

SU WHAN SUNG

JIETAE LEE

IN-BEUM LEE

Process Identification and PID Control



Companion Website



TP273
S958

PROCESS IDENTIFICATION AND PID CONTROL

Su Whan Sung
Jietae Lee

Kyungpook National University, Republic of Korea

In-Beum Lee

Pohang University of Science and Technology, Republic of Korea



IEEE PRESS

IEEE Communications Society, Sponsor



E2009002834

John Wiley & Sons (Asia) Pte Ltd

Copyright © 2009

John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop, # 02-01,
Singapore 129809

Visit our Home Page on www.wiley.com

MATLAB[®] and Simulink[®] are trademarks of The MathWorks, Inc. and are used with permission. The MathWorks does not warrant the accuracy of the text or exercises in this book. This book's use or discussion of MATLAB[®] and Simulink[®] software or related products does not constitute endorsement or sponsorship by The MathWorks of a particular pedagogical approach or particular use of the MATLAB[®] and Simulink[®] software.

All Rights Reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as expressly permitted by law, without either the prior written permission of the Publisher, or authorization through payment of the appropriate photocopy fee to the Copyright Clearance Center. Requests for permission should be addressed to the Publisher, John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop, #02-01, Singapore 129809, tel: 65-64632400, fax: 65-64646912, email: enquiry@wiley.com.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The Publisher is not associated with any product or vendor mentioned in this book. All trademarks referred to in the text of this publication are the property of their respective owners.

This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the Publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Other Wiley Editorial Offices

John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030, USA

Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstrasse 12, D-69469 Weinheim, Germany

John Wiley & Sons Australia Ltd, 42 McDougall Street, Milton, Queensland 4064, Australia

John Wiley & Sons Canada Ltd, 5353 Dundas Street West, Suite 400, Toronto, ONT, M9B 6H8, Canada

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Library of Congress Cataloging-in-Publication Data

Sung, Su Whan.

Process identification and PID control / Su Whan Sung, Jietae Lee, In-Beum Lee.

p. cm.

Includes bibliographical references and index.

ISBN 978-0-470-82410-8 (cloth)

1. Process control. 2. System identification. 3. PID controllers. I. Lee, Jietae. II. Lee, In, 1958- III. Title. TS156.8.P7585 2009 629.8-dc22

2009001953

ISBN 978-0-470-82410-8 (HB)

Typeset in 10/12pt Times by Thomson Digital, Noida, India.

Printed and bound in Singapore by Markono Print Media Pte Ltd, Singapore.

This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

PROCESS IDENTIFICATION AND PID CONTROL

To our wives and children

Preface

This book focuses on the basics of process control, process identification, PID controllers and autotuning. Our objective is to enable students and engineers who are not familiar with these topics to understand the basic concepts of feedback control, process identification, autotuning and design of real feedback controllers (especially PID controllers).

Parts One and Two are aimed at undergraduate students who have not taken any courses on process control. Parts Three and Four are appropriate for graduate students and control engineers who want to design real feedback controllers or perform research on process identification and autotuning. Parts One and Two introduce the basics of process control and dynamics, the analysis tools (Bode plot, Nyquist plot) to characterize the dynamics of the process, PID controllers and tuning, and advanced control strategies that have been widely used in industry. Also, simple simulation techniques required for practical controller designs and research on process identification and autotuning are also included. Part Three provides useful process identification methods actually used in industry. It includes several important identification algorithms to obtain frequency models or continuous-time/discrete-time transfer function models from the measured process input and output data sets. Part Four introduces various relay feedback methods to activate the process effectively for process identification and controller autotuning.

We have tried to include as many examples as possible. In particular, the readers can use the numerical examples and the MATLAB R codes with slight modifications to solve actual problems in their processes or research. The codes (MATLAB Rm-files) and real-time virtual processes for the simulations and practices are available from the Wiley website at www.wiley.com/go/swsung. The codes will be useful to those who want to understand the actual implementation techniques for control, process identification and autotuning. Also, the readers can design their own controllers, implement them and confirm the performances in real time using real-time virtual processes. Also, the problem-solving ability of students can be enhanced by performing a controller design project on the basis of the virtual process. We welcome the comments of students and instructors to improve the book and the materials for lectures and simulations. Please visit our other website at <http://pse.knu.ac.kr> for comments and questions about this book or process systems engineering. We hope this book is useful to you.

