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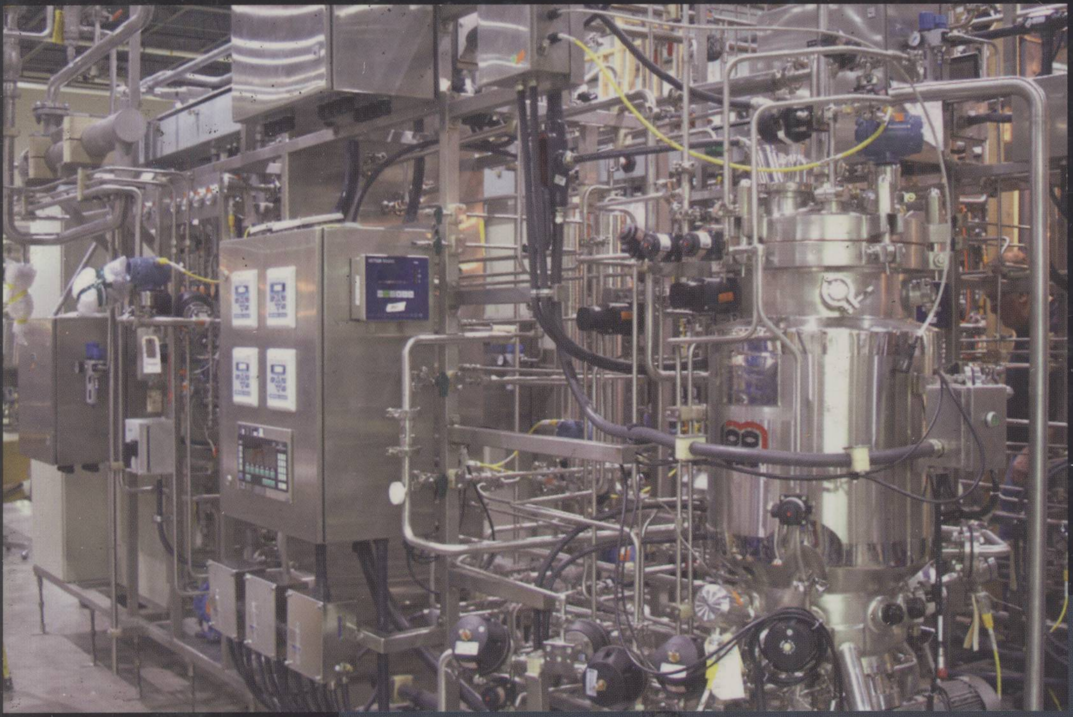
Chemical and Bio-Process Control

Third Edition



James B. Riggs

M. Nazmul Karim

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Preface

Example isn't another way to teach, it is the only way to teach. - Albert Einstein

This is the motivation for this new and revised edition of the textbook, *Chemical and Bio-Process Control*. In this revised edition, we have focused on traditional chemical process industries and as well as pointing out differences and similarities in the problems of modeling and controlling of bio-processes. However, the overwhelming theme has been examples, and as a result, we have added meaningful examples to each chapter. Moreover, we have coordinated our examples in such a way to emphasize the key points for the associated material. This book has benefitted from over forty years of combined experience of the authors, in the classroom and in industrial practice.

The objective of this textbook is to provide a framework for teaching undergraduate students the fundamentals of process dynamics and feedback systems while also developing industrially relevant control skills. In fact, the first two editions of this book were designed based on developing the skill set necessary for industrial control engineers. That is, an industrial control engineer should be able to tune control loops (Chapters 7-9), select the proper type of controller (Chapters 7 and 12-14), troubleshoot control loops (Chapters 2 and 10) and be proficient in the terminology of the field. In addition, process control analysis based on considering the individual dynamics of the actuator, process and sensor is introduced in the dynamic modeling chapter (Chapter 3) and used throughout the text. This overall emphasis remains, but it has been enhanced with the addition of improved examples and with a greater variety of homework problems. In addition, the chapter on model predictive control (Chapter 16), the leading advanced control technology, has been expanded and enhanced.

