

# Process Dynamics and Control

Third Edition

International Student Version

**Dale E. Seborg**

*University of California, Santa Barbara*

**Thomas J. Edgar**

*University of Texas at Austin*

**Duncan A. Mellichamp**

*University of California, Santa Barbara*

**Francis J. Doyle ffl**

*University of California, Santa Barbara*



WILEY

John Wiley & Sons, Inc.

# Contents

## *PART ONE*

### *INTRODUCTION TO PROCESS CONTROL*

#### **1. Introduction to Process Control 1**

- 1.1 Representative Process Control Problems 1
- 1.2 Illustrative Example—A Blending Process 3
- 1.3 Classification of Process Control Strategies 5
- 1.4 A More Complicated Example—A Distillation Column 7
- 1.5 The Hierarchy of Process Control Activities 8
- 1.6 An Overview of Control System Design 10

#### **2. Theoretical Models of Chemical Processes 15**

- 2.1 The Rationale for Dynamic Process Models 15
- 2.2 General Modeling Principles 17
- 2.3 Degrees of Freedom Analysis 21
- 2.4 Dynamic Models of Representative Processes 22
- 2.5 Process Dynamics and Mathematical Models 35

## *PART TWO*

### *DYNAMIC BEHAVIOR OF PROCESSES*

#### **3. Transfer Function Models 43**

- 3.1 An Illustrative Example: A Continuous Blending System 43
- 3.2 Transfer Functions of Complicated Models 45
- 3.3 Properties of Transfer Functions 46
- 3.4 Linearization of Nonlinear Models 49

#### **4. Dynamic Behavior of First-Order and Second-Order Processes 58**

- 4.1 Standard Process Inputs 58
- 4.2 Response of First-Order Processes 61

- 4.3 Response of Integrating Processes 64

- 4.4 Response of Second-Order Processes 66

#### **5. Dynamic Response Characteristics of More Complicated Processes 78**

- 5.1 Poles and Zeros and Their Effect on Process Response 78
- 5.2 Processes with Time Delays 82
- 5.3 Approximation of Higher-Order Transfer Functions 86
- 5.4 Interacting and Noninteracting Processes 88
- 5.5 State-Space and Transfer Function Matrix Models 90
- 5.6 Multiple-Input, Multiple-Output (MIMO) Processes 93

#### **6. Development of Empirical Models from Process Data 102**

- 6.1 Model Development Using Linear or Nonlinear Regression 103
- 6.2 Fitting First- and Second-Order Models Using Step Tests 107
- 6.3 Neural Network Models 112
- 6.4 Development of Discrete-Time Dynamic Models 113
- 6.5 Identifying Discrete-Time Models from Experimental Data 115

## *PART THREE*

### *FEEDBACK AND FEEDFORWARD CONTROL*

#### **7. Feedback Controllers 124**

- 7.1 Introduction 124
- 7.2 Basic Control Modes 126
- 7.3 Features of PID Controllers 131
- 7.4 On-Off Controllers 134
- 7.5 Typical Responses of Feedback Control Systems 134
- 7.6 Digital Versions of PID Controllers 135

## 8. Control System Instrumentation 141

- 8.1 Sensors, Transmitters, and Transducers 142
- 8.2 Final Control Elements 147
- 8.3 Signal Transmission and Digital Communication 153
- 8.4 Accuracy in Instrumentation 154

## 9. Process Safety and Process Control 160

- 9.1 Layers of Protection 161
- 9.2 Alarm Management 165
- 9.3 Abnormal Event Detection 169
- 9.4 Risk Assessment 171

## 10. Dynamic Behavior and Stability of Closed-Loop Control Systems 176

- 10.1 Block Diagram Representation 176
- 10.2 Closed-Loop Transfer Functions 179
- 10.3 Closed-Loop Responses of Simple Control Systems 182
- 10.4 Stability of Closed-Loop Control Systems 188
- 10.5 Root Locus Diagrams 194

## 11. PID Controller Design, Tuning, and Troubleshooting 204

- 11.1 Performance Criteria for Closed-Loop Systems 204
- 11.2 Model-Based Design Methods 206
- 11.3 Controller Tuning Relations 211
- 11.4 Controllers with Two Degrees of Freedom 216
- 11.5 On-Line Controller Tuning 217
- 11.6 Guidelines for Common Control Loops 223
- 11.7 Troubleshooting Control Loops 225

## 12. Control Strategies at the Process Unit Level 232

- 12.1 Degrees of Freedom Analysis for Process Control 232
- 12.2 Selection of Controlled, Manipulated, and Measured Variables 234
- 12.3 Applications 238

## 13. Frequency Response Analysis and Control System Design 248

- 13.1 Sinusoidal Forcing of a First-Order Process 248
- 13.2 Sinusoidal Forcing of an nth-Order Process 249