We wish to express special thanks to the students at KNU who provided the simulation results and detailed reviews: Cheol Ho Je, Chun Ho Jeon and Yu Jin Cheon. We acknowledge

John Wiley & Sons, especially James Murphy, Roger Bullen, Sarah Abdul Karim and Peter Lewis, for their effective cooperation and great care in preparing this book. We also gratefully acknowledge the financial support by Kyungpook National University (KNU Research Fund, 2006).

Su Whan Sung
Jietae Lee
In-Beum Lee

Contents

Preface	xi
Part One Basics of Process Dynamics	1
1 Mathematical Representations of Linear Processes	3
1.1 Introduction to Process Control and Identification	3
1.2 Properties of Linear Processes	9
1.3 Laplace Transform	16
1.4 Transfer Function and State-Space Systems	32
Problems	38
2 Simulations	45
2.1 Simulating Processes Composed of Differential Equations	45
2.2 Simulating Processes Including Time Delay	50
2.3 Simulating Closed-Loop Control Systems	57
2.4 Useful Numerical Analysis Methods	59
Problems	74
3 Dynamic Behavior of Linear Processes	79
3.1 Low-Order Plus Time-Delay Processes	79
3.2 Process Reaction Curve Method	84
3.3 Poles and Zeroes	86
3.4 Block Diagram	92
3.5 Frequency Responses	94
Problems	103
Part Two Process Control	109
4 Proportional–Integral–Derivative Control	111
4.1 Structure of Proportional–Integral–Derivative Controllers and Implementation in Computers/Microprocessors	111
4.2 Roles of Three Parts of Proportional–Integral–Derivative Controllers	122
4.3 Integral Windup	129

4.4	Commercial Proportional–Integral–Derivative Controllers Problems	135 147
5	Proportional–Integral–Derivative Controller Tuning	151
5.1	Trial-and-Error Tuning	151
5.2	Simple Process Identification Methods	154
5.3	Ziegler–Nichols Tuning Rule	157
5.4	Internal Model Control Tuning Rule	159
5.5	Integral of the Time-Weighted Absolute Value of the Error Tunning Rule for a First-Order Plus Time-Delay Model (ITAE-1)	161
5.6	Integral of the Time-Weighted Absolute Value of the Error Tunning Rule for a Second-Order Plus Time-Delay Model (ITAE-2)	166
5.7	Optimal Gain Margin Tuning Rule for an Unstable Second-Order Plus Time-Delay Model (OGM-unstable)	169
5.8	Model Reduction Method for Proportional–Integral–Derivative Controller Tuning	170
5.9	Consideration of Modeling Errors	196
5.10	Concluding Remarks	196
	Problems	197
6	Dynamic Behavior of Closed-Loop Control Systems	201
6.1	Closed-Loop Transfer Function and Characteristic Equation	201
6.2	Bode Stability Criterion	203
6.3	Nyquist Stability Criterion	207
6.4	Gain Margin and Phase Margin	210
	Problems	212
7	Enhanced Control Strategies	215
7.1	Cascade Control	215
7.2	Time-Delay Compensators	217
7.3	Gain Scheduling	225
7.4	Proportional–Integral–Derivative Control using Internal Feedback Loop	228
	Problems	231
Part Three Process Identification		233
8	Process Identification Methods for Frequency Response Models	235
8.1	Fourier Series	235
8.2	Frequency Response Analysis and Autotuning	240
8.3	Describing Function Analysis	241
8.4	Fourier Analysis	247
8.5	Modified Fourier Transform	250
8.6	Frequency Response Analysis with Integrals	261
	Problems	271

