Contents

| Preface page xv | | | |
|-----------------|---|----|--|
| 1 | INTRODUCTION | 1 | |
| | Study Objectives | | |
| | 1.1 What is Process Control? | 1 | |
| | 1.2 Feedback Control System: Key Ideas, Concepts and Terminology | 2 | |
| | 1.3 Process Control Notation and Control Loop Representation | 8 | |
| | 1.4 Understanding Process Dynamics is a Prerequisite for Learning | | |
| | Process Control | 9 | |
| | 1.5 Some Historical Notes | 11 | |
| | Learning Summary | 15 | |
| | Terms and Concepts | 15 | |
| | Further Reading | 16 | |
| | Problems | 17 | |
| 2 | DYNAMIC MODELS FOR CHEMICAL PROCESS SYSTEMS | 18 | |
| | Study Objectives | 18 | |
| | 2.1 Introduction | 18 | |
| | 2.2 Conservation Laws | 20 | |
| | 2.3 Modeling Examples of Nonreacting Systems | 23 | |
| | 2.4 Modeling of Reacting Systems | 28 | |
| | 2.5 Modeling of Equilibrium Separation Systems | 37 | |
| | 2.6 Modeling of Simple Electrical and Mechanical Systems | 39 | |
| | 2.7 Software Tools | 43 | |
| | Learning Summary | 45 | |
| | Terms and Concepts | 46 | |
| | Further Reading | 46 | |
| | Problems | 47 | |
| 3 | FIRST-ORDER SYSTEMS | 55 | |
| | Study Objectives | 55 | |
| | 3.1 Examples of First-Order Systems | 55 | |
| | 3.2 Deviation Variables | 58 | |
| | 3.3 Solution of Linear First-Order Differential Equations with Constant | | |
| | Coefficients | 59 | |
| | | iv | |

x Contents

| | 3.4 | The Choice of Reference Steady State Affects the Mathematical | |
|---|------------|---|------|
| | | Form of the Dynamics Problem | 62 |
| | 3.5 | Unforced Response: Effect of Initial Condition under Zero Input | 63 |
| | 3.6 | Forced Response: Effect of Nonzero Input under Zero Initial Condition | 63 |
| | 3.7 | Standard Idealized Input Variations | 65 |
| | 3.8 | Response of a First-Order System to a Step Input | 68 |
| | 3.9 | Response of a First-Order System to a Pulse Input | 73 |
| | 3.10 | Response of a First-Order System to a Ramp Input | 75 |
| | 3.11 | Response of a First-Order System to a Sinusoidal Input | 77 |
| | 3.12 | Response of a First-Order System to an Arbitrary Input – Time | |
| | | Discretization of the First-Order System | 82 |
| | 3.13 | Another Example of a First-Order System: Liquid Storage Tank | 88 |
| | 3.14 | Nonlinear First-Order Systems and their Linearization | 94 |
| | 3.15 | Liquid Storage Tank with Input Bypass | 97 |
| | 3.16 | General Form of a First-Order System | 99 |
| | 3.17 | Software Tools | 102 |
| | Lear | ning Summary | 106 |
| | Tern | ns and Concepts | 107 |
| | Furt | her Reading | 108 |
| | Prob | lems | 108 |
| 4 | CON | NECTIONS OF FIRST-ORDER SYSTEMS | 115 |
| | Stud | v Objectives | 115 |
| | 4.1 | First-Order Systems Connected in Series | 115 |
| | 4.2 | First-Order Systems Connected in Parallel | 119 |
| | 4.3 | Interacting First-Order Systems | 122 |
| | 4.4 | Response of First-Order Systems Connected in Series or in Parallel | 123 |
| | 4.5 | Software Tools | 132 |
| | Lear | ning Summary | 134 |
| | Tern | and Concepts | 136 |
| | Furt | her Reading | 136 |
| | Prob | lems | 137 |
| 5 | SECO | NND-ORDER SYSTEMS | 144 |
| - | Stud | | 144 |
| | 5 1 | A Classical Example of a Second Order System | 144 |
| | 5.1 5.2 | A Classical Example of a Second-Order System A Second Order System can be Described by Either a Set of Two | 145 |
| | 5.2 | First Order ODEs or a Single Second Order ODE | 147 |
| | 53 | Calculating the Response of a Second Order System Stan Response of a | 14/ |
| | 5.5 | Second Order System | 110 |
| | 5 / | Qualitative and Quantitative Characteristics of the Stan Despanse of a | 140 |
| | 5.4 | Second-Order System | 154 |
| | | Scong-Order System | 1.74 |

