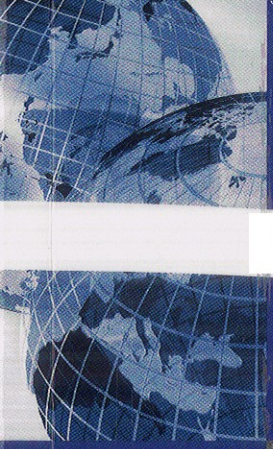
Pearson International Edition



Modern Control Systems

ELEVENTH EDITION

Richard C. Dorf Robert H. Bishop

Contents

Preface xiii
About the Authors xxv

CHAPTER 1 *Introduction to Control Systems 1*

1.1 Introduction 2
1.2 Brief History of Automatic Control 4
1.3 Examples of Control Systems 8
1.4 Engineering Design 16
1.5 Control System Design 17
1.6 Mechatronic Systems 20
1.7 The Future Evolution of Control Systems 24
1.8 Design Examples 25
1.9 Sequential Design Example: Disk Drive Read System 28
1.10 Summary 30
Exercises 30
Problems 31
Advanced Problems 36
Design Problems 38
Terms and Concepts 39

CHAPTER 2 *Mathematical Models of Systems 41*

2.1 Introduction 42
2.2 Differential Equations of Physical Systems 42
2.3 Linear Approximations of Physical Systems 47
2.4 The Laplace Transform 50
2.5 The Transfer Function of Linear Systems 57
2.6 Block Diagram Models 71
2.7 Signal-Flow Graph Models 76
2.8 Design Examples 82
2.9 The Simulation of Systems Using Control Design Software 102
2.10 Sequential Design Example: Disk Drive Read System 117
2.11 Summary 119
Exercises 120
Problems 126
Advanced Problems 137
Design Problems 139
Computer Problems 140
Terms and Concepts 142

CHAPTER 3 *State Variable Models 144*

3.1 Introduction 145
3.2 The State Variables of a Dynamic System 145
3.3 The State Differential Equation 149
3.4 Signal-Flow Graph and Block Diagram Models 154
3.5 Alternative Signal-Flow Graph and Block Diagram Models 165
3.6 The Transfer Function from the State Equation 170
3.7 The Time Response and the State Transition Matrix 172
3.8 Design Examples 176
3.9 Analysis of State Variable Models Using Control Design Software 189
3.10 Sequential Design Example: Disk Drive Read System 192
3.11 Summary 196
Exercises 197
Problems 199
Advanced Problems 207
Design Problems 208
Computer Problems 210
Terms and Concepts 211

CHAPTER 4 *Feedback Control System Characteristics 212*

4.1 Introduction 213
4.2 Error Signal Analysis 215
4.3 Sensitivity of Control Systems to Parameter Variations 217
4.4 Disturbance Signals in a Feedback Control System 220
4.5 Control of the Transient Response 225
4.6 Steady-State Error 228
4.7 The Cost of Feedback 231
4.8 Design Examples 232
4.9 Control System Characteristics Using Control Design Software 246
4.10 Sequential Design Example: Disk Drive Read System 251
4.11 Summary 255
Exercises 257
Problems 261
Advanced Problems 267
Design Problems 270
Computer Problems 273
Terms and Concepts 276

CHAPTER 5 *The Performance of Feedback Control Systems 277*

5.1 Introduction 278
5.2 Test Input Signals 278
5.3 Performance of Second-Order Systems 281

5.4 Effects of a Third Pole and a Zero on the Second-Order System Response 287
5.5 The *s*-Plane Root Location and the Transient Response 293
5.6 The Steady-State Error of Feedback Control Systems 295
5.7 Performance Indices 303
5.8 The Simplification of Linear Systems 312
5.9 Design Examples 315
5.10 System Performance Using Control Design Software 329
5.11 Sequential Design Example: Disk Drive Read System 333
5.12 Summary 337
Exercises 337
Problems 341
Advanced Problems 346
Design Problems 348
Computer Problems 350
Terms and Concepts 353

CHAPTER 6 ***The Stability of Linear Feedback Systems 355***

6.1 The Concept of Stability 356
6.2 The Routh–Hurwitz Stability Criterion 360
6.3 The Relative Stability of Feedback Control Systems 368
6.4 The Stability of State Variable Systems 370
6.5 Design Examples 373
6.6 System Stability Using Control Design Software 382
6.7 Sequential Design Example: Disk Drive Read System 390
6.8 Summary 393
Exercises 394
Problems 396
Advanced Problems 400
Design Problems 402
Computer Problems 404
Terms and Concepts 406

CHAPTER 7 ***The Root Locus Method 407***

7.1 Introduction 408
7.2 The Root Locus Concept 408
7.3 The Root Locus Procedure 413
7.4 Parameter Design by the Root Locus Method 431
7.5 Sensitivity and the Root Locus 437
7.6 Three-Term (PID) Controllers 444
7.7 Design Examples 447
7.8 The Root Locus Using Control Design Software 458
7.9 Sequential Design Example: Disk Drive Read System 463

7.10 Summary 465
Exercises 469
Problems 472
Advanced Problems 482
Design Problems 485
Computer Problems 490
Terms and Concepts 492

