CHEMICAL PROCESS CONTROL

Second Edition

James B. Riggs

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Preface to the First Edition

Over the past 15 years, process control engineering has emerged as a major technical specialty for chemical engineers. As a result, more and more chemical engineers are developing careers in the process control field. The objective of this text is to provide a framework for teaching undergraduate students the fundamentals of process dynamics and feedback systems while also teaching these students the critical skills necessary to function as process control engineers in industry.

An industrial process control engineer needs to be able to tune and troubleshoot control loops, make process control design decisions and understand the terminology of the profession. It is important to teach these skills in an undergraduate control class (if we are going to produce engineers who are productive when they begin work), but these skills by themselves can be limiting without a fundamental understanding of process dynamics and feedback systems. In addition, much of the terminology of the process control profession is strongly tied to the theoretical analysis of control systems. Professional terminology is crucial if control engineers are going to be able to convey their ideas and sell their approaches to their peers, their boss, and the process operators. (A summary of additional terminology is listed at the end of each chapter and the first time that a new term is used, it appears in bold letters in the text.) Clearly, there needs to be a proper balance between teaching industrially relevant process control skills and developing a fundamental understanding of process control theory.

This text is my attempt at this challenging balancing act. Moreover, I have attempted to clearly delineate within this text between material that directly relates to the industrial practice of process control and theoretical material that is presented for the fundamental understanding of process control systems and for the introduction to important terminology. For example, it is important for a student to understand that even though transfer functions (Chapter 4) are an important approach to analyzing and understanding the dynamic behavior of feedback systems, they are rarely directly used by industrial control engineers to analyze the behavior of their control loops. The material in this text that is primarily oriented toward control theory is contained in Chapter 4 (Laplace Transforms and Transfer Functions), Chapter 5 (Idealized Dynamic Behavior), Chapter 9 (Frequency Response Analysis) and a large part of Chapter 6 (PID Control). On the other hand, Chapter 2 (Control Loop Hardware) and Chapter 8 (Troubleshooting) are largely descriptive and are directly related to industrial control practice. But in general, most of the remaining chapters contain elements of both theory and practice. That is, the fundamental understanding of feedback systems and the analysis tools developed in theoretically oriented chapters are used to guide the study of control approaches relevant to industrial practice.

Certain industrial leaders in the field of process control have called for academia to put the "process" back into process control. That is, they would like for academia to teach process control with a process point of view. Industrial process control engineers use their knowledge of the entire process that they are working on along with their knowledge of control systems to solve control problems. Control engineers that do not understand the process are vulnerable to developing control solutions that appear fine to them, but in fact work against the overall objectives of the process. Moreover, this situation can result in serious safety problems.

In Chapter 3 (Dynamic Modeling), dynamic models of the actuator, the process, and the sensor are developed and combined to model the dynamic behavior of several process systems. Dynamic models for a thermal mixer, a composition mixer, a level in a tank, two continuous stirred tank reactors (CSTR's), and a heat exchanger are developed and used throughout the text. This approach to process modeling is quite simple and computationally efficient while exposing the student to process dynamics not unlike those demonstrated by industrial processes. The addition of sensor noise (Section 3.6) provides additional realism to these simple simulators. The exercises at the end of the chapters call for the student to use the simulators for a variety of functions including controller tuning and the application of advanced PID techniques. This approach provides the student with valuable hands-on dynamic and control experience and is quite different from the classical approach which is based on using transfer functions to study these problems. Also, the actuator/process/sensor view of process systems is used in Chapter 6 to evaluate the feedback behavior of a number of control loops commonly encountered in the chemical processing industries and provides an important process based view of control systems.

Chapter 7 presents an approach to process controller tuning which is based upon using an evaluation of the process nonlinearity and the magnitude of the disturbances affecting the process to determine the appropriate tuning criteria. This approach is developed by analyzing a nonlinear CSTR to demonstrate that process nonlinearity and disturbance magnitude can combine to produce unstable feedback behavior. Moreover, chemical engineering examples are used to introduce and demonstrate advanced PID techniques such as cascade, ratio, and feedforward (Chapter 10), inferential control and scheduling of controller settings (Chapter 11), and configuration selection for the control of multiple input/multiple output processes (Chapter 13).

