DONALD R. COUGHANOWR

Process Systems Analysis and Control

SECOND EDITION

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PROCESS SYSTEMS ANALYSIS AND CONTROL

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Second Edition

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Hamburg Lisbon London Madrid Mexico Milan Montreal New Delhi
Paris San Juan São Paulo Singapore Sydney Tokyo Toronto

PROCESS SYSTEMS ANALYSIS AND CONTROL

International Edition 1991

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34567890 BJE FC 965432

This book was set in Times Roman by Publication Services.
The editors were B. J. Clark and John M. Morriss.
The production supervisor was Louise Karam.
The cover was designed by Rafael Hernandez.
Project supervision was done by Publication Services.

Library of Congress Cataloging in Publication Data

Coughanowr, Donald R.
Process systems analysis and control / by Donald Ft. Coughanowr. — 2nd ed.
p. cm. — (McGraw-Hill chemical engineering series)
Includes index.
ISBN o-07-013212-7
1. Chemical process control. I. Title. II. Series.
TP155.75.C68 1991
660'.02815--dc20 90-41740

When ordering this title use ISBN 0-07-I 00807-I

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Donald R. Coughanowr is the Fletcher Professor of Chemical Engineering at Drexel University. He received a Ph.D. in chemical engineering from the University of Illinois in 1956, an M.S. degree in chemical engineering from the University of Pennsylvania in 1951, and a B.S. degree in chemical engineering from the Rose-Hulman Institute of Technology in 1949. He joined the faculty at Drexel University in 1967 as department head, a position he held until 1988. Before going to Drexel, he was a faculty member of the School of Chemical Engineering at Purdue University for eleven years.

At Drexel and Purdue he has taught a wide variety of courses, which include material and energy balances, thermodynamics, unit operations, transport phenomena, petroleum refinery engineering, environmental engineering, chemical engineering laboratory, applied mathematics, and process dynamics and control. At Purdue, he developed a new course and laboratory in process control and collaborated with Dr. Lowell B. Koppel on the writing of the first edition of *Process Systems Analysis and Control.*

His research interests include environmental engineering, diffusion with chemical reaction, and process dynamics and control. Much of his research in control has emphasized the development and evaluation of new control algorithms for processes that cannot be controlled easily by conventional control; some of the areas investigated are time-optimal control, adaptive pH control, direct digital control, and batch control of fermentors. He has reported on his research in numerous publications and has received support for research projects from the N.S.F. and industry. He has spent sabbatical leaves teaching and writing at Case-Western Reserve University, the Swiss Federal Institute, the University of Canterbury, the University of New South Wales, the University of Queensland, and Lehigh University.

Dr. Coughanowr's industrial experience includes process design and pilot plant at Standard Oil Co. (Indiana) and summer employment at Electronic Associates and Dow Chemical Company.

He is a member of the American Institute of Chemical Engineers, the Instrument Society of America, and the American Society for Engineering Education. He is also a delegate to the Council for Chemical Research. He has served the AIChE by participating in accreditation visits to departments of chemical engineering for. ABET and by chairing sessions of the Department Heads Forum at the annual meetings of AIChE.

To
Effie, Corinne, Christine, and David

CONTENTS

PREFACE

Since the first edition of this book was published in 1965, many changes have taken place in process control. Nearly all undergraduate students in chemical engineering are now required to take a course‘in process dynamics and control. The purpose of this book is to take the student from the basic mathematics to a variety of design applications in a clear, concise manner.

The most significant change since the first edition is the use of the digital computer in complex problem-solving and in process control instrumentation. However, the fundamentals of process control, which remain the same, must be acquired before one can appreciate the advanced topics of control.

In its present form, this book represents a major revision of the first edition. The material for this book evolved from courses taught at Purdue University and Drexel University. The first 17 chapters on fundamentals are quite close to the first 20 chapters of the first edition. The remaining 18 chapters contain many new topics, which were considered very advanced when the first edition was published.

A knowledge of calculus, unit operations, and complex numbers is presumed on the part of the student. In certain later chapters, more advanced mathematical preparation is useful. Some examples would include partial differential equations in Chap. 21, linear algebra in Chaps. 28-30, and Fourier series in Chap. 33.

