

Contents

Preface xiii

1 An Overview and Brief History of Feedback Control 1

A Perspective on Feedback Control	1
Chapter Overview	2
1.1 A Simple Feedback System	3
1.2 A First Analysis of Feedback	6
1.3 Feedback System Fundamentals	10
1.4 A Brief History	11
1.5 An Overview of the Book	17
Summary	19
Review Questions	19
Problems	20

2 Dynamic Models 23

A Perspective on Dynamic Models	23
Chapter Overview	24
2.1 Dynamics of Mechanical Systems	24
2.1.1 Translational Motion	24
2.1.2 Rotational Motion	31
2.1.3 Combined Rotation and Translation	39
2.1.4 Complex Mechanical Systems (W)**	42
2.1.5 Distributed Parameter Systems	42
2.1.6 Summary: Developing Equations of Motion for Rigid Bodies	44
2.2 Models of Electric Circuits	45
2.3 Models of Electromechanical Systems	50
2.3.1 Loudspeakers	50
2.3.2 Motors	52
2.3.3 Gears	56
△ 2.4 Heat and Fluid-Flow Models	57
2.4.1 Heat Flow	58
2.4.2 Incompressible Fluid Flow	61
2.5 Historical Perspective	68
Summary	71
Review Questions	71
Problems	72

**Sections with (W) indicates that additional material is located on the web at www.FPE7e.com.

3 Dynamic Response 84

A Perspective on System Response	84
Chapter Overview	85
3.1 Review of Laplace Transforms	85
3.1.1 Response by Convolution	86
3.1.2 Transfer Functions and Frequency Response	91
3.1.3 The \mathcal{L} -Laplace Transform	101
3.1.4 Properties of Laplace Transforms	103
3.1.5 Inverse Laplace Transform by Partial-Fraction Expansion	105
3.1.6 The Final Value Theorem	107
3.1.7 Using Laplace Transforms to Solve Differential Equations	109
3.1.8 Poles and Zeros	111
3.1.9 Linear System Analysis Using Matlab [®]	112
3.2 System Modeling Diagrams	118
3.2.1 The Block Diagram	118
3.2.2 Block-Diagram Reduction Using Matlab	122
3.2.3 Mason's Rule and the Signal Flow Graph (W)	123
3.3 Effect of Pole Locations	123
3.4 Time-Domain Specifications	131
3.4.1 Rise Time	132
3.4.2 Overshoot and Peak Time	132
3.4.3 Settling Time	134
3.5 Effects of Zeros and Additional Poles	137
3.6 Stability	146
3.6.1 Bounded Input–Bounded Output Stability	147
3.6.2 Stability of LTI Systems	148
3.6.3 Routh's Stability Criterion	149
△ 3.7 Obtaining Models from Experimental Data: System Identification (W)	156
△ 3.8 Amplitude and Time Scaling (W)	156
3.9 Historical Perspective	156
Summary	157
Review Questions	159
Problems	159

4 A First Analysis of Feedback 180

A Perspective on the Analysis of Feedback	180
Chapter Overview	181
4.1 The Basic Equations of Control	182
4.1.1 Stability	183
4.1.2 Tracking	184
4.1.3 Regulation	185
4.1.4 Sensitivity	186

4.2	Control of Steady-State Error to Polynomial Inputs: System Type	188
4.2.1	System Type for Tracking	189
4.2.2	System Type for Regulation and Disturbance Rejection	194
4.3	The Three-Term Controller: PID Control	196
4.3.1	Proportional Control (P)	196
4.3.2	Integral Control (I)	198
4.3.3	Derivative Control (D)	201
4.3.4	Proportional Plus Integral Control (PI)	201
4.3.5	PID Control	202
4.3.6	Ziegler–Nichols Tuning of the PID Controller	206
4.4	Feedforward Control by Plant Model Inversion	212
△	4.5 Introduction to Digital Control (W)	214
△	4.6 Sensitivity of Time Response to Parameter Change (W)	215
4.7	Historical Perspective	215
	Summary	217
	Review Questions	218
	Problems	218

