Contents

PREFACE *xi*

PREFACE TO COMPUTER-AIDED ANALYSIS AND DESIGN PROGRAMS *xv*

1 INTRODUCTION *1*

1.1 Overview 1
1.2 Digital Control System 3
1.3 The Control Problem 7
1.4 Satellite Model 9
1.5 Servomotor System Model 10
1.6 Temperature Control System 16
1.7 Summary 18
References 18
Problems 19

2 DISCRETE-TIME SYSTEMS AND THE z-TRANSFORM *27*

2.1 Introduction 27
2.2 Discrete-Time Systems 27
2.3 Transform Methods 30
2.4 Properties of the z-Transform 31
2.5 Solution of Difference Equations 37

2.6 The Inverse z-Transform 40
2.7 Simulation Diagrams and Flow Graphs, 48
2.8 State Variables 53
2.9 Other State-Variable Formulations 62
2.10 Transfer Functions 68
2.11 Solutions of the State Equations 71
2.12 Linear Time-Varying Systems 76
2.13 Summary 77
References and Further Reading 77
Problems 78

3 *SAMPLING AND RECONSTRUCTION* 89

3.1 Introduction 89
3.2 Sampled-Data Control Systems 89
3.3 The Ideal Sampler 92
3.4 Evaluation of $E^*(s)$ 95
3.5 Results from the Fourier Transform 97
3.6 Properties of $E^*(s)$ 99
3.7 Data Reconstruction 102
3.8 Digital-to-Analog Conversion 111
3.9 Analog-to-Digital Conversion 113
3.10 Summary 124
References and Further Reading 125
Problems 125

4 *OPEN-LOOP DISCRETE-TIME SYSTEMS* 131

4.1 Introduction 131
4.2 The Relationship between $E(z)$ and $E^*(s)$ 132
4.3 The Pulse Transfer Function 133
4.4 Open-Loop Systems Containing Digital Filters 138
4.5 The Modified z-Transform 142
4.6 Systems with Time Delays 144
4.7 Nonsynchronous Sampling 147
4.8 State-Variable Models 150
4.9 Review of Continuous State Variables 152
4.10 Discrete State Equations 156
4.11 Practical Calculations 159
4.12 Summary 161
References and Further Reading 161
Problems 162

5 *CLOSED-LOOP SYSTEMS* 173

5.1 Introduction 173
5.2 Preliminary Concepts 173
5.3 Derivation Procedure 176
5.4 State-Variable Models 183
5.5 Summary 191
References and Further Reading 192
Problems 192

6 *SYSTEM TIME-RESPONSE CHARACTERISTICS* 202

6.1 Introduction 202
6.2 System Time Response 202
6.3 System Characteristic Equation 210
6.4 Mapping the s-Plane into the z-Plane 210
6.5 Steady-State Accuracy 218
6.6 Simulation 221
6.7 Control Software 226
6.8 Summary 227
References and Further Reading 227
Problems 227

7 *STABILITY ANALYSIS TECHNIQUES* 235

7.1 Introduction 235
7.2 Stability 235
7.3 Bilinear Transformation 240
7.4 The Routh–Hurwitz Criterion 242
7.5 Jury's Stability Test 245
7.6 Root Locus 249
7.7 The Nyquist Criterion 252
7.8 The Bode Diagram 261
7.9 Interpretation of the Frequency Response 264
7.10 Closed-Loop Frequency Response 266
7.11 Summary 271
References and Further Reading 271
Problems 272

8 *DIGITAL CONTROLLER DESIGN* 281

8.1 Introduction 281
8.2 Control System Specifications 282
8.3 Compensation 289

8.4 Phase-Lag Compensation 291
8.5 Phase-Lead Compensation 297
8.6 Phase-Lead Design Procedure 300
8.7 Lag–Lead Compensation 307
8.8 Integration and Differentiation Filters 310
8.9 PID Controllers 312
8.10 PID Controller Design 315
8.11 Design by Root Locus 319
8.12 Summary 327
References and Further Reading 327
Problems 328

9 *POLE-ASSIGNMENT DESIGN AND STATE ESTIMATION* 337

9.1 Introduction 337
9.2 Pole Assignment 338
9.3 State Estimation 345
9.4 Reduced-Order Observers 357
9.5 Current Observers 361
9.6 Controllability and Observability 365
9.7 Systems with Inputs 369
9.8 Summary 374
References and Further Reading 375
Problems 376

10 *LINEAR QUADRATIC OPTIMAL CONTROL* 382

10.1 Introduction 382
10.2 The Quadratic Cost Function 384
10.3 The Principle of Optimality 386
10.4 Linear Quadratic Optimal Control 389
10.5 The Minimum Principle 397
10.6 Steady-State Optimal Control 398
10.7 Least-Squares Curve Fitting 404
10.8 Least-Squares System Identification 406
10.9 Recursive Least-Squares System Identification 410
10.10 Optimal State Estimation–Kalman Filters 413
10.11 Least-Squares Minimization 420
10.12 Summary 421
References and Further Reading 421
Problems 422

11 *SAMPLED-DATA TRANSFORMATION OF ANALOG FILTERS* 430

11.1 Introduction 430
11.2 Sampled-Data Transformations 430
11.3 Review of Continuous Filter Design 447
11.4 Transforming Analog Filters 455
11.5 Summary 462
References 462
Problems 463

12 *DIGITAL FILTER STRUCTURES* 465

12.1 Introduction 465
12.2 Direct Structures 465
12.3 Second-Order Modules 470
12.4 Cascade Realization 475
12.5 Parallel Realization 478
12.6 PID Controllers 483
12.7 Ladder Realization 485
12.8 Other Structures 490
12.9 Summary 490
References 490
Problems 491

13 *MICROCOMPUTER IMPLEMENTATION OF DIGITAL FILTERS* 493

13.1 Introduction 493
13.2 The Intel 80 × 86 [1] 493
13.3 Implementing Second-Order Modules [3] 497
13.4 Parallel Implementation of Higher-Order Filters 505
13.5 Cascade Implementation of Higher-Order Filters 506
13.6 Comparison of Structures 512
13.7 LabVIEW [7, 8] 512
13.8 Summary 523
References 524
Problems 524

14 *FINITE-WORDLENGTH EFFECTS* 525

14.1 Introduction 525
14.2 Fixed-Point Number Systems 525

14.3 Coefficient Quantization 541
14.4 Signal Quantization Analysis 546
14.5 Limit Cycles 561
14.6 Impact of Finite Wordlength on Filter Implementation 574
14.7 Cascaded Second-Order Modules 575
14.8 Parallel Second-Order Modules 590
14.9 Summary 593
References 593
Problems 595

15 CASE STUDIES **597**

15.1 Introduction 597
15.2 Servomotor System 598
15.3 Environmental Chamber Control System 605
15.4 Aircraft Landing System 613
References 622

APPENDIXES

I Design Equations 624
II Mason's Gain Formula 626
III Evaluation of $E^*(s)$ 631
IV Review of Matrices 637
V Second-Order Module Subroutines 645
VI Control Software 654
VII The Laplace Transform 660
VIII z-Transform Tables 675

INDEX **679**