9 Process Identification Methods for Continuous-Time Differential Equation Models	275
9.1 Identification Methods Using Integral Transforms	275
9.2 Prediction Error Identification Method	291
Problems	315
10 Process Identification Methods for Discrete-Time Difference Equation Models	317
10.1 Prediction Model: Autoregressive Exogenous Input Model and Output Error Model	317
10.2 Prediction Error Identification Method for the Autoregressive Exogenous Input Model	319
10.3 Prediction Error Identification Method for the Output Error Model	325
10.4 Concluding Remarks	335
Problems	336
11 Model Conversion from Discrete-Time to Continuous-Time Linear Models	337
11.1 Transfer Function of Discrete-Time Processes	337
11.2 Frequency Responses of Discrete-Time Processes and Model Conversion	338
Problems	342
Part Four Process Activation	343
12 Relay Feedback Methods	345
12.1 Conventional Relay Feedback Methods	345
12.2 Relay Feedback Method to Reject Static Disturbances	352
12.3 Relay Feedback Method under Nonlinearity and Static Disturbances	357
12.4 Relay Feedback Method for a Large Range of Operation	365
Problems	370
13 Modifications of Relay Feedback Methods	373
13.1 Process Activation Method Using Pulse Signals	373
13.2 Process Activation Method Using Sine Signals	387
Problems	397
Appendix Use of Virtual Control System	399
A.1 Setup of the Virtual Control System	399
A.2 Examples	400
Index	409

Part One

Basics of Process Dynamics

Part One introduces the basics of process dynamics which are appropriate for an undergraduate course. Chapter 1 defines linear processes and discusses how to represent linear processes in a mathematical way. Chapter 2 introduces several simulation and numerical analysis techniques required to simulate/design process controllers. Chapter 3 discusses the dynamic behaviors of linear processes and provides several analysis tools to characterize the dynamics of the control system.

1

Mathematical Representations of Linear Processes

1.1 Introduction to Process Control and Identification

The basic concepts and terms of process control and identification are first introduced.

1.1.1 Process Control

Process control consists of manipulating variables, controlled variables and processes. The manipulating variables and the controlled variables usually correspond to the process inputs and the process outputs respectively. The objective of process control is to make the process outputs (controlled variables) behave in a desired way by adjusting the process inputs (manipulating variables). Consider the temperature control system in Figure 1.1.

The SCR unit is to provide electrical power to the heating coil, which is proportional to the voltage $u(t)$. The temperature is measured by the thermocouple sensor. The objective of the temperature control system in Figure 1.1 is to drive the temperature $y(t)$ to the desired value by adjusting $u(t)$. So, $u(t)$ and $y(t)$ are the process input (manipulating variable) and the process output (controlled variable) respectively. The role of the feedback controller is to determine $u(t)$ appropriately on the basis of the measured $y(t)$ to achieve the control objective.

Example 1.1

Consider the control system in Figure 1.2. It consists of two tanks, a control valve, a DP cell and a controller. The DP cell and the control valve are to measure the liquid level of the last tank and adjust the inlet flow rate respectively. The objective of the control system is to drive the liquid level of the last tank to a desired value. In this case, the manipulating variable is the inlet flow rate and the controlled variable is the level of the last tank.

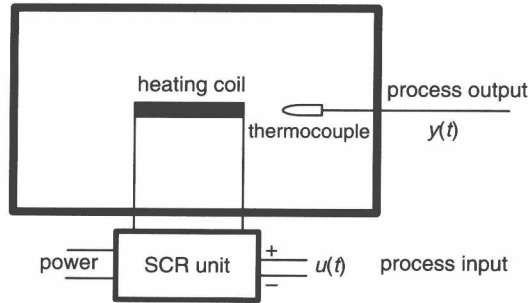


Figure 1.1 Temperature control system.

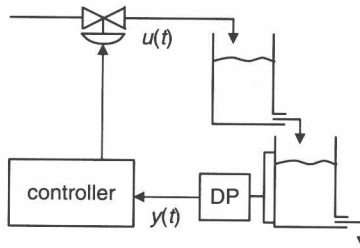


Figure 1.2 Level control system.

1.1.2 Process Identification

Process identification is the obtaining of a model of which the role is to predict the behavior of the process output for a given process input. The models are in the form of differential equations or frequency data sets (which will be explained later). From the energy balance equation for the temperature control system in Figure 1.1, the model of the following simple differential equation form can be derived:

$$\tau \frac{dy(t)}{dt} + y(t) = ku(t) + b \quad (1.1)$$

where τ , k and b are known constants determined by the heat capacity, mass, amplification coefficient, heat transfer coefficient, area and ambient temperature. This is a simple example of process identification. The behavior of $y(t)$ can be predicted by solving the differential equation for a given $u(t)$. In this book, how to obtain the model from historical data of the process input and the process output will be treated without considering physical principles such as material balance, energy balance and chemical reactions. This kind of model is called a “black-box model.”