| | | Contents | xi |
|---|------|---|-----|
| | 5 5 | | |
| | 5.5 | Frequency Response and Bode Diagrams of Second-Order Systems with $\zeta > 0$ | 150 |
| | 56 | with $\zeta \geq 0$ The General Form of a Linear Second-Order System | 161 |
| | 5.0 | Software Tools | 163 |
| | Lear | ning Summary | 166 |
| | Tern | and Concepts | 166 |
| | Furt | her Reading | 167 |
| | Prob | lems | 168 |
| 6 | LINE | AR HIGHER-ORDER SYSTEMS | 171 |
| | Stud | v Objectives | 171 |
| | 6.1 | Representative Examples of Higher-Order Systems – Using Vectors | |
| | | and Matrices to Describe a Linear System | 171 |
| | 6.2 | Steady State of a Linear System – Deviation Variables | 175 |
| | 6.3 | Using the Laplace-Transform Method to Solve the Linear Vector | |
| | | Differential Equation and Calculate the Response – Transfer Function | |
| | | of a Linear System | 177 |
| | 6.4 | The Matrix Exponential Function | 179 |
| | 6.5 | Solution of the Linear Vector Differential Equation using the Matrix | |
| | | Exponential Function | 182 |
| | 6.6 | Dynamic Response of a Linear System | 187 |
| | 6.7 | Response to an Arbitrary Input – Time Discretization of a Linear System | 191 |
| | 6.8 | Calculating the Response of a Second-Order System via the Matrix | |
| | | Exponential Function | 195 |
| | 6.9 | Multi-Input–Multi-Output Linear Systems | 197 |
| | 6.10 | Software Tools | 202 |
| | Lear | ning Summary | 206 |
| | Tern | ns and Concepts | 206 |
| | Furt | her Keading | 206 |
| | Prob | lems | 207 |
| 7 | EIGE | NVALUE ANALYSIS – ASYMPTOTIC STABILITY | 215 |
| | Stud | y Objectives | 215 |
| | 7.1 | Introduction | 215 |
| | 7.2 | The Role of System Eigenvalues on the Characteristics of the Response of | |
| | | a Linear System | 216 |
| | 7.3 | Asymptotic Stability of Linear Systems | 220 |
| | 7.4 | Properties of the Forced Response of Asymptotically Stable Linear Systems | 224 |
| | 7.5 | The Role of Eigenvalues in Time Discretization of Linear Systems – | a |
| | | Stability Test on a Discretized Linear System | 225 |
| | 7.6 | Nonlinear Systems and their Linearization | 228 |
| | 7.7 | Software Tools | 240 |

xii Contents

| | Learning Summary | 244 |
|----|---|-----|
| | Further Deciding | 245 |
| | Purchase | 243 |
| | Problems | 245 |
| 8 | TRANSFER-FUNCTION ANALYSIS OF THE INPUT-OUTPUT BEHAVIOR | 251 |
| | Study Objectives | 251 |
| | 8.1 Introduction | 251 |
| | 8.2 A Transfer Function is a Higher-Order Differential Equation in | |
| | Disguise | 252 |
| | 8.3 Proper and Improper Transfer Functions – Relative Order | 257 |
| | 8.4 Poles, Zeros and Static Gain of a Transfer Function | 259 |
| | 8.5 Calculating the Output Response to Common Inputs from the | |
| | Transfer Function – the Role of Poles in the Response | 261 |
| | 8.6 Effect of Zeros on the Step Response | 268 |
| | 8.7 Bounded-Input–Bounded-Output (BIBO) Stability | 273 |
| | 8.8 Asymptotic Response of BIBO-Stable Linear Systems | 275 |
| | 8.9 Software Tools | 279 |
| | Learning Summary | 287 |
| | Terms and Concepts | 287 |
| | Further Reading | 288 |
| | Problems | 288 |
| 9 | FREQUENCY RESPONSE | 297 |
| | Study Objectives | 297 |
| | 9.1 Introduction | 297 |
| | 9.2 Frequency Response and Bode Diagrams | 298 |
| | 9.3 Straight-Line Approximation Method for Sketching Bode Diagrams | 303 |
| | 9.4 Low-Frequency and High-Frequency Response | 311 |
| | 9.5 Nyquist Plots | 312 |
| | 9.6 Software Tools | 319 |
| | Learning Summary | 321 |
| | Terms and Concepts | 321 |
| | Further Reading | 322 |
| | Problems | 322 |
| 10 |) THE FEEDBACK CONTROL SYSTEM | 327 |
| | Study Objectives | 327 |
| | 10.1 Heating Tank Process Example | 327 |
| | 10.2 Common Sensors and Final Control Elements | 329 |
| | 10.3 Block-Diagram Representation of the Heating Tank Process Example | 332 |