Finally, the approach taken in this text is not to exhaustively cover the full range of process control topics, but rather to focus on material that develops a fundamental understanding of feedback systems and develop the skill set required for an industrial process control engineer. It is my hope that this text inspires more students to enter the important and interesting field of chemical process control.

James B. Riggs
Lubbock, Texas

August 1998

Preface to the Second Edition

Even though the first edition of the textbook was well received in many ways by the chemical engineering university community, professors and students who used the text pointed out that it suffered from a lack of examples in the text and did not have enough problems. The objective of the second edition is to retain the focus of the first edition while addressing these limitations. The opportunity was taken to add some new material and reorganize certain sections to improve their presentation.

Joe Pekny of Purdue University helped me understand that "most students learn by examples in textbooks". I came to understand that it is not enough to present examples to demonstrate the use of the technical material. Instead, a series of examples can be used to lead the student from the most basic application of the material to more complex applications. For example, in Chapter 2, I had originally considered adding an example for sizing a control valve after the equation for flow through a control valve was introduced. Then, I realized that this was too large a "conceptual jump" for most of the students. Instead, I added a series of examples from a simple application of the flow equation, to comparing installed valve characteristics, to sizing a control valve. In this manner, I have attempted to use examples as a means of communicating control approaches and principles to the uninitiated student and not just provide a verbal explanation.

A range of new material was added, including a capstone chapter on case studies for heat exchangers, CSTRs, and distillation columns, an appendix on piping and instrumentation diagrams, detailed examples that demonstrate the differences in installed valve characteristics between linear and equal percentage valves, a short section on controller tuning by pole placement, and a section for block diagram algebra. Upon reexamination of the first edition, I noticed that certain sections are quite long and lack organization. As a result, I subdivided these sections into a number of smaller sections to improve the presentation of the material. This approach is used for the material on transfer functions in Chapter 4, the presentation of types of PID controllers in Chapter 6, and the recommended approach to tuning in Chapter 7. The material on troubleshooting, which was previously included in Chapter 2, now appears as a separate chapter (Chapter 8) after controller tuning is addressed.

It is my hope that these modifications make this text a more effective teaching tool for providing undergraduates with the necessary skills to function in industry with a fundamental understanding of process dynamics and feedback control.

James B. Riggs
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March, 2001

Note to Students

In this text, two general types of material are presented: theoretically- and industrially-oriented material. The theoretical material, which is largely based upon Laplace transforms, is presented to provide a fundamental understanding of the dynamic behavior of feedback control systems. In addition, much of the terminology used by control engineers is based upon the theoretical analysis of process control systems.

The industrially-oriented material involves an analysis of the hardware that actually makes up industrial control loops, presentations of a wide range of control approaches, and using a model-based approach to understand control loop behavior. The model-based approach analyzes the dynamic behavior of the components of a process control loop: controller, actuator, process and sensor. **It is important to keep track of what is theoretical material, which is intended for fundamental understanding, and what is directly related to the industrial practice of process control.**

The simulation software that goes with this textbook can be downloaded from

www.che.ttu.edu/pcoc/software

Each program contains the dynamic model of the process (i.e., actuator/process/sensor) and software for a variety of controllers. To complete certain homework exercises, the simulators are used by enabling or disabling certain sections of the program and applying the proper tuning parameters. These programs are available as FORTRAN and MATLAB files. In addition, a number of the simulators are available as "point-and-click" EXCEL files.

Note to Instructors

Teaching process control is a challenging task because it is generally the first time that the students are exposed to dynamic behavior, and it is difficult to keep the study of this field from becoming abstract to the student. One approach that I have found helpful in this regard is to use laboratory demonstrations of hardware to show the different types of hardware involved, process dynamics, and feedback behavior. It has been my observation that students tend to have an easier time learning technical material when they can physically see this equipment in operation. Our process control laboratory is a fluid-flow/heat-transfer process that uses industrial-type hardware with a distributed control system (DCS). Alternatively, a laboratory unit operation process without industrial hardware can be used to demonstrate process dynamics by having the instructor operate the process as the controller. In the latter case, control valves and a range of sensors donated by industry can be put on display for the student to examine.