Example 1.2

Assume that the black-box model structure for a given process has the following form:

$$\tau \frac{dy(t)}{dt} + y(t) = ku(t) \quad (1.2)$$

And assume that $y(t) = 1 - \exp(-2t)$ is obtained from an experiment when $u(t) = 1$ is applied to the process. Then, it is straightforward to estimate the model parameters of τ and k from the experiment. Replace $y(t)$ and $u(t)$ in (1.2) by $y(t) = 1 - \exp(-2t)$ and $u(t) = 1$. Then, (1.2) becomes $(2\tau - 1) \exp(-2t) + 1 = k$. So, $\tau = 0.5$ and $k = 1$ is obtained. This is a simple example of parameter estimation. The determination of the model structure and the parameter estimation are the core parts of process identification.

Example 1.3

Assume that the black-box model structure for a given process has the following form:

$$\tau^2 \frac{d^2y(t)}{dt^2} + 2\tau \frac{dy(t)}{dt} + y(t) = ku(t) \quad (1.3)$$

And assume that $y(t) = 0.5 \sin(t - \pi/2)$ is obtained from an experiment when $u(t) = \sin(t)$ is applied to the process. Estimate the model parameters τ and k from the experiment.

Solution Replace $y(t)$ and $u(t)$ in (1.3) by $y(t) = 0.5 \sin(t - \pi/2)$ and $u(t) = \sin(t)$. Then, (1.3) becomes

$$-0.5\tau^2 \sin(t - \pi/2) + \tau \cos(t - \pi/2) + 0.5 \sin(t - \pi/2) = k \sin(t)$$

which can be rewritten as $(0.5\tau^2 - 0.5) \cos(t) + \tau \sin(t) = k \sin(t)$ because $\sin(t - \pi/2) = -\cos(t)$ and $\cos(t - \pi/2) = \sin(t)$. So, $\tau = 1.0$ and $k = 1$ is obtained.

1.1.3 Steady State

When all the derivatives of the process input and process output are zero, this is called the steady state. For example, the process (1.4) will be (1.5) at steady state:

$$\frac{d^2y(t)}{dt^2} + 2 \frac{dy(t)}{dt} + y(t) = \frac{du(t)}{dt} + 2u(t) + 2 \quad (1.4)$$

$$\frac{d^2y_{ss}(t)}{dt^2} + 2 \frac{dy_{ss}(t)}{dt} + y_{ss}(t) = \frac{du_{ss}(t)}{dt} + 2u_{ss}(t) + 2 \rightarrow y_{ss}(t) = 2u_{ss}(t) + 2 \quad (1.5)$$

where the subscript 'ss' denotes steady state. As shown in (1.5), all the derivatives go to zeroes at steady state. On the other hand, a cyclic steady state means that the process output and input are periodic signals.

Example 1.4

Consider the process input $u(t)$ and the process output $y(t)$ in Figure 1.3. It can be seen that the process is in steady state after $t = 8$.