5 The Root-Locus Design Method **234**

	A Perspective on the Root-Locus Design Method	234
	Chapter Overview	235
5.1	Root Locus of a Basic Feedback System	235
5.2	Guidelines for Determining a Root Locus	240
5.2.1	Rules for Determining a Positive (180°) Root Locus	242
5.2.2	Summary of the Rules for Determining a Root Locus	248
5.2.3	Selecting the Parameter Value	249
5.3	Selected Illustrative Root Loci	251
5.4	Design Using Dynamic Compensation	264
5.4.1	Design Using Lead Compensation	266
5.4.2	Design Using Lag Compensation	270
5.4.3	Design Using Notch Compensation	272
△	5.4.4 Analog and Digital Implementations (W)	274
5.5	A Design Example Using the Root Locus	275
5.6	Extensions of the Root-Locus Method	281
5.6.1	Rules for Plotting a Negative (0°) Root Locus	281
△	5.6.2 Consideration of Two Parameters	284
△	5.6.3 Time Delay (W)	286
5.7	Historical Perspective	287

Summary	289
Review Questions	290
Problems	291

6 The Frequency-Response Design Method 308

A Perspective on the Frequency-Response Design Method	308
Chapter Overview	309
6.1 Frequency Response	309
6.1.1 Bode Plot Techniques	317
6.1.2 Steady-State Errors	330
6.2 Neutral Stability	331
6.3 The Nyquist Stability Criterion	333
6.3.1 The Argument Principle	334
6.3.2 Application of The Argument Principle to Control Design	335
6.4 Stability Margins	348
6.5 Bode's Gain-Phase Relationship	357
6.6 Closed-Loop Frequency Response	361
6.7 Compensation	363
6.7.1 PD Compensation	363
6.7.2 Lead Compensation (W)	364
6.7.3 PI Compensation	374
6.7.4 Lag Compensation	375
6.7.5 PID Compensation	381
6.7.6 Design Considerations	387
6.7.7 Specifications in Terms of the Sensitivity Function	389
6.7.8 Limitations on Design in Terms of the Sensitivity Function	394
6.8 Time Delay	398
6.8.1 Time Delay via the Nyquist Diagram (W)	400
6.9 Alternative Presentation of Data	400
6.9.1 Nichols Chart	400
6.9.2 The Inverse Nyquist Diagram (W)	404
6.10 Historical Perspective	404
Summary	405
Review Questions	408
Problems	408

7 State-Space Design 433

A Perspective on State-Space Design	433
Chapter Overview	434
7.1 Advantages of State-Space	434
7.2 System Description in State-Space	436
7.3 Block Diagrams and State-Space	442

7.4	Analysis of the State Equations	444
7.4.1	Block Diagrams and Canonical Forms	445
7.4.2	Dynamic Response from the State Equations	457
7.5	Control-Law Design for Full-State Feedback	463
7.5.1	Finding the Control Law	464
7.5.2	Introducing the Reference Input with Full-State Feedback	473
7.6	Selection of Pole Locations for Good Design	477
7.6.1	Dominant Second-Order Poles	477
7.6.2	Symmetric Root Locus (SRL)	479
7.6.3	Comments on the Methods	488
7.7	Estimator Design	489
7.7.1	Full-Order Estimators	489
7.7.2	Reduced-Order Estimators	495
7.7.3	Estimator Pole Selection	499
7.8	Compensator Design: Combined Control Law and Estimator (W)	501
7.9	Introduction of the Reference Input with the Estimator (W)	514
7.9.1	General Structure for the Reference Input	515
7.9.2	Selecting the Gain	524
7.10	Integral Control and Robust Tracking	525
7.10.1	Integral Control	526
△	7.10.2 Robust Tracking Control: The Error-Space Approach	528
△	7.10.3 Model-Following Design	539
△	7.10.4 The Extended Estimator	543
△	7.11 Loop Transfer Recovery	547
△	7.12 Direct Design with Rational Transfer Functions	552
△	7.13 Design for Systems with Pure Time Delay	556
7.14	Solution of State Equations (W)	559
7.15	Historical Perspective	559
	Summary	562
	Review Questions	565
	Problems	566

8

Digital Control 590

A Perspective on Digital Control	590
Chapter Overview	591
8.1 Digitization	591
8.2 Dynamic Analysis of Discrete Systems	594
8.2.1 z -Transform	594
8.2.2 z -Transform Inversion	595

