

Brief Contents

| | |
|---|------------|
| PART I ■ INTRODUCTION | 1 |
| 1 ■ INTRODUCTION TO PROCESS CONTROL | 3 |
| 2 ■ CONTROL OBJECTIVES AND BENEFITS | 19 |
| PART II ■ PROCESS DYNAMICS | 45 |
| 3 ■ MATHEMATICAL MODELLING PRINCIPLES | 49 |
| 4 ■ MODELLING AND ANALYSIS FOR PROCESS CONTROL | 97 |
| 5 ■ DYNAMIC BEHAVIOR OF TYPICAL PROCESS SYSTEMS | 135 |
| 6 ■ EMPIRICAL MODEL IDENTIFICATION | 175 |
| PART III ■ FEEDBACK CONTROL | 207 |
| 7 ■ THE FEEDBACK LOOP | 211 |
| 8 ■ THE PID ALGORITHM | 239 |
| 9 ■ PID CONTROLLER TUNING FOR DYNAMIC PERFORMANCE | 267 |
| 10 ■ STABILITY ANALYSIS AND CONTROLLER TUNING | 303 |
| 11 ■ DIGITAL IMPLEMENTATION OF PROCESS CONTROL | 357 |
| 12 ■ PRACTICAL APPLICATION OF FEEDBACK CONTROL | 381 |
| 13 ■ PERFORMANCE OF FEEDBACK CONTROL SYSTEMS | 409 |
| PART IV ■ ENHANCEMENTS TO SINGLE-LOOP PID FEEDBACK CONTROL | 453 |

| | |
|--|-------------|
| 14 ■ CASCADE CONTROL | 457 |
| 15 ■ FEEDFORWARD CONTROL | 483 |
| 16 ■ ADAPTING SINGLE-LOOP CONTROL SYSTEMS FOR NONLINEAR PROCESSES | 511 |
| 17 ■ INFERENTIAL CONTROL | 535 |
| 18 ■ LEVEL AND INVENTORY CONTROL | 561 |
| 19 ■ SINGLE-VARIABLE MODEL PREDICTIVE CONTROL | 583 |
| PART V ■ MULTIVARIABLE CONTROL | 615 |
| 20 ■ MULTILoop CONTROL: EFFECTS OF INTERACTION | 619 |
| 21 ■ MULTILoop CONTROL: PERFORMANCE ANALYSIS | 661 |
| 22 ■ VARIABLE-STRUCTURE AND CONSTRAINT CONTROL | 705 |
| 23 ■ CENTRALIZED MULTIVARIABLE CONTROL | 727 |
| PART VI ■ PROCESS CONTROL DESIGN | 761 |
| 24 ■ PROCESS CONTROL DESIGN: DEFINITION AND DECISIONS | 765 |
| 25 ■ PROCESS CONTROL DESIGN: MANAGING THE DESIGN PROCEDURE | 819 |
| 26 ■ CONTINUAL IMPROVEMENT | 859 |
| APPENDIX A ■ PROCESS CONTROL DRAWINGS | 889 |
| APPENDIX B ■ INTEGRATING FACTOR | 895 |
| APPENDIX C ■ CHEMICAL REACTOR MODELING AND ANALYSIS | 897 |
| APPENDIX D ■ APPROXIMATE DYNAMIC MODELS | 909 |
| APPENDIX E ■ DETERMINING CONTROLLER CONSTANTS TO SATISFY PERFORMANCE SPECIFICATIONS | 915 |
| APPENDIX F ■ DISCRETE MODELS FOR DIGITAL CONTROL | 921 |
| APPENDIX G ■ GUIDE TO SELECTED PROCESS EXAMPLES | 925 |
| APPENDIX H ■ PARTIAL FRACTIONS AND FREQUENCY RESPONSE | 931 |
| APPENDIX I ■ PROCESS EXAMPLES OF PARALLEL SYSTEMS | 939 |
| APPENDIX J ■ PROCESS CONTROL CASE STUDY: TWO-PRODUCT DISTILLATION | 949 |
| APPENDIX K ■ PROCESS CONTROL CASE STUDY: FIRED HEATER | 961 |
| APPENDIX L ■ ANALYSIS OF DIGITAL CONTROL SYSTEMS | 973 |
| INDEX | 1003 |