CAMBRIDGE

Cambridge University Press 978-1-107-03558-4 — Understanding Process Dynamics and Control Costas Kravaris , Ioannis K. Kookos Table of Contents <u>More Information</u>

| | Contents | xiii |
|--|----------|------|
| 10.4 Eurther Examples of Process Control Loops | | 335 |
| 10.5 Commonly Used Control Laws | | 338 |
| Learning Summary | | 345 |
| Terms and Concepts | | 345 |
| Further Reading | | 346 |
| Problems | | 346 |
| 11 BLOCK-DIAGRAM REDUCTION AND TRANSIENT-RESPONSE CALCUL | ATION | |
| IN A FEEDBACK CONTROL SYSTEM | | 350 |
| Study Objectives | | 350 |
| 11.1 Calculation of the Overall Closed-Loop Transfer Functions | in a | |
| Standard Feedback Control Loop | | 350 |
| 11.2 Calculation of Overall Transfer Functions in a Multi-Loop | Feedback | |
| Control System | | 356 |
| 11.3 Stirred Tank Heater under Negligible Sensor Dynamics: | | |
| Closed-Loop Response Calculation under P or PI Control | | 359 |
| 11.4 Software Tools | | 366 |
| Learning Summary | | 372 |
| Terms and Concepts | | 373 |
| Further Reading | | 373 |
| Problems | | 374 |
| 12 STEADY-STATE AND STABILITY ANALYSIS OF THE CLOSED-LOOP SYS | TEM | 377 |
| Study Objectives | | 377 |
| 12.1 Steady-State Analysis of a Feedback Control System | | 377 |
| 12.2 Closed-Loop Stability, Characteristic Polynomial and | | |
| Characteristic Equation | | 385 |
| 12.3 The Routh Criterion | | 389 |
| 12.4 Calculating Stability Limits via the Substitution $s = i\omega$ | | 394 |
| 12.5 Some Remarks about the Role of Proportional, | | |
| Integral and Derivative Actions | | 395 |
| 12.6 Software Tools | | 399 |
| Learning Summary | | 404 |
| Terms and Concepts | | 405 |
| Further Reading | | 405 |
| Problems | | 405 |
| 13 STATE-SPACE DESCRIPTION AND ANALYSIS OF THE CLOSED-LOOP S | YSTEM | 409 |
| Study Objectives | | 409 |
| 13.1 State-Space Description and Analysis of the Heating Tank | | 409 |
| 13.2 State-Space Analysis of Closed-Loop Systems | | 415 |

xiv Contents

| | 13.3 Time Discretization of the Closed-Loop System | 422 |
|----|--|-----|
| | 13.4 State-Space Description of Nonlinear Closed-Loop Systems | 426 |
| | 13.5 Software Tools | 428 |
| | Learning Summary | 434 |
| | Further Reading | 435 |
| | Problems | 435 |
| 14 | SYSTEMS WITH DEAD TIME | 437 |
| | Study Objectives | 437 |
| | 14.1 Introduction | 437 |
| | 14.2 Approximation of Dead Time by Rational Transfer Functions | 446 |
| | 14.3 Parameter Estimation for FOPDT Systems | 456 |
| | 14.4 Feedback Control of Systems with Dead Time – Closed-Loop | |
| | Stability Analysis | 460 |
| | 14.5 Calculation of Closed-Loop Response for Systems involving Dead Time | 467 |
| | 14.6 Software Tools | 473 |
| | Learning Summary | 475 |
| | Terms and Concepts | 476 |
| | Further Reading | 476 |
| | Problems | 476 |
| 15 | PARAMETRIC ANALYSIS OF CLOSED-LOOP DYNAMICS – ROOT-LOCUS DIAGRAMS | 484 |
| | Study Objectives | 484 |
| | 15.1 What is a Root-Locus Diagram? Some Examples | 484 |
| | 15.2 Basic Properties of the Root Locus – Basic Rules for Sketching | |
| | Root-Locus Diagrams | 502 |
| | 15.3 Further Properties of the Root Locus – Additional Rules for Sketching | |
| | Root-Locus Diagrams | 508 |
| | 15.4 Calculation of the Points of Intersection of the Root Locus with the | |
| | Imaginary Axis | 524 |
| | 15.5 Root Locus with Respect to Other Controller Parameters | 527 |
| | 15.6 Software Tools | 531 |
| | Learning Summary | 536 |
| | Terms and Concepts | 537 |
| | Further Reading | 537 |
| | Problems | 537 |
| 16 | OPTIMAL SELECTION OF CONTROLLER PARAMETERS | 541 |
| | Study Objectives | 541 |
| | 16.1 Control Performance Criteria | 541 |
| | 16.2 Analytic Calculation of Quadratic Criteria for a Stable System and a | |
| | Step Input | 549 |

