

PROCESS CONTROL

MODELING, DESIGN, AND SIMULATION

SECOND EDITION

B. WAYNE BEQUETTE



INTERNATIONAL SERIES IN THE
PHYSICAL AND CHEMICAL ENGINEERING SCIENCES



Process Control

Second Edition

Process Control: Modeling, Design, and Simulation

Table of Contents

Cover

Half Title

Title Page

Copyright Page

Contents

Preface to the Second Edition

About the Author

Chapter 1 Introduction

1.1 Introduction

Example 1.1: Liquid Surge Tank

Example 1.2: Glucose Regulation by the Pancreas

1.2 Instrumentation

Analog

Digital

Wireless

Techniques Used in This Textbook

1.3 Process Models and Dynamic Behavior

Example 1.3: Liquid Surge Vessel Model

1.4 Redundancy and Operability

1.5 Industrial IoT and Smart Manufacturing

1.6 Control Textbooks

1.7 A Look Ahead

Table of Contents

1.8 Summary

References

Student Exercises

Chapter 2 Fundamental Models

2.1 Background

Reasons for Modeling

2.2 Balance Equations

Integral Balances

Instantaneous Balances

Steady State

2.3 Material Balances

Example 2.1: Gas Surge Drum

Example 2.2: An Isothermal Chemical Reactor

2.4 Constitutive Relationships

Gas Law

Chemical Reactions

Equilibrium Relationships

Heat Transfer

Flow Through Valves

2.5 Material and Energy Balances

Review of Thermodynamics

Example 2.3: Heated Mixing Tank

2.6 Form of Dynamic Models

State Variables

Input Variables

Parameters

Output Variables

Vector Notation

Table of Contents

Numerical Solutions

2.7 Linear Models and Deviation Variables

Deviation Variable Formulation

Linearization of Nonlinear Models

Example 2.4: Jacketed Heater

2.8 Summary

Suggested Reading

Student Exercises

Chapter 3 Dynamic Behavior

3.1 Background

3.2 Linear State-Space Models

Stability

Example 3.1: Exothermic CSTR

MATLAB Eigenvalue Function

Generalization

3.3 Laplace Transforms

Exponential Function

Derivatives

Time Delays (Dead Time)