CHAPTER 8 *Frequency Response Methods 493*

8.1 Introduction 494
8.2 Frequency Response Plots 496
8.3 Frequency Response Measurements 517
8.4 Performance Specifications in the Frequency Domain 519
8.5 Log Magnitude and Phase Diagrams 522
8.6 Design Examples 523
8.7 Frequency Response Methods Using Control Design Software 534
8.8 Sequential Design Example: Disk Drive Read System 540
8.9 Summary 541
Exercises 546
Problems 549
Advanced Problems 558
Design Problems 560
Computer Problems 564
Terms and Concepts 566

CHAPTER 9 *Stability in the Frequency Domain 567*

9.1 Introduction 568
9.2 Mapping Contours in the *s*-Plane 569
9.3 The Nyquist Criterion 575
9.4 Relative Stability and the Nyquist Criterion 586
9.5 Time-Domain Performance Criteria in the Frequency Domain 594
9.6 System Bandwidth 601
9.7 The Stability of Control Systems with Time Delays 601
9.8 Design Examples 606
9.9 PID Controllers in the Frequency Domain 620
9.10 Stability in the Frequency Domain Using Control Design Software 621
9.11 Sequential Design Example: Disk Drive Read System 629
9.12 Summary 632
Exercises 640
Problems 646
Advanced Problems 656
Design Problems 659
Computer Problems 664
Terms and Concepts 665

CHAPTER 10 *The Design of Feedback Control Systems 667*

10.1 Introduction 668
10.2 Approaches to System Design 669
10.3 Cascade Compensation Networks 671
10.4 Phase-Lead Design Using the Bode Diagram 675
10.5 Phase-Lead Design Using the Root Locus 681
10.6 System Design Using Integration Networks 688
10.7 Phase-Lag Design Using the Root Locus 691
10.8 Phase-Lag Design Using the Bode Diagram 696
10.9 Design on the Bode Diagram Using Analytical Methods 700
10.10 Systems with a Prefilter 702
10.11 Design for Deadbeat Response 705
10.12 Design Examples 707
10.13 System Design Using Control Design Software 720
10.14 Sequential Design Example: Disk Drive Read System 726
10.15 Summary 728
Exercises 730
Problems 734
Advanced Problems 744
Design Problems 747
Computer Problems 752
Terms and Concepts 754

CHAPTER 11 *The Design of State Variable Feedback Systems 756*

11.1 Introduction 757
11.2 Controllability and Observability 757
11.3 Full-State Feedback Control Design 763
11.4 Observer Design 769
11.5 Integrated Full-State Feedback and Observer 773
11.6 Reference Inputs 779
11.7 Optimal Control Systems 781
11.8 Internal Model Design 791
11.9 Design Examples 795
11.10 State Variable Design Using Control Design Software 804
11.11 Sequential Design Example: Disk Drive Read System 810
11.12 Summary 812
Exercises 812
Problems 814
Advanced Problems 818
Design Problems 821
Computer Problems 824
Terms and Concepts 826

CHAPTER 12 *Robust Control Systems 828*

12.1 Introduction 829
12.2 Robust Control Systems and System Sensitivity 830
12.3 Analysis of Robustness 834
12.4 Systems with Uncertain Parameters 836
12.5 The Design of Robust Control Systems 838
12.6 The Design of Robust PID-Controlled Systems 844
12.7 The Robust Internal Model Control System 850
12.8 Design Examples 853
12.9 The Pseudo-Quantitative Feedback System 870
12.10 Robust Control Systems Using Control Design Software 871
12.11 Sequential Design Example: Disk Drive Read System 876
12.12 Summary 878
Exercises 879
Problems 881
Advanced Problems 887
Design Problems 891
Computer Problems 897
Terms and Concepts 899

CHAPTER 13 *Digital Control Systems 901*

13.1 Introduction 902
13.2 Digital Computer Control System Applications 902
13.3 Sampled-Data Systems 904
13.4 The z-Transform 907
13.5 Closed-Loop Feedback Sampled-Data Systems 912
13.6 Performance of a Sampled-Data, Second-Order System 916
13.7 Closed-Loop Systems with Digital Computer Compensation 918
13.8 The Root Locus of Digital Control Systems 921
13.9 Implementation of Digital Controllers 925
13.10 Design Examples 926
13.11 Digital Control Systems Using Control Design Software 935
13.12 Sequential Design Example: Disk Drive Read System 940
13.13 Summary 942
Exercises 942
Problems 945
Advanced Problems 946
Design Problems 947
Computer Problems 949
Terms and Concepts 950

APPENDIX A *MATLAB Basics 953*

APPENDIX B *MathScript Basics 971*

WEB RESOURCES

APPENDIX C *Symbols, Units, and Conversion Factors*

APPENDIX D *Laplace Transform Pairs*

APPENDIX E *An Introduction to Matrix Algebra*

APPENDIX F *Decibel Conversion*

APPENDIX G *Complex Numbers*

APPENDIX H *z-Transform Pairs Preface*

APPENDIX I *Discrete-Time Evaluation of the Time Response*

References 993

Index 1007