The classical approach to homework problems for process control is based on developing analytical solutions for control problems using simplified transfer functions of a process, which generally do not consider the dynamics of the sensor or actuator system. The student gets a steady diet of tedious partial fraction expansions to arrive at the analytical solutions. The approach taken here is to use discussion questions and exercises with process simulators for homework problems. Simplified simulators that involve models of the actuator, process, and sensor along with software models for PID controllers, filters, autotune testing, and several advanced PID control functions are available as software that can be used with the text. In this manner, the student is able to have a hands-on experience with process dynamics, tuning, and advanced PID control.

Finally, I have found that it is important to expose the students to the components that make-up a feedback control loop (Chapter 2) before they study modeling and feedback behavior so that they understand how a feedback loop is actually implemented industrially. There are several terms and approaches that are discussed in Chapter 2 that may not be fully understood by the student. I have found it necessary to return to Chapter 2 near the end of the course to review the important aspects of control hardware after exposure to the full range of process control topics.

Acknowledgments

The revision of this book would not have been possible without the help of my graduate students: Hatim D. Al-Dekhiel, J. Govindhakannan, Kishor G. Gudekar, Rohit Kawathekar, Alpesh Shah, Dale D. Slaback, and Bryan M. Street. In the category of above and beyond the call, Govind provided detailed analysis of several technical topics, Dale (grammar man) significantly reduced the wordiness and increased the clarity of the text, and Bryan solved my computer software problems. Dale Green, one of my undergraduate students, developed visual basic versions of the simulators that execute as macros in Microsoft Excel.

A number of individuals from industry made major contributions to the chapter on control loop hardware. Dave Clough from the University of Colorado, who is a former industrial instrument engineer, provided extensive feedback on the material in Chapter 2. Ken Junk from Fisher-Rosemount supplied invaluable assistance by answering my questions and reviewing the material on final control elements. Bob Sogge of Fisher-Rosemount provided a number of photographs that are important for this chapter. Mohammad Khalfia from Yokogawa Corporation of America supplied information on flow indicators.

Karlene Hoo provided very valuable feedback on the chapters on transfer functions and frequency response analysis, and served as a valuable sounding board for issues related to control theory. Dominique Bonvin (I speeled it correctly this time!) contributed excellent reviews of several chapters and clarified a number of important issues as the result of the philosophical discussions on our trip through the desert on the way to Tucson. Jim Downs of Tennessee Eastman supplied information for sensor and controller tuning. Scott Boyden served as a technical sounding board for a number of technical topics. Charlie Cutler helped me better understand how DMC functions. Joe Pekny and Peter Rony shared ideas on ways to improve the first edition. My wife, Brenda, solved a number of problems with using the publication software.

Last but not least, H. R. Heichelheim provided copy editing and technical review of the manuscript. His 20-plus years of experience with teaching the uninitiated undergraduate student the principles of process control and his keen eye for detail contributed directly to the overall quality of this book.

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PART I

INTRODUCTION

Chapter 1

Introduction

1.1 Chemical Process Control

Chemical Process Control (CPC) is concerned with operating a plant such that the product quality and production rate specifications are met in a safe and reliable manner. To attain these objectives, various flow rates, in most cases, are adjusted to maintain the operation (e.g., important levels, pressures, temperatures, and compositions) near the desired operating points. CPC is part of the larger field of automatic control, which ranges from controlling aircraft to controlling robots to controlling the critical systems in a computer.