Step Functions

Pulse Functions

Impulse Functions

Other Functions

Initial- and Final-Value Theorems

Example 3.2: Application of Initial- and Final-Value Theorems

General Solution Procedure

Example 3.3: Second-Order Differential Equation

3.4 Transfer Functions

Table of Contents

3.5 First-Order Behavior

Step Response

Impulse Response

Pulse Response

Dimensionless Analysis

Example 3.4: Stirred-Tank Heater

3.6 Integrating Behavior

Purely Integrating Systems

Example 3.5: Tank-Height Problem

First-Order + Integrating Systems

Example 3.6: First-Order + Integrator

3.7 Second-Order Behavior

Pure Second-Order Systems

Underdamped Step Response Characteristics

Interacting and Non-interacting Tank Examples

3.8 Summary

References

Student Exercises

Chapter 4 Dynamic Behavior: Complex Systems

4.1 Introduction

4.2 Poles and Zeros

Example 4.1: Second-Order with Numerator Dynamics

Example 4.2: Effect of Transfer Function Zero

4.3 Lead-Lag Behavior

4.4 Processes with Deadtime

First-Order + Deadtime

First-Order + Integrator + Deadtime

Second-Order + Deadtime

Table of Contents

Second-Order + Integrator + Deadtime

Example 4.3: InsulinGlucose Model for Type 1 Diabetes

4.5 Padé Approximation for Deadtime

Example 4.4: Application of the Padé Approximations for Deadtime

4.6 Converting State-Space Models to Transfer Functions

Example 4.5: Isothermal CSTR

4.7 Converting Transfer Functions to State-Space Models

4.8 MATLAB and SIMULINK

conv and roots

step and impulse

ss2tf and tf2ss

SIMULINK

4.9 Summary

Student Exercises

Chapter 5 Empirical and Discrete-Time Models

5.1 Introduction

5.2 First-Order + Deadtime

Time for 63.2% Approach to New Steady State

Example 5.1: Numerical Application of 63.2% Method

Maximum Slope Method

Two-Point Method for Estimating Time Constant

Limitation to FODT Models

5.3 Integrator + Deadtime

5.4 Other Continuous Models

Second-Order + Deadtime

First-Order + Integrator + Deadtime

Example 5.2: Insulin-Glucose Model for Type 1 Diabetes

5.5 Discrete-Time Autoregressive Models

Table of Contents

Introduction to Autoregressive Models

Z-Transforms

Poles/Zeros of Discrete Models

Example 5.3: Discrete Poles and Stability

Final- and Initial-Values Theorems for Discrete Systems

5.6 Parameter Estimation

Example 5.4: Process Identification

5.7 Discrete Step and Impulse Response Models

Step Response Models

Impulse Response Models

5.8 Converting Continuous Models to Discrete

First-Order Process

FODT Process

5.9 Digital Filtering

Example 5.5: First-Order Filter

Contrast: First-Order Lag vs. First-Order Filter

Smoothing vs. Filtering

5.10 Summary

References

Student Exercises

Appendix 5.1: Discretization

Chapter 6 Introduction to Feedback Control

6.1 Motivation

On/Off Control

Proportional Control

Valve Gains

6.2 Control Block Diagrams

Controller Transfer Function

Table of Contents

Valve Transfer Function

Process Transfer Function

Disturbance Transfer Function

Measurement (Sensor) Transfer Function

Control Block Diagram

6.3 Closed-Loop Analysis

Response to Setpoint Changes

Possible Problems with Offset Using Proportional Controllers

Example 6.1: Offset with Proportional (P) Control of a First-Order Process

Response to Disturbances

Example 6.2: First-Order Process and Load Transfer Functions with P-Only Control

6.4 PID Controller Algorithms

PI Control

Example 6.3: First-Order Process with a PI Controller

PID Control

Proportional Band

6.5 Routh Stability Criterion

Example 6.4: Third-Order Process with a P-Only Controller

6.6 Effect of Tuning Parameters

Effect of Controller Gain

Integral Time

Derivative Time

6.7 Open-Loop Unstable Systems

Example 6.5: First-Order Open-Loop Unstable Process with P-Only Control

6.8 SIMULINK Block Diagrams

6.9 ODEs to Solve PID Problems

PI Controller Formulated as an ODE

Example 6.6: First-Order Process with PI Control

Table of Contents

PID Controller Formulated as Two ODEs

6.10 Summary

References

Student Exercises

Chapter 7 Model-Based Control

7.1 Introduction

7.2 Direct Synthesis

Direct Synthesis for Minimum-Phase Processes

Example 7.1: Direct Synthesis for a First-Order Process

7.3 Internal Model Control

Perfect Model, No Disturbances

Perfect Model, Disturbance Effect

Model Uncertainty, No Disturbances

The IMC Design Procedure

Example 7.2: Second-Order with an RHP Zero and Time Delay

7.4 IMC-Based PID

The IMC-Based PID Control Design Procedure

Example 7.3: IMC-Based PID Design for a Second-Order Process

Focus on Disturbance Rejection

Integrating Processes

Summary for Delay-Free Processes

7.5 IMC-Based PID for Time-Delay Processes

First-Order + Deadtime

Example 7.4: IMC-Based PID Design for a First-Order + Deadtime Process

Summary of PI(D) Control of First-Order + Time-Delay Processes

Integrator + Deadtime

Gain + Deadtime

First-Order + Integrator + Deadtime

Table of Contents

Example 7.5: Automated Insulin Delivery

7.6 IMC-Based PID for Unstable Processes

Example 7.6: IMC-Based PID Design for a First-Order Unstable Process

Summary of IMC-Based PID Controller Design for Unstable Processes

7.7 Summary

Terms

References

Student Exercises

Appendix 7.1: SIMC-Based PID Design

Chapter 8 PID Controller Tuning

8.1 Introduction

PID Controller Forms

Series PID

8.2 Closed-Loop Oscillation-Based Tuning

Ziegler-Nichols Closed-Loop Method

Example 8.1: Third-Order Process

8.3 Tuning Rules for First-Order + Deadtime Processes

Ziegler-Nichols Open-Loop Method

Cohen-Coon Parameters

IMC and Skogestad Modification (SIMC)