Contents



| | |
|---|-----------|
| Preface | vii |
| Symbols and Acronyms | xxv |
| PART I ■ INTRODUCTION | 1 |
| 1 ■ INTRODUCTION TO PROCESS CONTROL | 3 |
| 1.1 Introduction | 3 |
| 1.2 What Does a Control System Do? | 4 |
| 1.3 Why Is Control Necessary? | 7 |
| 1.4 Why Is Control Possible? | 7 |
| 1.5 How Is Control Done? | 8 |
| 1.6 Where Is Control Implemented? | 9 |
| 1.7 What Does Control Engineering “Engineer”? | 10 |
| 1.8 How Is Process Control Documented? | 12 |
| 1.9 What Are Some Sample Control Strategies? | 13 |
| 1.10 Conclusions | 14 |
| 2 ■ CONTROL OBJECTIVES AND BENEFITS | 19 |
| 2.1 Introduction | 19 |
| 2.2 Control Objectives | 20 |

| | | |
|-----|--|----|
| 2.3 | Determining Plant Operating Conditions | 25 |
| 2.4 | Benefits for Control | 28 |
| 2.5 | Importance of Control Engineering | 35 |
| 2.6 | Conclusions | 38 |

PART II ■ PROCESS DYNAMICS **45**

3 ■ MATHEMATICAL MODELLING PRINCIPLES **49**

| | | |
|-----|--|----|
| 3.1 | Introduction | 49 |
| 3.2 | A Modelling Procedure | 50 |
| 3.3 | Modelling Examples | 62 |
| 3.4 | Linearization | 69 |
| 3.5 | Numerical Solutions of Ordinary Differential Equations | 82 |
| 3.6 | The Nonisothermal Chemical Reactor | 85 |
| 3.7 | Conclusions | 86 |

4 ■ MODELLING AND ANALYSIS FOR PROCESS CONTROL **97**

| | | |
|-----|--|-----|
| 4.1 | Introduction | 97 |
| 4.2 | The Laplace Transform | 98 |
| 4.3 | Input-Output Models and Transfer Functions | 110 |
| 4.4 | Block Diagrams | 115 |
| 4.5 | Frequency Response | 119 |
| 4.6 | Conclusions | 125 |

5 ■ DYNAMIC BEHAVIOR OF TYPICAL PROCESS SYSTEMS **135**

| | | |
|-----|--|-----|
| 5.1 | Introduction | 135 |
| 5.2 | Basic System Elements | 136 |
| 5.3 | Series Structures of Simple Systems | 143 |
| 5.4 | Parallel Structures of Simple Systems | 152 |
| 5.5 | Recycle Structures | 155 |
| 5.6 | Staged Processes | 157 |
| 5.7 | Multiple Input—Multiple Output Systems | 163 |
| 5.8 | Conclusions | 165 |

| | |
|--|----------------|
| 6 ■ EMPIRICAL MODEL IDENTIFICATION | 175 |
| 6.1 Introduction | 175 |
| 6.2 An Empirical Model Building Procedure | 176 |
| 6.3 The Process Reaction Curve | 179 |
| 6.4 Statistical Model Identification | 188 |
| 6.5 Additional Topics in Identification | 196 |
| 6.6 Conclusions | 198 |
| PART III ■ FEEDBACK CONTROL | 207 |
| 7 ■ THE FEEDBACK LOOP | 211 |
| 7.1 Introduction | 211 |
| 7.2 Process and Instrument Elements of the Feedback Loop | 212 |
| 7.3 Selecting Controlled and Manipulated Variables | 216 |
| 7.4 Control Performance Measures for Common Input Changes | 218 |
| 7.5 Approaches to Process Control | 228 |
| 7.6 Conclusions | 231 |
| 8 ■ THE PID ALGORITHM | 239 |
| 8.1 Introduction | 239 |
| 8.2 Desired Features of a Feedback Control Algorithm | 240 |
| 8.3 Block Diagram of the Feedback Loop | 242 |
| 8.4 Proportional Mode | 245 |
| 8.5 Integral Mode | 248 |
| 8.6 Derivative Mode | 249 |
| 8.7 The PID Controller | 252 |
| 8.8 Analytical Expression for a Closed-Loop Response | 253 |
| 8.9 Importance of the PID Controller | 257 |
| 8.10 Conclusions | 258 |
| 9 ■ PID CONTROLLER TUNING FOR DYNAMIC PERFORMANCE | 267 |
| 9.1 Introduction | 267 |
| 9.2 Defining the Tuning Problem | 268 |
| 9.3 Determining Good Tuning Constant Values | 269 |