Over the past 15 to 20 years, the **Chemical Processing Industries** (**CPI**, i.e., the companies that operate refineries and chemical plants) have been in a transition from a relatively young industry, largely driven by innovation in new products and new processing approaches, to a more mature industry in which the technology of the industry is changing much more slowly. In earlier times, new products such as nylon and Teflon® were developed, and new process designs such as fluidized catalytic cracking (FCC) and plastic processing technologies were implemented. These innovative products and processing approaches provided a major economic advantage to their developers. The resulting profit margins associated with these technological breakthroughs far outweighed the incremental benefits of optimal or near-optimal operation. For example, the addition of an FCC unit, which converts low-valued gas oils to high-valued gasoline, to a refinery provided much higher profit margins than the additional incremental benefit of optimal operation of the FCC unit. Optimal operation of an FCC unit is economically important but pales in comparison to the economic incentive of adding an FCC unit to a refinery in the first place. Today all refineries have FCC units; therefore, for a refinery to remain competitive, it must be concerned with the optimal operation of the FCC unit. CPC is an integral part of attaining the most efficient operation of an FCC unit and most other processes in the CPI.

During the 1970's and 1980's, significant advancements in instrumentation and process computers made the rapid development that has been observed in CPC possible. In the 1960's, the chemical engineering staff of a company consisted largely of process engineers and design engineers. During the 1970's and 1980's, CPC consulting companies and control experts within operating companies were able to

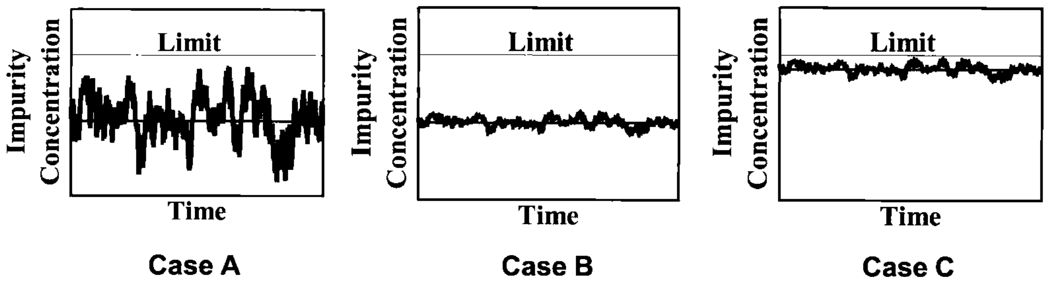

Figure 1.1 Comparison between impurity measurements and the upper limit on the impurity in a product for the original control system (case A), the improved control system with the original impurity target (case B), and the improved control system with a new impurity target (case C).

demonstrate that improved process control can provide significant economic return, usually with relatively low capital investment. As a result, today a typical chemical engineering staff of an operating company in the CPI consists of process engineers and process control engineers. Now, most operating companies in the CPI use consulting companies to provide design services.

CPC is intimately involved in the effort to meet the operational objectives of the process while striving for the most efficient operation of the plant. Minimizing the **variability** (i.e., magnitude of the deviations from the target) in the product is, many times, a key operational objective and is directly affected by the performance of the process control system. In fact, the performance of an overall process control system is many times expressed in terms of the variability in the products produced by the process. Figure 1.1 shows the measurement of the impurity in a product for the original control system (case A). Case B represents the performance of a new control system. The controller corresponding to case B produces a product with less variability in the impurity than for case A; therefore, case B is referred to as producing a lower variability product than case A. For many products, low variability is an important product specification. If a product does not meet its product variability specifications, the resulting product can be low-valued with low demand, while products that meet the variability specification can be high-valued with high demand. Because case B has a lower variability, the average impurity level can be moved closer to the impurity specification (case C), usually allowing greater production rates or lower energy usage, both of which result in more efficient operation of the process. Other types of operational limits are encountered resulting from environmental regulations, capacity limits on equipment, and safety limits. In a similar manner, operating close to these limits can also be economically important. Figure 1.2 shows the impurity distribution or frequency of impurity measurements for the three cases shown in Figure 1.1.

Summarizing, the benefits of improved control can be (a) producing a lower variability product, (b) increasing the process throughput, and/or (c) reducing the energy usage. It should be emphasized that these economic benefits can generally be attained with modest or no additional capital investment.