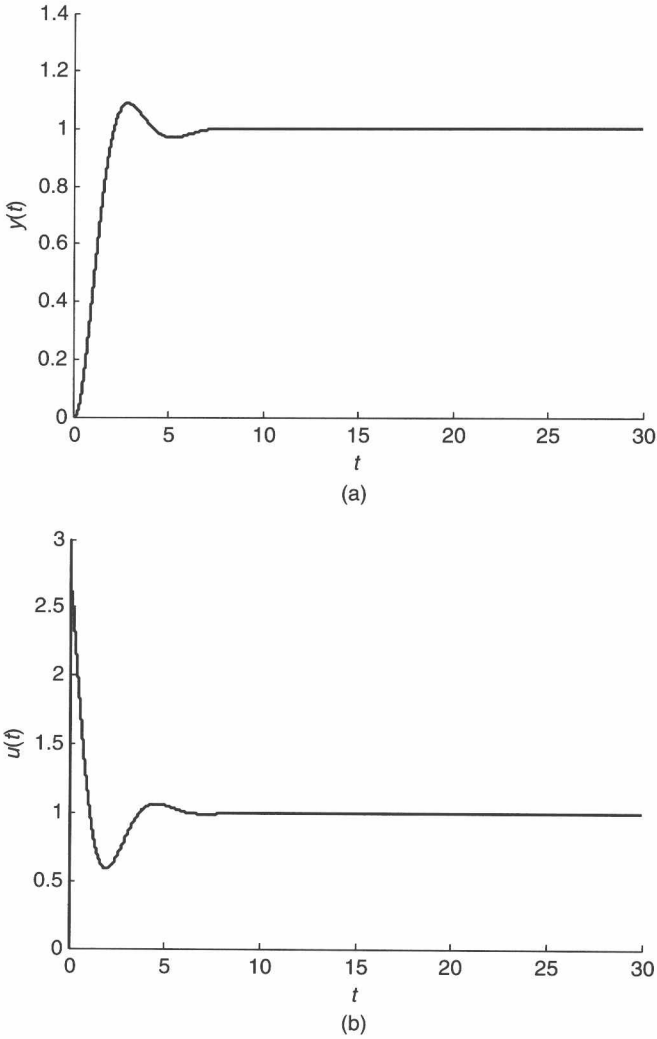


Figure 1.3 The process output and the process input of a control system.

Example 1.5

Obtain $y(t)$ for $u(t) = 2.0$ at steady state for the following process:

$$0.2 \frac{d^2 y(t)}{dt^2} + \frac{dy(t)}{dt} (0.1 + 0.05u(t)) + y(t) = \frac{du(t)}{dt} + \sqrt{u(t)} \quad (1.6)$$

Because all the derivatives are zero at steady state, $y_{ss}(t) = \sqrt{u_{ss}(t)}$. So, $y_{ss}(t) = \sqrt{2.0}$ for $u_{ss}(t) = 2.0$ at steady state.

Example 1.6

Obtain $y(t)$ for $y_s(t) = 1.0$ at steady state for the following process:

$$\frac{d^2y(t)}{dt^2} + 2\frac{dy(t)}{dt} + y(t) = 0.1\frac{du(t)}{dt} + u(t) \quad (1.7)$$

$$u(t) = 1.5(y_s(t) - y(t)) + 0.5\frac{d(y_s(t) - y(t))}{dt} \quad (1.8)$$

Because all the derivatives in (1.7) are zero at steady state, $y_{ss}(t) = u_{ss}(t)$ and $u_{ss} = 1.5(y_{s,ss} - y_{ss})$ are obtained from (1.7) and (1.8). So, $y_{ss}(t) = 1.5/2.5$ at steady state.

Example 1.7

Consider the process input $u(t)$ and the process output $y(t)$ in Figure 1.4. It can be seen that the process is in cyclic steady state after about $t = 15$ because $u(t)$ and $y(t)$ are periodic after $t = 15$.

1.1.4 Deviation Variables

The deviation variable $\bar{x}(t)$ is the difference between the original variable $x(t)$ and a reference value x_{ref} . That is, $\bar{x}(t) = x(t) - x_{ref}$. So, it represents how far the original variable deviates from the reference value. The deviation variables for the process output and process input can be defined like $\bar{y}(t) = y(t) - y_{ref}$ and $\bar{u}(t) = u(t) - u_{ref}$ respectively. Here, y_{ref} and u_{ref} are usually the process output and the process input at steady state if there is no special notice. Note, y_{ref} is automatically fixed for the given u_{ref} at steady state. For example, the process (1.4) can be rewritten using deviation variables by subtracting (1.5) from (1.4):

$$\frac{d^2\bar{y}(t)}{dt^2} + 2\frac{d\bar{y}(t)}{dt} + \bar{y}(t) = \frac{d\bar{u}(t)}{dt} + 2\bar{u}(t) \quad (1.9)$$

$$\bar{y}(t) = y(t) - y_{ss}, \quad \bar{u}(t) = u(t) - u_{ss} \quad (1.10)$$

where $\bar{u}(t)$ and $\bar{y}(t)$ are deviation variables. u_{ss} and y_{ss} are the reference values for $u(t)$ and $y(t)$ respectively. Here, u_{ss} and y_{ss} should satisfy (1.5). So, y_{ss} is automatically fixed for the given u_{ss} at steady state.

Example 1.8

Rewrite the following process with deviation variables when the reference value for the process input $u(t)$ is chosen as 2.0.

$$\frac{d^3y(t)}{dt^3} + 3\frac{d^2y(t)}{dt^2} + 3\frac{dy(t)}{dt} + y(t) + 1 = 2\frac{du(t)}{dt} + 3u(t) \quad (1.11)$$