8.4 Digital Control

Z-Transform Representation of PID Control

8.5 Stability of Digital Control Systems

Example 8.2: Stability of a Discrete Control System

8.6 Performance of Digital Control Systems

Example 8.3: Effect of Sample Time on PI Control Performance

8.7 Summary

References

Table of Contents

Student Exercises

Chapter 9 Frequency-Response Analysis

9.1 Motivation

9.2 Bode and Nyquist Plots

Example 9.1: First-Order System

Complex Transfer Functions

Example 9.2: First-Order + Time Delay

9.3 Effect of Process Parameters on Bode and Nyquist Plots

Effect of Process Order

Concepts of All-Pass and Nonminimum Phase

Frequency Response Introductory Summary

9.4 Closed-Loop Stability

9.5 Bode and Nyquist Stability

Bode Stability Criterion

Nyquist Stability Criterion

Gain Margin

Phase Margin

Example 9.3: Nonminimum-Phase Process

9.6 Robustness

9.7 MATLAB Control Toolbox: Bode and Nyquist Functions

9.8 Summary

Reference

Student Exercises

Chapter 10 Cascade and Feedforward Control

10.1 Background

10.2 Introduction to Cascade Control

Cascade to Flow Control

Reactor Temperature Cascade Control

Table of Contents

10.3 Cascade-Control Analysis

10.4 Cascade-Control Design

Rules of Thumb for Cascade Control

10.5 Feedforward Control

10.6 Feedforward Controller Design

Example 10.1: First-Order Process and Disturbance Transfer Functions

Numerical Example

Example 10.2: First-Order + Deadtime Process and Disturbance Transfer Functions

Example 10.3: Process Higher Order than Disturbance Transfer Function

Numerical Simulation

Example 10.4: Process Has Inverse Response, Disturbance Does Not
Static Feedforward Control

Example 10.5: Disturbance Is a Pulse Input

10.7 Summary of Feedforward Control

10.8 Combined Feedforward and Cascade

10.9 Summary

References

Student Exercises

Chapter 11 PID Enhancements

11.1 Background

11.2 Antireset Windup

Reset (Integral) Windup

Example 11.1: Illustration of Reset Windup

Antireset Windup Techniques

Example 11.2: Illustration of Reset Windup Compensation (ARW)

Example 11.3: Cascade Control of a CSTR

11.3 Autotuning Techniques

Table of Contents

Control Block Diagram

Relay Deadband (Hysteresis)