| | | |
|-----------|---|------------|
| 9.4 | Correlations for Tuning Constants | 278 |
| 9.5 | Fine Tuning the Controller Tuning Constants | 289 |
| 9.6 | Conclusions | 293 |
| 10 | ■ STABILITY ANALYSIS AND CONTROLLER TUNING | 303 |
| 10.1 | Introduction | 303 |
| 10.2 | The Concept of Stability | 303 |
| 10.3 | Stability of Linear Systems—A Simple Example | 304 |
| 10.4 | Stability Analysis of Linear and Linearized Systems | 305 |
| 10.5 | Stability Analysis of Control Systems: Principles | 308 |
| 10.6 | Stability Analysis of Control Systems: The Bode Method | 313 |
| 10.7 | Controller Tuning Based on Stability: Ziegler-Nichols Closed-Loop | 329 |
| 10.8 | Controller Tuning and Stability — Some Important Interpretations | 334 |
| 10.9 | Additional Tuning Methods in Common Use, with a Recommendation | 345 |
| 10.10 | Conclusions | 348 |
| 11 | ■ DIGITAL IMPLEMENTATION OF PROCESS CONTROL | 357 |
| 11.1 | Introduction | 357 |
| 11.2 | Structure of the Digital Control System | 358 |
| 11.3 | Effects of Sampling a Continuous Signal | 362 |
| 11.4 | The Discrete PID Control Algorithm | 365 |
| 11.5 | Effects of Digital Control on Stability, Tuning, and Performance | 367 |
| 11.6 | Example of Digital Control Strategy | 372 |
| 11.7 | Trends in Digital Control | 373 |
| 11.8 | Conclusions | 374 |
| 12 | ■ PRACTICAL APPLICATION OF FEEDBACK CONTROL | 381 |
| 12.1 | Introduction | 381 |
| 12.2 | Equipment Specification | 383 |
| 12.3 | Input Processing | 387 |
| 12.4 | Feedback Control Algorithm | 396 |

| | | |
|------|-------------------|-----|
| 12.5 | Output Processing | 403 |
| 12.6 | Conclusions | 403 |

13 ■ PERFORMANCE OF FEEDBACK CONTROL SYSTEMS 409

| | | |
|------|---|-----|
| 13.1 | Introduction | 409 |
| 13.2 | Control Performance | 410 |
| 13.3 | Control Performance via Closed-Loop Frequency Response | 412 |
| 13.4 | Control Performance via Closed-Loop Simulation | 422 |
| 13.5 | Process Factors Influencing Single-Loop Control Performance | 425 |
| 13.6 | Control System Factors Influencing Control Performance | 433 |
| 13.7 | Conclusions | 443 |

PART IV ■ ENHANCEMENTS TO SINGLE-LOOP PID FEEDBACK CONTROL 453

14 ■ CASCADE CONTROL 457

| | | |
|------|--|-----|
| 14.1 | Introduction | 457 |
| 14.2 | An Example of Cascade Control | 458 |
| 14.3 | Cascade Design Criteria | 461 |
| 14.4 | Cascade Performance | 462 |
| 14.5 | Controller Algorithm and Tuning | 468 |
| 14.6 | Implementation Issues | 469 |
| 14.7 | Further Cascade Examples | 471 |
| 14.8 | Cascade Control Interpreted as Distributed Decision Making | 476 |
| 14.9 | Conclusions | 477 |

15 ■ FEEDFORWARD CONTROL 483

| | | |
|------|--------------------------------------|-----|
| 15.1 | Introduction | 483 |
| 15.2 | An Example and Controller Derivation | 483 |
| 15.3 | Feedforward Control Design Criteria | 486 |
| 15.4 | Feedforward Performance | 489 |
| 15.5 | Controller Algorithm and Tuning | 492 |
| 15.6 | Implementation Issues | 494 |
| 15.7 | Further Feedforward Examples | 495 |

| | | |
|-------------|--|------------|
| 15.8 | Feedforward Control Is General | 503 |
| 15.9 | Conclusions | 504 |
| 16 ■ | ADAPTING SINGLE-LOOP CONTROL SYSTEMS FOR NONLINEAR PROCESSES | 511 |
| 16.1 | Introduction | 511 |
| 16.2 | Analyzing a Nonlinear Process with Linear Feedback Control | 512 |
| 16.3 | Improving Nonlinear Process Performance through Deterministic Control Loop Calculations | 517 |
| 16.4 | Improving Nonlinear Process Performance through Calculations of the Measured Variable | 519 |
| 16.5 | Improving Nonlinear Process Performance through Final Element Selection | 520 |
| 16.6 | Improving Nonlinear Process Performance through Cascade Design | 525 |
| 16.7 | Real-Time Implementation Issues | 526 |
| 16.8 | Additional Topics in Control Loop Adaptation | 526 |
| 16.9 | Conclusions | 528 |
| 17 ■ | INFERENCEAL CONTROL | 535 |
| 17.1 | Introduction | 535 |
| 17.2 | An Example of Inferential Control | 537 |
| 17.3 | Inferential Control Design Criteria | 541 |
| 17.4 | Implementation Issues | 543 |
| 17.5 | Inferential Control Example: Distillation | 545 |
| 17.6 | Inferential Control Example: Chemical Reactor | 549 |
| 17.7 | Inferential Control Example: Fired Heater | 553 |
| 17.8 | Additional Topics in Inferential Control | 554 |
| 17.9 | Conclusions | 555 |
| 18 ■ | LEVEL AND INVENTORY CONTROL | 561 |
| 18.1 | Introduction | 561 |
| 18.2 | Reasons for Inventories in Plants | 562 |
| 18.3 | Level Processes and Controllers | 564 |
| 18.4 | A Nonlinear Proportional-Integral Controller | 567 |
| 18.5 | Matching Controller Tuning to Performance Objectives | 567 |
| 18.6 | Determining Inventory Size | 572 |

