



CONTROL SYSTEMS **ENGINEERING**

THIRD EDITION

Suranaree University of Technology



31051000606356

Norman S. Nise

Contents

1. Introduction

1

- 1.1 Introduction, 2
- 1.2 A History of Control Systems, 4
- 1.3 The Control Systems Engineer, 9
- 1.4 Response Characteristics and System Configurations, 10
- 1.5 Analysis and Design Objectives, 14
 - Introduction to a Case Study, 17
- 1.6 The Design Process, 21
- 1.7 Computer-Aided Design, 26
 - Summary, 28
 - Review Questions, 29
 - Problems, 29
 - Bibliography, 35

2. Modeling in the Frequency Domain

37

- 2.1 Introduction, 38
- 2.2 Laplace Transform Review, 39
- 2.3 The Transfer Function, 49

- 2.4 Electric Network Transfer Functions, 52
- 2.5 Translational Mechanical System Transfer Functions, 68
- 2.6 Rotational Mechanical System Transfer Functions, 76
- 2.7 Transfer Functions for Systems with Gears, 82
- 2.8 Electromechanical System Transfer Functions, 87
- 2.9 Electric Circuit Analogs, 94
- 2.10 Nonlinearities, 97
- 2.11 Linearization, 99
 - Case Studies, 105
 - Summary, 109
 - Review Questions, 109
 - Problems, 110
 - Bibliography, 125

3. Modeling in the Time Domain 127

- 3.1 Introduction, 128
- 3.2 Some Observations, 129
- 3.3 The General State-Space Representation, 133
- 3.4 Applying the State-Space Representation, 136
- 3.5 Converting a Transfer Function to State Space, 144
- 3.6 Converting from State Space to a Transfer Function, 151
- 3.7 Linearization, 154
 - Case Studies, 157
 - Summary, 162
 - Review Questions, 163
 - Problems, 163
 - Bibliography, 172

4. Time Response 174

- 4.1 Introduction, 175
- 4.2 Poles, Zeros, and System Response, 175

- 4.3 First-Order Systems, 179**
- 4.4 Second-Order Systems: Introduction, 182**
- 4.5 The General Second-Order System, 188**
- 4.6 Underdamped Second-Order Systems, 191**
- 4.7 System Response with Additional Poles, 202**
- 4.8 System Response with Zeros, 206**
- 4.9 Effects of Nonlinearities Upon Time Response, 212**
- 4.10 Laplace Transform Solution of State Equations, 216**
- 4.11 Time Domain Solution of State Equations, 219**
 - Case Studies, 227**
 - Summary, 232**
 - Review Questions, 234**
 - Problems, 235**
 - Design Problems, 245**
 - Bibliography, 249**

5. Reduction of Multiple Subsystems

250

- 5.1 Introduction, 251**
- 5.2 Block Diagrams, 251**
- 5.3 Analysis and Design of Feedback Systems, 261**
- 5.4 Signal-Flow Graphs, 264**
- 5.5 Mason's Rule, 267**
- 5.6 Signal-Flow Graphs of State Equations, 270**
- 5.7 Alternative Representations in State Space, 273**
- 5.8 Similarity Transformations, 283**
 - Case Studies, 295**
 - Summary, 301**
 - Review Questions, 302**
 - Problems, 303**
 - Design Problems, 320**
 - Bibliography, 323**

6. Stability	324
6.1 Introduction, 325	
6.2 Routh-Hurwitz Criterion, 329	
6.3 Routh-Hurwitz Criterion: Special Cases, 332	
6.4 Routh-Hurwitz Criterion: Additional Examples, 340	
6.5 Stability in State Space, 348	
Case Studies, 351	
Summary, 353	
Review Questions, 354	
Problems, 354	
Design Problems, 362	
Bibliography, 365	
7. Steady-State Errors	367
7.1 Introduction, 368	
7.2 Steady-State Error for Unity Feedback Systems, 372	
7.3 Static Error Constants and System Type, 378	
7.4 Steady-State Error Specifications, 383	
7.5 Steady-State Error for Disturbances, 385	
7.6 Steady-State Error for Nonunity Feedback Systems, 388	
7.7 Sensitivity, 392	
7.8 Steady-State Error for Systems in State Space, 395	
Case Studies, 399	
Summary, 402	
Review Questions, 403	
Problems, 404	
Design Problems, 418	
Bibliography, 421	
8. Root Locus Techniques	422
8.1 Introduction, 423	
8.2 Defining the Root Locus, 427	

- 8.3 Properties of the Root Locus, 430
- 8.4 Sketching the Root Locus, 433
- 8.5 Refining the Sketch, 438
- 8.6 An Example, 449
- 8.7 Transient Response Design via Gain Adjustment, 452
- 8.8 Generalized Root Locus, 458
- 8.9 Root Locus for Positive-Feedback Systems, 459
- 8.10 Pole Sensitivity, 463
 - Case Studies, 465
 - Summary, 470
 - Review Questions, 471
 - Problems, 472
 - Design Problems, 487
 - Bibliography, 494