Controller Tuning

11.4 Nonlinear PID Control

11.5 Controller Parameter (Gain) Scheduling

11.6 Measurement/Actuator Selection

11.7 Implementing PID Enhancements in SIMULINK

ARW

Autotuning

11.8 Summary

References

Student Exercises

Chapter 12 Ratio, Selective, and Split-Range Control

12.1 Motivation

12.2 Ratio Control

12.3 Selective and Override Control

12.4 Split-Range Control

Example 12.1: 1000-Liter Stirred-Tank Heater

12.5 SIMULINK Functions

12.6 Summary

References

Student Exercises

Chapter 13 Control-Loop Interaction

13.1 Introduction

13.2 Motivation

Example 13.1: Whiskey Blending

13.3 The General Pairing Problem

Table of Contents

Two InputTwo Output Processes

Input 1Output 1 Dynamic Behavior

Example 13.1, Continued

Steady-State Effective Gain

13.4 The Relative Gain Array

Two-Inputs and Two-Outputs

Definition of the Relative Gain

Relative Gain Between Input 1 and Output 1 for a Two InputTwo Output System

The RGA

13.5 Properties and Application of the RGA

Use of RGA to Determine Variable Pairing

Example 13.2: RGA for Variable Pairing

Two InputTwo Output Systems

Implications for the Sign of a Relative Gain

Midchapter Summarizing Remarks

13.6 Return to the Motivating Example

Total Material Balance

Component Material Balance on Ethanol

13.7 RGA and Sensitivity

Failure Sensitivity

Sensitivity to Model Uncertainty

Example 13.3: Model Uncertainty and the RGA

13.8 Using the RGA to Determine Variable Pairings

Example 13.1, Revisited

Example 13.4: A Three InputThree Output System

Example 13.5: A Four InputFour Output Distillation Column

13.9 MATLAB RGA Function File

13.10 Summary

Table of Contents

References

Student Exercises

Appendix 13.1: Derivation of the Relative Gain for an n-Inputn-Output
System

Appendix 13.2: m-File to Calculate the RGA

Chapter 14 Multivariable Control

14.1 Background

14.2 Zeros and Performance Limitations

SISO Zeros

Multivariable Transmission Zeros

Example 14.1: Calculation of Transmission Zeros

Example 14.2: Quadruple Tank Problem

14.3 Scaling Considerations

Example 14.3: Mixing Tank

14.4 Directional Sensitivity and Operability

SVD

Example 14.3, Continued

Operating Window

Example 14.3, Continued

14.5 Block-Diagram Analysis

14.6 Decoupling

Ideal Decoupling

Simplified Decoupling

Static Decoupling

14.7 MATLAB tzero, svd

Transmission Zero Calculation

Example 14.2, Continued

SVD

Table of Contents

Example 14.3, Continued

14.8 Summary

References

Student Exercises

Appendix 14.1

Chapter 15 Plantwide Control

15.1 Background

15.2 Steady-State and Dynamic Effects of Recycle

Steady-State Effects of Recycle

Example 15.1: A Simple Recycle Problem

Dynamic Effects of Recycle

Example 15.2: Dynamic Effects of Recycle

15.3 Unit Operations Not Previously Covered

Supply-Side vs. Demand-Side Control of Production

Compressor Control

Heat Exchangers

Adiabatic Plug Flow Reactors

15.4 The Control and Optimization Hierarchy

Operating Levels

Petroleum Refining Example

Discussion

15.5 Further Plantwide Control Examples

Example 15.3: HDA Process

The Art of Process Engineering

Example 15.4: HDA Back-of-the-Envelope Material Balance

15.6 Simulations

Example 15.5: A Simple Recycle System

15.7 Startup, Safety, and the Human-in-the-Loop

Table of Contents

15.8 Summary

References

Student Exercises

Appendix 15.1

Example A15.1: MPN Process and Instrumentation Diagram

Chapter 16 Model Predictive Control

16.1 Motivation

Basic Description

16.2 Optimization Problem

Objective Functions

Models

16.3 Dynamic Matrix Control

Example 16.1: First-Order Process

Example 16.2: Van de Vusse Reactor

16.4 Constraints and Multivariable Systems

Quadratic DMC

Multivariable Systems

16.5 Other MPC Methods

Alternative Objective Functions

Problems with DMC

16.6 MATLAB

16.7 Summary

References and Relevant Literature

Student Exercises

Appendix 16.1: Derivation of the Step Response Formulation