| | | |
|------|-----------------------|-----|
| 18.7 | Implementation Issues | 574 |
| 18.8 | Vessels in Series | 574 |
| 18.9 | Conclusions | 576 |

19 ■ SINGLE-VARIABLE MODEL PREDICTIVE CONTROL 583

| | | |
|------|---|-----|
| 19.1 | Introduction | 583 |
| 19.2 | The Model Predictive Control Structure | 584 |
| 19.3 | The IMC Controller | 590 |
| 19.4 | The Smith Predictor | 600 |
| 19.5 | Implementation Guidelines | 604 |
| 19.6 | Algorithm Selection Guidelines | 605 |
| 19.7 | Additional Topics in Single-Loop Model Predictive Control | 608 |
| 19.8 | Conclusions | 609 |

PART V ■ MULTIVARIABLE CONTROL 615

20 ■ MULTILoop CONTROL: EFFECTS OF INTERACTION 619

| | | |
|------|--|-----|
| 20.1 | Introduction | 619 |
| 20.2 | Modeling and Transfer Functions | 621 |
| 20.3 | Influence of Interaction on the Possibility of Feedback Control | 624 |
| 20.4 | Process Interaction: Important Effects on Multivariable System Behavior | 628 |
| 20.5 | Process Interaction: The Relative Gain Array (RGA) | 633 |
| 20.6 | Effect of Interaction on Stability and Tuning of Multiloop Control Systems | 638 |
| 20.7 | Additional Topics in Interaction Analysis | 650 |
| 20.8 | Conclusions | 651 |

21 ■ MULTILoop CONTROL: PERFORMANCE ANALYSIS 661

| | | |
|------|--|-----|
| 21.1 | Introduction | 661 |
| 21.2 | Demonstration of Key Multiloop Issues | 662 |
| 21.3 | Multiloop Control Performance through Loop Pairing | 671 |
| 21.4 | Multiloop Control Performance through Tuning | 682 |
| 21.5 | Multiloop Control Performance through Enhancements: Decoupling | 683 |

| | | |
|----------------|---|------------|
| 21.6 | Multiloop Control Performance through Enhancements: Single-Loop Enhancements | 690 |
| 21.7 | Additional Topics in Multiloop Performance | 691 |
| 21.8 | Conclusions | 693 |
| 22 | ■ VARIABLE-STRUCTURE AND CONSTRAINT CONTROL | 705 |
| 22.1 | Introduction | 705 |
| 22.2 | Split Range Control for Processes with Excess Manipulated Variables | 706 |
| 22.3 | Signal Select Control for Processes with Excess Controlled Variables | 710 |
| 22.4 | Applications of Variable-Structure Methods for Constraint Control | 715 |
| 22.5 | Conclusions | 720 |
| 23 | ■ CENTRALIZED MULTIVARIABLE CONTROL | 727 |
| 23.1 | Introduction | 727 |
| 23.2 | Multivariable Model Predictive Control | 728 |
| 23.3 | An Alternative Dynamic Modelling Approach | 730 |
| 23.4 | The Single-Variable Dynamic Matrix Control (DMC) Algorithm | 735 |
| 23.5 | Multivariable Dynamic Matrix Control | 744 |
| 23.6 | Implementation Issues in Dynamic Matrix Control | 748 |
| 23.7 | Extensions to Basic Dynamic Matrix Control | 751 |
| 23.8 | Conclusions | 757 |
| PART VI | ■ PROCESS CONTROL DESIGN | 761 |
| 24 | ■ PROCESS CONTROL DESIGN: DEFINITION AND DECISIONS | 765 |
| 24.1 | Introduction | 765 |
| 24.2 | Defining the Design Problem | 766 |
| 24.3 | Measurements | 771 |
| 24.4 | Final Elements | 776 |
| 24.5 | Process Operability | 778 |
| 24.6 | Control Structure | 789 |
| 24.7 | Control Algorithms | 792 |
| 24.8 | Control for Safety | 794 |

| | | |
|-------|-----------------------------|-----|
| 24.9 | Performance Monitoring | 799 |
| 24.10 | The Flash Example Revisited | 801 |
| 24.11 | Conclusions | 804 |