8.2.3	Relationship Between s and z	597
8.2.4	Final Value Theorem	599
8.3	Design Using Discrete Equivalents	601
8.3.1	Tustin's Method	602
8.3.2	Zero-Order Hold (ZOH) Method	605
8.3.3	Matched Pole–Zero (MPZ) Method	607
8.3.4	Modified Matched Pole–Zero (MMPZ) Method	611
8.3.5	Comparison of Digital Approximation Methods	612
8.3.6	Applicability Limits of the Discrete Equivalent Design Method	613
8.4	Hardware Characteristics	613
8.4.1	Analog-to-Digital (A/D) Converters	614
8.4.2	Digital-to-Analog Converters	614
8.4.3	Anti-Alias Prefilters	615
8.4.4	The Computer	616
8.5	Sample-Rate Selection	617
8.5.1	Tracking Effectiveness	618
8.5.2	Disturbance Rejection	618
8.5.3	Effect of Anti-Alias Prefilter	619
8.5.4	Asynchronous Sampling	620
△ 8.6	Discrete Design	620
8.6.1	Analysis Tools	621
8.6.2	Feedback Properties	622
8.6.3	Discrete Design Example	623
8.6.4	Discrete Analysis of Designs	626
8.7	Discrete State-Space Design Methods (W)	628
8.8	Historical Perspective	628
	Summary	629
	Review Questions	631
	Problems	631

9 Nonlinear Systems 637

	A Perspective on Nonlinear Systems	637
	Chapter Overview	638
9.1	Introduction and Motivation: Why Study Nonlinear Systems?	639
9.2	Analysis by Linearization	641
9.2.1	Linearization by Small-Signal Analysis	641
9.2.2	Linearization by Nonlinear Feedback	646
9.2.3	Linearization by Inverse Nonlinearity	647
9.3	Equivalent Gain Analysis Using the Root Locus	648
9.3.1	Integrator Antiwindup	655

- 9.4 Equivalent Gain Analysis Using Frequency Response: Describing Functions 658
 - 9.4.1 Stability Analysis Using Describing Functions 665
- △ 9.5 Analysis and Design Based on Stability 670
 - 9.5.1 The Phase Plane 670
 - 9.5.2 Lyapunov Stability Analysis 677
 - 9.5.3 The Circle Criterion 683
- 9.6 Historical Perspective 690
- Summary 691
- Review Questions 691
- Problems 692

10 Control System Design: Principles and Case Studies 703

- A Perspective on Design Principles 703
- Chapter Overview 704
- 10.1 An Outline of Control Systems Design 705
- 10.2 Design of a Satellite's Attitude Control 711
- 10.3 Lateral and Longitudinal Control of a Boeing 747 729
 - 10.3.1 Yaw Damper 733
 - 10.3.2 Altitude-Hold Autopilot 741
- 10.4 Control of the Fuel–Air Ratio in an Automotive Engine 747
- 10.5 Control of the Read/Write Head Assembly of a Hard Disk 755
- 10.6 Control of RTP Systems in Semiconductor Wafer Manufacturing 763
- 10.7 Chemotaxis or How *E. Coli* Swims Away from Trouble 777
- 10.8 Historical Perspective 786
- Summary 788
- Review Questions 790
- Problems 790

Appendix A Laplace Transforms 804

- A.1 The \mathcal{L} -Laplace Transform 804
 - A.1.1 Properties of Laplace Transforms 805
 - A.1.2 Inverse Laplace Transform by Partial-Fraction Expansion 813
 - A.1.3 The Initial Value Theorem 816
 - A.1.4 Final Value Theorem 817

Appendix B Solutions to the Review Questions 819

Appendix C Matlab Commands 835

Bibliography 840

Index 848

List of Appendices on the web at www.fpe7e.com

Appendix WA: A Review of Complex Variables

Appendix WB: Summary of Matrix Theory

Appendix WC: Controllability and Observability

Appendix WD: Ackermann's Formula for Pole Placement

Appendix W2.1.4: Complex Mechanical Systems

Appendix W3.2.3: Mason's Rule and Signal Flow Graph

Appendix W3.6.3.1: Routh Special Cases

Appendix W3.7: System Identification

Appendix W3.8: Amplitude and Time Scaling

Appendix W4.1.4.1: The Filtered Case

**Appendix W4.2.2.1: Truxal's Formula for the Error
Constants**

Appendix W4.5: Introduction to Digital Control

**Appendix W4.6: Sensitivity of Time Response to Parameter
Change**

Appendix W5.4.4: Analog and Digital Implementations

Appendix W5.6.3: Root Locus with Time Delay

**Appendix W6.7.2: Digital Implementation of
Example 6.15**

Appendix W6.8.1: Time Delay via the Nyquist Diagram

Appendix W6.9.2: The Inverse Nyquist Diagram

Appendix W7.8: Digital Implementation of Example 7.31

Appendix W7.9: Digital Implementation of Example 7.33

Appendix W7.14: Solution of State Equations

Appendix W8.7: Discrete State-Space Design Methods