CAMBRIDGE

Cambridge University Press 978-1-107-03558-4 — Understanding Process Dynamics and Control Costas Kravaris , Ioannis K. Kookos Table of Contents <u>More Information</u>

| | Contents | xv |
|--|------------------|-----|
| 16.3 Calculation of Optimal Controller Parameters for Ou | adratic Criteria | 557 |
| 16.4 Software Tools | | 563 |
| Learning Summary | | 570 |
| Terms and Concepts | | 571 |
| Further Reading | | 571 |
| Problems | | 572 |
| 17 BODE AND NYQUIST STABILITY CRITERIA – GAIN AND PHAS | E MARGINS | 575 |
| Study Objectives | | 575 |
| 17.1 Introduction | | 575 |
| 17.2 The Bode Stability Criterion | | 576 |
| 17.3 The Nyquist Stability Criterion | | 594 |
| 17.4 Example Applications of the Nyquist Criterion | | 597 |
| 17.5 Software Tools | | 604 |
| Learning Summary | | 607 |
| Terms and Concepts | | 607 |
| Further Reading | | 608 |
| Problems | | 608 |
| 18 MULTI-INPUT–MULTI-OUTPUT SYSTEMS | | 613 |
| Study Objectives | | 613 |
| 18.1 Introduction | | 613 |
| 18.2 Dynamic Response of MIMO Linear Systems | | 620 |
| 18.3 Feedback Control of MIMO Systems: State-Space ve | ersus | |
| Transfer-Function Description of the Closed-Loop S | ystem | 623 |
| 18.4 Interaction in MIMO Systems | | 627 |
| 18.5 Decoupling in MIMO Systems | | 632 |
| 18.6 Software Tools | | 634 |
| Learning Summary | | 638 |
| Terms and Concepts | | 639 |
| Further Reading | | 639 |
| Problems | | 639 |
| 19 SYNTHESIS OF MODEL-BASED FEEDBACK CONTROLLERS | | 641 |
| Study Objectives | | 641 |
| 19.1 Introduction | | 641 |
| 19.2 Nearly Optimal Model-Based Controller Synthesis | | 648 |
| 19.3 Controller Synthesis for Low-Order Models | | 650 |
| 19.4 The Smith Predictor for Processes with Large Dead T | ime | 657 |
| 19.5 Effect of Modeling Error | | 660 |
| 19.6 State-Space Form of the Model-Based Controller | | 668 |

xvi Contents

| | 19.7 | Model-Based Controller Synthesis for MIMO Systems | 674 |
|------------------------------|-------------|--|-----|
| | Lear | ning Summary | 678 |
| | Tern | ns and Concepts | 678 |
| | Furt | her Reading | 679 |
| | Prob | lems | 679 |
| 20 | CAS | CADE, RATIO AND FEEDFORWARD CONTROL | 683 |
| | Stud | y Objectives | 683 |
| | 20.1 | Introduction | 683 |
| | 20.2 | Cascade Control | 684 |
| | 20.3 | Ratio Control | 694 |
| | 20.4 | Feedforward Control | 695 |
| | 20.5 | Model-Based Feedforward Control | 700 |
| | Lear | ning Summary | 714 |
| | Tern | ns and Concepts | 715 |
| | Furt | her Reading | 715 |
| | Prob | lems | 715 |
| APPENDIX A LAPLACE TRANSFORM | | 719 | |
| | A.1 | Definition of the Laplace Transform | 719 |
| | A.2 | Laplace Transforms of Elementary Functions | 720 |
| | A.3 | Properties of Laplace Transforms | 721 |
| | A.4 | Inverse Laplace Transform | 725 |
| | A.5 | Calculation of the Inverse Laplace Transform of Rational | |
| | | Functions via Partial Fraction Expansion | 725 |
| | A.6 | Solution of Linear Ordinary Differential Equations using the | |
| | | Laplace Transform | 732 |
| | A.7 | Software Tools | 735 |
| | Prob | lems | 739 |
| AP | PEND | IX B BASIC MATRIX THEORY | 743 |
| | B .1 | Basic Notations and Definitions | 743 |
| | B.2 | Determinant of a Square Matrix | 747 |
| | B.3 | Matrix Inversion | 749 |
| | B.4 | Eigenvalues | 750 |
| | B.5 | The Cayley–Hamilton Theorem and the Resolvent Identity | 752 |
| | B.6 | Differentiation and Integration of Matrices | 755 |
| | B .7 | Software Tools | 756 |
| | | | |

760

Index