feedback 652
- 11.8 Internal Model Design 652
- 11.9 Design Example: Automatic Test System 655
- 11.10 State Variable Design Using MATLAB 658
- 11.11 Sequential Design Example: Disk Drive Read System 666
- 11.12 Summary 668
 - Exercises 668
 - Problems 669
 - Advanced Problems 672
 - Design Problems 674
 - MATLAB Problems 677
 - Terms and Concepts 679

CHAPTER 12 *Robust Control Systems* **680**

- 12.1 Introduction 681
- 12.2 Robust Control Systems and System Sensitivity 682
- 12.3 Analysis of Robustness 685
- 12.4 Systems with Uncertain Parameters 688
- 12.5 The Design of Robust Control Systems 690
- 12.6 PID Controllers 695
- 12.7 The Design of Robust PID Controlled Systems 697
- 12.8 Design Example: Aircraft Autopilot 702
- 12.9 The Design of a Space Telescope Control System 703
- 12.10 The Design of a Robust Bobbin Drive 705
- 12.11 The Robust Internal Model Control System 708
- 12.12 The Design of an Ultra-Precision Diamond Turning Machine 710
- 12.13 The Pseudo-Quantitative Feedback System 714
- 12.14 Robust Control Systems Using MATLAB 716
- 12.15 Sequential Design Example: Disk Drive Read System 719
- 12.16 Summary 721
 - Exercises 723
 - Problems 724
 - Advanced Problems 730
 - Design Problems 733
 - MATLAB Problems 741
 - Terms and Concepts 742

CHAPTER 13 *Digital Control Systems* 743

- 13.1 Introduction 744
- 13.2 Digital Computer Control System Applications 744
- 13.3 Sampled-Data Systems 746
- 13.4 The z -Transform 749
- 13.5 Closed-Loop Feedback Sampled-Data Systems 754
- 13.6 Stability Analysis in the z -Plane 756
- 13.7 Performance of a Sampled-Data, Second-Order System 757
- 13.8 Closed-Loop Systems with Digital Computer Compensation 760
- 13.9 The Design of a Worktable Motion Control System 762
- 13.10 The Root Locus of Digital Control Systems 764
- 13.11 Implementation of Digital Controllers 768
- 13.12 Digital Control Systems Using MATLAB 769
- 13.13 Sequential Design Example: Disk Drive Read System 774
- 13.14 Summary 776
 - Exercises 776
 - Problems 778
 - Advanced Problems 780
 - Design Problems 782
 - MATLAB Problems 783
 - Terms and Concepts 784

APPENDIX A *MATLAB Basics* 787

APPENDIX B *Simulink Basics* 805

APPENDIX C *Symbols, Units, and Conversion Factors*
On WWW

APPENDIX D *Laplace Transform Pairs*

APPENDIX E *An Introduction to Matrix Algebra*
On WWW

APPENDIX F *Decibel Conversion* *On WWW*

APPENDIX G *Complex Numbers* *On WWW*

APPENDIX H *z -Transfer Pairs* *On WWW*

References 813

Index 825