Appendix 16.2: Derivation of the Least-Squares Solution for Control

Moves

Appendix 16.3: State Space Formulation for MPC

Table of Contents

Chapter 17 Summary

17.1 Overview of Topics Covered in This Textbook

Chapters

Modules

17.2 Process Engineering in Practice

Topics Not Covered

Art and Philosophy of Process Engineering

Rules of Process Operations

17.3 Suggested Further Reading

Student Exercises

Module 1 Introduction to MATLAB

M1.1 Background

M1.2 Matrix Operations

Matrix Notation Review

MATLAB Matrix Operations

M1.3 The MATLAB Workspace

M1.4 Complex Variables

M1.5 Plotting

M1.6 More Matrix Stuff

M1.7 for Loops

M1.8 m-Files

Script Files

Function Routines

Commonly Used MATLAB Functions

M1.9 Summary of Commonly Used Commands

M1.10 Frequently Used MATLAB Functions

Additional Exercises

Table of Contents

Module 2 Introduction to SIMULINK

M2.1 Background

M2.2 Open-Loop Simulations

M2.3 Feedback-Control Simulations

Other Commonly Used Icons

M2.4 Summary

Additional Exercises

Module 3 Ordinary Differential Equations

M3.1 MATLAB™ odeBasic

Example M3.1: Van de Vusse Reaction

M3.2 MATLAB odeOptions

M3.3 SIMULINK sfun

Example M3.2: Van de Vusse Reaction

M3.4 Summary

Additional Exercises

Module 4 MATLAB LTI Models

M4.1 Forming Continuous-Time Models

State Space

Transfer Function

Zero-Pole-Gain

Converting between Model Types

Continuous-Time State-Space Model

Multiple Inputs and/or Outputs

Input Time Delays

M4.2 Forming Discrete-Time Models

Discrete State-Space Models

Discrete Transfer Function

Table of Contents

Discrete Filter Form

Converting between Discrete Model Types

M4.3 Converting Continuous Models to Discrete

M4.4 Converting Discrete Models to Continuous

M4.5 Step and Impulse Responses

M4.6 Summary

Additional Exercises

Module 5 Isothermal Chemical Reactor

M5.1 Background

M5.2 Model

M5.3 Steady-State and Dynamic Behavior

Steady-State Input-Output Curve

Linear Analysis

Case 1 Operation on the Left-Hand Side of the Peak Concentration

M5.4 Closed-Loop Control

Problem Statements

Reference

Additional Exercises

Module 6 Biochemical Reactors

M6.1 Background

Model

Scale-Up

M6.2 Steady-State and Dynamic Behavior

Steady-State Conditions

Linear Model

M6.3 Stable Steady-State Operating Point

M6.4 Unstable Steady-State Operating Point

Table of Contents

M6.5 SIMULINK Model File

Reference

Additional Exercises

Module 7 CSTR

M7.1 Background

M7.2 Simplified Modeling Equations

Overall Reactor Material Balance

Balance on Component A

Reactor Energy Balance

State Variable Form of the Equations

Steady-State Solution

Linearization

M7.3 Example Chemical Process Propylene Glycol Production

Parameter Values

M7.4 Effect of Reactor Scale

Reactor Scale

Steady-State (Nonlinear) Results

Linear Open-Loop Results

Linear Closed-Loop Results

M7.5 For Further Study: Detailed Model

Linear Open-Loop Results

Nonlinear Open-Loop Results

Linear Closed-Loop Results

M7.6 Other Considerations

Nonlinear Behavior

Split-Range Control

M7.7 Summary

References

Table of Contents

Additional Exercises

Appendix M7.1

Module 8 Steam Drum Level

M8.1 Background

M8.2 Process Model

M8.3 Feedback Controller Design

IMC-Based PID

Ziegler-Nichols (or Tyreus-Luyben)

M8.4 Feedforward Controller Design

M8.5 Three-Mode Level Control

Appendix M8.1: SIMULINK Diagram for Feedforward/Feedback
Control of Steam Drum Level

Appendix M8.2: SIMULINK Diagram for Three-Mode Control of Steam
Drum Level

Module 9 Surge Vessel Level Control

M9.1 Background

M9.2 Process Model

M9.3 Controller Design

Proportional Gain

Nonlinear Proportional Gain

M9.4 Numerical Example

Step Disturbances

Sinusoidal Disturbances

Additional Simulations

M9.5 Summary

Reference

Additional Exercises

Table of Contents

Appendix M9.1: The SIMULINK Block Diagram

Module 10 Batch Reactor

M10.1 Background

M10.2 Batch Model 1: Jacket Temperature Manipulated

Effect of Scale (Size)