Analog computation and pneumatic controllers in the first edition have been replaced by digital computation and microprocessor-based controllers in Chaps. 34 and 35. The student should be assigned material from these chapters at the appropriate time in the development of the fundamentals. For example, obtaining the transient response for a system containing a transport lag can be obtained easily only with the use of computer simulation of transport lag. Some of the software now available for solving control problems should be available to the student; such software is described in Chap. 34. To understand the operation of modem microprocessor-based controllers, the student should have hands-on experience with these instruments in a laboratory.

Chapter 1 is intended to meet one of the problems consistently faced in presenting this material to chemical engineering students, that is, one of perspective. The methods of analysis used in the control area are so different from the previous experiences of students that the material comes to be regarded as a sequence of special mathematical techniques, rather than an integrated design approach to a class of real and practically significant industrial problems. Therefore, this chapter presents an overall, albeit superficial, look at a simple control-system design problem. The body of the text covers the following topics:

1. Laplace transforms, Chaps 2 to 4.
2. Transfer functions and responses of open-loop systems, Chaps. 5 to 8.
3. Basic techniques of closed-loop control, Chaps. 9 to 13.
4. Stability, Chap. 14.
5. Root-locus methods, Chap. 15.
6. Frequency-response methods and design, Chaps. 16 and 17.
7. Advanced control strategies (cascade, feedforward, Smith predictor, internal model control), Chap. 18.
8. Controller tuning and process identification, Chap. 19.
9. Control valves, Chap. 20.
10. Advanced process dynamics, Chap. 21.
11. Sampled-data control, Chaps. 22 to 27.
12. State-space methods and multivariable control, Chaps. 28 to 30.
13. Nonlinear control, Chaps. 31 to 33.
14. Digital computer simulation, Chap. 34.
15. Microprocessor-based controllers, Chap. 35.

It has been my experience that the book covers sufficient material for a one-semester (15-week) undergraduate course and an elective undergraduate course or part of a graduate course. In a lecture course meeting three hours per week during a lo-week term, I have covered the following Chapters: 1 to 10, 12 to 14, 16, 17, 20, 34, and 35.

After the first 14 chapters, the instructor may select the remaining chapters to fit a course of particular duration and scope. The chapters on the more advanced topics are written in a logical order; however, some can be skipped without creating a gap in understanding.

I gratefully acknowledge the support and encouragement of the Drexel University Department of Chemical Engineering for fostering the evolution of this text in its curriculum and for providing clerical staff and supplies for several editions of class notes. I want to acknowledge Dr. Lowell B. Koppel's important contribution as co-author of the first edition of this book. I also want to thank my colleague, Dr. Rajakannu Mutharasan, for his most helpful discussions and suggestions and for his sharing of some of the new problems. For her assistance

in typing, I want to thank Dorothy Porter. Helpful suggestions were also provided by Drexel students, in particular Russell Anderson, Joseph Hahn, and Barbara Hayden. I also want to thank my wife Effie for helping me check the page proofs by reading to me the manuscript, the subject matter of which is far removed from her specialty of Greek and Latin.

McGraw-Hill and I would like to thank Ali Cinar, Illinois Institute of Technology; Joshua S. Dranoff, Northwestern University; H. R. Heichelheim, Texas Tech University; and James H. McMicking, Wayne State University, for their many helpful comments and suggestions in reviewing this second edition.

Donald R. Coughanowr

CHAPTER 1

ANINTRODUCTORY EXAMPLE

In this chapter we consider an illustrative example of a control system. The goal is to introduce some of the basic principles and problems involved in process control and to give the reader an early look at an overall problem typical of those we shall face in later chapters.

The System

A liquid stream at temperature T_i is available at a constant flow rate of w in units of mass per time. It is desired to heat this stream to a higher temperature T_R. The proposed heating system is shown in Fig. 1.1. The fluid flows into a well-agitated tank equipped with a heating device. It is assumed that the agitation is sufficient to ensure that all fluid in the tank will be at the same temperature, T. Heated fluid is removed from the bottom of the tank at the flow rate w as the product of this heating process. Under these conditions, the mass of fluid retained in the tank remains constant in time, and the temperature of the effluent fluid is the same as that of the fluid in the tank. For a satisfactory design this temperature must be T_R. The specific heat of the fluid C is assumed to be constant, independent of temperature.

Steady-State Design

A process is said to be at steady state when none of the variables are changing with time. At the desired steady state, an energy balance around the heating process may be written as follows:

$$q_s = wC(T_s - T_{i_s}) \tag{1.1}$$