## 13.3 Bode Diagrams 251

## 13.4 Frequency Response Characteristics of Feedback Controllers 255

## 13.5 Nyquist Diagrams 260

## 13.6 Bode Stability Criterion 260

## 13.7 Gain and Phase Margins 264

## 14. Feedforward and Ratio Control 271

### 14.1 Introduction to Feedforward Control 271

### 14.2 Ratio Control 273

### 14.3 Feedforward Controller Design Based on Steady-State Models 275

### 14.4 Feedforward Controller Design Based on Dynamic Models 277

### 14.5 The Relationship Between the Steady-State and Dynamic Design Methods 281

### 14.6 Configurations for Feedforward-Feedback Control 282

### 14.7 Tuning Feedforward Controllers 282

## PART FOUR

## ADVANCED PROCESS CONTROL

## 15. Enhanced Single-Loop Control Strategies 288

### 15.1 Cascade Control 288

### 15.2 Time-Delay Compensation 293

### 15.3 Inferential Control 296

### 15.4 Selective Control/Override Systems 297

### 15.5 Nonlinear Control Systems 300

### 15.6 Adaptive Control Systems 307

## 16. Multiloop and Multivariable Control 317

### 16.1 Process Interactions and Control Loop Interactions 317

### 16.2 Pairing of Controlled and Manipulated Variables 323

### 16.3 Singular Value Analysis 330

### 16.4 Tuning of Multiloop PID Control Systems 334

### 16.5 Decoupling and Multivariable Control Strategies 334

### 16.6 Strategies for Reducing Control Loop Interactions 336

## 17. Digital Sampling, Filtering, and Control 344

### 17.1 Sampling and Signal Reconstruction 344

### 17.2 Signal Processing and Data Filtering 347

- 17.3 z-Transform Analysis for Digital Control 352
- 17.4 Tuning of Digital PID Controllers 358
- 17.5 Direct Synthesis for Design of Digital Controllers 360
- 17.6 Minimum Variance Control 364

## **18. Batch Process Control 371**

- 18.1 Batch Control Systems 373
- 18.2 Sequential and Logic Control 374
- 18.3 Control During the Batch 380
- 18.4 Run-to-Run Control 386
- 18.5 Batch Production Management 387

Chapters 19 through 23 are online at  
[www.wiley.com/go/global/seborg](http://www.wiley.com/go/global/seborg)

## **19. Real-Time Optimization 395**

- 19.1 Basic Requirements in Real-Time Optimization 396
- 19.2 The Formulation and Solution of RTO Problems 399
- 19.3 Unconstrained and Constrained Optimization 401
- 19.4 Linear Programming 404
- 19.5 Quadratic and Nonlinear Programming 408

## **20. Model Predictive Control 414**

- 20.1 Overview of Model Predictive Control 414
- 20.2 Predictions for SISO Models 416
- 20.3 Predictions for MIMO Models 421
- 20.4 Model Predictive Control Calculations 423
- 20.5 Set-Point Calculations 427
- 20.6 Selection of Design and Tuning Parameters 429
- 20.7 Implementation of MPC 434

## **21. Process Monitoring 439**

- 21.1 Traditional Monitoring Techniques 440
- 21.2 Quality Control Charts 441
- 21.3 Extensions of Statistical Process Control 447
- 21.4 Multivariate Statistical Techniques 449
- 21.5 Control Performance Monitoring 451

## **PART FIVE APPLICATIONS TO BIOLOGICAL SYSTEMS**

### **22. Biosystems Control Design 456**

- 22.1 Process Modeling and Control in Pharmaceutical Operations 456
- 22.2 Process Modeling and Control for Drug Delivery 462

### **23. Dynamics and Control of Biological Systems 470**

- 24.1 Systems Biology 470
- 24.2 Gene Regulatory Control 472
- 24.3 Signal Transduction Networks 476

### **Appendix A: Laplace Transforms A-1**

- A.1 The Laplace Transform of Representative Functions A-1
- A.2 Solution of Differential Equations by Laplace Transform Techniques A-5
- A.3 Partial Fraction Expansion A-7
- A.4 Other Laplace Transform Properties A-10
- A.5 A Transient Response Example A-13

### **Appendix B: Digital Process Control Systems: Hardware and Software A-21**

- B.1 Distributed Digital Control Systems A-22
- B.2 Analog and Digital Signals and Data Transfer A-22
- B.3 Microprocessors and Digital Hardware in Process Control A-24
- B.4 Software Organization A-27

### **Appendix C: Review of Thermodynamic Concepts for Conservation Equations A-34**

- C.1 Single-Component Systems A-34
- G.2 Multicomponent Systems A-35

### **Appendix D: Control Simulation Software A-36**

- D.1 MATLAB Operations and Equation Solving A-36
- D.2 Computer Simulation with Simulink A-38
- D.3 Computer Simulation with Lab VIEW A-40

### **Appendix E: Process Control Modules A-43**

- E.1. Introduction A-43
- E.2. Module Organization A-43

- E.3. Hardware and Software Requirements A-44
- E.4. Installation A-44
- E.5. Running the Software A-44

Appendices F through K are online at  
[www.wiley.com/go/global/seborg](http://www.wiley.com/go/global/seborg)

**Appendix F: Introduction to Plantwide  
Control A-45**

- F.I Plantwide Control Issues A-45
- F.2 Hypothetical Plant for Plantwide Control  
Studies A-47
- F.3 Internal Feedback of Material  
and Energy A-51
- F.4 Interaction of Plant Design and Control  
System Design A-59

**Appendix G: Plantwide Control  
System Design A-63**

- G.I Procedures for the Design of Plantwide  
Control Systems A-63
- G.2 A Systematic Procedure for Plantwide  
Control System Design A-64
- G.3 Case Study: The Reactor/Flash  
Unit Plant A-67
- G.4 Effect of Control Structure on Closed-Loop  
Performance A-78

**Appendix H: Dynamic Models and  
Parameters Used for Plantwide  
Control Chapters A-82**

- H.I Energy Balance and Parameters for  
the Reactor/Distillation Column  
Model A-82
- H.2 Core Reactor/Flash Unit Model and  
Parameters A-82

**Appendix I: Instrumentation Symbols A-88**

**Appendix J: Review of Basic Concepts  
from Probability and  
Statistics A-90**

- J.I Probability Concepts A-90
- J.2 Means and Variances A-91
- J.3 Standard Normal Distribution A-91
- J.4 Error Analysis A-92

**Appendix K: Contour Mapping and the  
Principle of the Argument A-93**

- K.I Development of the Nyquist Stability  
Criterion A-93

**Index 1-1**