Quasi-Steady-State Behavior

IMC-Based Design

M10.3 Batch Model 2: Jacket Inlet Temperature Manipulated

IMC-Based PID Tuning Parameters

M10.4 Batch Model 3: Cascade Control

M10.5 Summary

Reference

Additional Exercises

Module 11 Biomedical Systems

M11.1 Overview

M11.2 Pharmacokinetic Models

Modeling Equations

M11.3 Intravenous Delivery of Anesthetic Drugs

M11.4 Blood Glucose Control in ICU Patients

Nonlinear Model

M11.5 Critical Care Patients

M11.6 Summary

References

Additional Exercises

Module 12 Automated Insulin Delivery

M12.1 Background: Physiology of Blood Glucose Regulation

M12.2 Type 1 Diabetes

Table of Contents

Insulin Pumps

Carbohydrate-to-Insulin Ratio and Correction Factor

Glucose Measurements

Glycated Hemoglobin (A1c)

M12.3 Closed-Loop Components and Diagram

M12.4 Simulation Model

Overview of Simulation Study

Steady-State Insulin Infusion and Blood Glucose Concentration

M12.5 Open-Loop Responses to Meal and Insulin

Response to Insulin

Response to Meal Carbohydrates

Response to Simultaneous Meal Carbohydrates and Insulin

M12.6 Closed-Loop Responses

M12.7 Summary

Important Topics Not Covered in This Module

Terminology

References

Suggested Further Study

Additional Exercises

Module 13 Distillation Control

M13.1 Description of Distillation Control

Simplified Model

M13.2 Open-Loop Behavior

Response to Reflux Change

Response to Vapor Boil-Up Change

Response to Simultaneous Changes in Reflux and Vapor Boil-Up

M13.3 SISO Control

M13.4 RGA Analysis

Table of Contents

M13.5 Multiple SISO Controllers

Setpoint Changes

Disturbance Rejection

M13.6 Singular Value Analysis

MATLAB SVD Analysis

M13.7 Nonlinear Effects

M13.8 Other Issues in Distillation Column Control

M13.9 Summary

References

Additional Exercises

Module 14 Case Study Problems

M14.1 Background

M14.2 Reactive Ion Etcher

Questions to Answer

M14.3 Rotary Lime Kiln Temperature Control

M14.4 Fluidized Catalytic Cracking Unit

M14.5 Anaerobic Sludge Digester

M14.6 Suggested Case Study Schedule

M14.7 Summary

Additional Exercises

Module 15 Process Monitoring

M15.1 Concise Review of Probability

Example M15.1: Histograms

M15.2 Statistical Process Control

Example M15.2: Quality Control of an Oxygen Product

Process Capability Ratio (C_p)

Process Capability Index (C_{pk})

Table of Contents

CUSUM

M15.3 Characteristic Process Noise

M15.4 Filtering and Smoothing

Filtering

Smoothing

M15.5 Data Reconciliation

Generalization

Example M15.3: Single Streams In and Out

Example M15.4: Single Stream In and Two Streams Out

M15.6 Gross Error Detection

Example M15.5: Gross Error Detection

Limitations to Presentation

M15.7 Summary

References

Literature Sources

Additional Exercises

Appendix M15.1

Module 16 Safety

M16.1 Overview

M16.2 Chemical Process Disasters

Bhopal, 1984

Texas City, 2005

M16.3 Aircraft Disasters

US Airways Flight 1549, January 15, 2009

Air France Flight 447, June 2009

Asiana Flight 214, July 2013

Boeing 737 Max 8

M16.4 Fault Detection Algorithms and Safety Science

Table of Contents

M16.5 Summary

References

General Fault Detection and Safety References

Bhopal Disaster References

Texas City Disaster References

Aircraft Disaster References

Additional Exercises

Index