9. Design via Root Locus

495

- 9.1 Introduction, 496
- 9.2 Improving Steady-State Error via Cascade Compensation, 499
- 9.3 Improving Transient Response via Cascade Compensation, 510
- 9.4 Improving Steady-State Error and Transient Response, 527
- 9.5 Feedback Compensation, 543
- 9.6 Physical Realization of Compensation, 554
 - Case Studies, 560
 - Summary, 566
 - Review Questions, 567
 - Problems, 568
 - Design Problems, 578
 - Bibliography, 584

10. Frequency Response Techniques

585

- 10.1 Introduction, 586
- 10.2 Asymptotic Approximations: Bode Plots, 593
- 10.3 Introduction to the Nyquist Criterion, 614
- 10.4 Sketching the Nyquist Diagram, 619

- 10.5 Stability via the Nyquist Diagram, 626
- 10.6 Gain Margin and Phase Margin via the Nyquist Diagram, 630
- 10.7 Stability, Gain Margin, and Phase Margin via Bode Plots, 633
- 10.8 Relation between Closed-Loop Transient and Closed-Loop Frequency Responses, 636
- 10.9 Relation between Closed- and Open-Loop Frequency Responses, 640
- 10.10 Relation between Closed-Loop Transient and Open-Loop Frequency Responses, 646
- 10.11 Steady-State Error Characteristics from Frequency Response, 650
- 10.12 Systems with Time Delay, 655
- 10.13 Obtaining Transfer Functions Experimentally, 660
 - Case Study, 665
 - Summary, 667
 - Review Questions, 668
 - Problems, 669
 - Bibliography, 682

11. Design via Frequency Response

684

- 11.1 Introduction, 685
- 11.2 Transient Response via Gain Adjustment, 686
- 11.3 Lag Compensation, 690
- 11.4 Lead Compensation, 694
- 11.5 Lag-Lead Compensation, 701
 - Case Studies, 707
 - Summary, 709
 - Review Questions, 710
 - Problems, 710
 - Design Problems, 715
 - Bibliography, 718

12. Design via State Space

719

- 12.1 Introduction, 720
- 12.2 Controller Design, 721

- 12.3 Controllability, 728**
- 12.4 Alternative Approaches to Controller Design, 733**
- 12.5 Observer Design, 738**
- 12.6 Observability, 746**
- 12.7 Alternative Approaches to Observer Design, 750**
- 12.8 Steady-State Error Design via Integral Control, 757**
 - Case Study, 761**
 - Summary, 766**
 - Review Questions, 768**
 - Problems, 769**
 - Design Problems, 774**
 - Bibliography, 776**

13. Digital Control Systems

778

- 13.1 Introduction, 779**
- 13.2 Modeling the Digital Computer, 783**
- 13.3 The z-Transform, 786**
- 13.4 Transfer Functions, 792**
- 13.5 Block Diagram Reduction, 795**
- 13.6 Stability, 798**
- 13.7 Steady-State Errors, 806**
- 13.8 Transient Response on the z-Plane, 811**
- 13.9 Gain Design on the z-Plane, 813**
- 13.10 Cascade Compensation via the s-plane, 817**
- 13.11 Implementing the Digital Compensator, 821**
 - Case Studies, 824**
 - Summary, 829**
 - Review Questions, 830**
 - Problems, 831**
 - Design Problems, 837**
 - Bibliography, 838**

Appendix A List of Symbols	839
Appendix B MATLAB Tutorial	843
Appendix C MATLAB's Simulink Tutorial	897
Appendix D MATLAB's GUI Tools Tutorial	911
Appendix E MATLAB's Symbolic Math Toolbox Tutorial	924
Appendix F Derivation of a Schematic for a DC Motor	936
Glossary	940
Answers to Selected Problems	949
Credits	955
Index	957
Appendix G Matrices, Determinants, and Systems of Equations	CD-ROM
G.1 Matrix Definitions and Notations	
G.2 Matrix Operations	
G.3 Matrix and Determinant Identities	
G.4 Systems of Equations	
Bibliography	
Appendix H Control System Computational Aids	CD-ROM
H.1 Step Response of a System Represented in State Space	
H.2 Root Locus and Frequency Response	
Appendix I Solution of State Equations for $t_0 \neq 0$	CD-ROM
Appendix J Root Locus Rules: Derivations	CD-ROM
J.1 Behavior of the Root Locus at Infinity	
J.2 Derivation of Transition Method for Breakaway and Break-in Points	
Solutions to Skill-Assessment Exercises	CD-ROM
MATLAB Files	CD-ROM
Lecture Graphics	CD-ROM