25 ■ PROCESS CONTROL DESIGN: MANAGING THE DESIGN PROCEDURE 819

| | | |
|------|---|-----|
| 25.1 | Introduction | 819 |
| 25.2 | Defining the Design Problem | 820 |
| 25.3 | Sequence of Design Steps | 823 |
| 25.4 | Temporal Hierarchy of Control Structure | 825 |
| 25.5 | Process Decomposition | 831 |
| 25.6 | Integrating the Control Design Methods | 833 |
| 25.7 | Example Design: Chemical Reactor with Recycle | 835 |
| 25.8 | Summary of Key Design Guidelines | 849 |
| 25.9 | Conclusions | 852 |

26 ■ CONTINUAL IMPROVEMENT 859

| | | |
|------|-----------------------------------|-----|
| 26.1 | Introduction | 859 |
| 26.2 | Optimization | 860 |
| 26.3 | Statistical Process Control (SPC) | 876 |
| 26.4 | Conclusions | 881 |

APPENDIXES 889

APPENDIX A ■ PROCESS CONTROL DRAWINGS 889

| | | |
|-----|------------------------|-----|
| A.1 | Identification Letters | 889 |
| A.2 | Final Element | 891 |
| A.3 | Process Equipment | 892 |

APPENDIX B ■ INTEGRATING FACTOR 895

APPENDIX C ■ CHEMICAL REACTOR MODELING AND ANALYSIS 897

| | | |
|-----|--|-----|
| C.1 | Energy Balance | 897 |
| C.2 | Modelling of an Example Nonisothermal CSTR | 899 |
| C.3 | The Reactor Transfer Functions | 901 |
| C.4 | Multiple Steady States | 902 |

| | | |
|--|--|------------|
| C.5 | Continuous Oscillations Due to Limit Cycles | 906 |
| C.6 | Conclusions | 907 |
| APPENDIX D ■ APPROXIMATE DYNAMIC MODELS | | 909 |
| D.1 | Method of Moments | 909 |
| D.2 | Padé Dead Time Approximations | 913 |
| APPENDIX E ■ DETERMINING CONTROLLER CONSTANTS TO SATISFY PERFORMANCE SPECIFICATIONS | | 915 |
| E.1 | Simulation of the Controlled System Transient Response | 915 |
| E.2 | Optimization of the Tuning Constants | 917 |
| APPENDIX F ■ DISCRETE MODELS FOR DIGITAL CONTROL | | 921 |
| F.1 | Gain | 922 |
| F.2 | Dead Time | 922 |
| F.3 | First-Order System | 922 |
| F.4 | Lead/Lag | 923 |
| APPENDIX G ■ GUIDE TO SELECTED PROCESS EXAMPLES | | 925 |
| G.1 | Heat Exchanger | 925 |
| G.2 | Three-Tank Mixing Process | 926 |
| G.3 | Nonisothermal Stirred-Tank Chemical Reactor (CSTR) | 926 |
| G.4 | Two-Product Distillation Column | 926 |
| G.5 | Two Series Isothermal Continuous Stirred-Tank Reactors (CSTR) | 927 |
| G.6 | Heat Exchange and Flash Drum | 929 |
| APPENDIX H ■ PARTIAL FRACTIONS AND FREQUENCY RESPONSE | | 931 |
| H.1 | Partial Fractions | 931 |
| H.2 | Frequency Response | 936 |
| APPENDIX I ■ PROCESS EXAMPLES OF PARALLEL SYSTEMS | | 939 |

| | |
|--|-------------|
| APPENDIX J ■ PROCESS CONTROL CASE STUDY: TWO-PRODUCT DISTILLATION | 949 |
| APPENDIX K ■ PROCESS CONTROL CASE STUDY: FIRED HEATER | 961 |
| APPENDIX L ■ ANALYSIS OF DIGITAL CONTROL SYSTEMS | 973 |
| L.1 Introduction | 973 |
| L.2 The z-transform | 973 |
| L.3 Methods for Analyzing Digital Control Systems | 983 |
| L.4 Digital Control Performance | 989 |
| L.5 Conclusions | 1001 |
| INDEX | 1003 |