Substantial improvements have been made in this edition with regard to presenting the fundamental issues associated with process control. In the development of Laplace transforms (Chapter 4), transfer functions (Chapter 5) and idealized dynamic behavior (Chapter 6), we have provided a coordinated sequence of examples in each chapter to convey the key issues and concepts related to process dynamics. Substantial sections on transfer function zeros, the Routh stability criterion and state space models have been added to Chapter 5. Also, a section on internal model control has been added to the PID tuning chapter (Chapter 9). Moreover, the analytical tools developed in Chapters 4-6 are used in examples in Chapters 7 and 8 to illustrate the primary features of feedback control, and more specifically, PID control. Also, the material on frequency response analysis (Chapter 11) has been upgraded with new material on Nyquist diagrams.

This book is written in the spirit of genuine curriculum development in Chemical Engineering. The national dialog in the forum, "Frontiers in Chemical Engineering Education", lead by Professor Bob Armstrong of MIT, recommends exposing students to various interdisciplinary fields, in particular to include applications of biology in all curriculum. We have addressed this issue in the context of this text. Chapter 1 provides an overview discussion of the key elements of bio-process control and what separates it from the control in the chemical process industries as well as introducing several simple bio-control examples. Chapter 2 covers the hardware used in the biotechnology field to implement control loops and Chapter 3 presents models for a variety bio-process systems. In addition, Chapter 10

contains a section on troubleshooting the controls on bio-processes. Moreover, examples of bio-processes and control systems applied to bio-processes have been liberally added to the other chapters. -
We assume that the students typically will have experience in most of the major chemical engineering topics. No assumption is made with respect to students' preparedness in biotechnology, though a course in fundamentals of microbiology or biotechnology will be helpful to better understand the various examples of bio-systems provided in the text.

The text has its own simulator, which provides the student a relatively realistic control loop tuning experience that is quite efficient to use from the standpoint of the ease of use and the time required to obtain simulation results. "Self-Assessment Questions and Problems," have been added to the end of most sections and the answers to these questions and problems are provided in Appendix A. Also added is the degree of difficulty for each homework problem. At the end of each chapter, a succinct summary is provided.

Throughout the book, practical and industrially relevant guidelines are provided to the reader. Our objective has been to make a difference in the teaching and industrially relevant discussions of process control.

James B. Riggs
M. Nazmul Karim
Lubbock, Texas
April 2006

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About the Authors

James B. Riggs has been a professor of chemical engineering at Texas Tech University since 1983. He received his BS and MS degrees in chemical engineering from the University of Texas at Austin and his PhD degree in chemical engineering from the University of California, Berkeley. He co-founded the Texas Tech Process Control and Optimization Consortium (www.che.ttu.edu/pcoc/) in 1992 and has over 80 technical publications on process modeling, control and optimization. He is the author of *An Introduction to Numerical Methods for Chemical Engineers* (1988, 1994) and co-author of *Basic Principles and Calculations in Chemical Engineering, 7th edition* (2004). In addition, he has a total of over five years industrial experience.

M. Nazmul Karim is a Professor and the Department Chair of Chemical Engineering at Texas Tech University. He received the BSc. (Honors) degree in Chemical Engineering from the Bangladesh University of Engineering and Technology, Dhaka. He earned his MSc. degree in Control Engineering and Ph.D. degree in Chemical Engineering from the University of Manchester Institute of Science and Technology, U.K. Before joining Texas Tech University in 2004, he taught at Colorado State University for more than twenty years. He has published widely in the area of bio-process control. Dr. Karim was the Director of the Advanced Industrial Bio-Processing Short Course, which he offered at Colorado State University for over twenty years. More than 130 companies have participated in this course. Dr. Karim has co-authored seventy refereed journal papers and published hundreds of conference papers, and has given numerous invited and keynote talks in professional meetings. He has co-edited a book, *Modeling and Control of Biotechnical Processes 1992,* with Professor Gregory Stepanopoulos (MIT). He is a Fellow of the American Institute of Chemical Engineers.

Note to Students

This textbook is designed with a number of features to assist you in your study of process control. For example, there are a large number of examples throughout the chapters that are designed to demonstrate how to apply the principles that are introduced in the body of the text. These examples demonstrate the approaches and methodologies necessary to solve the homework problems. At the end of most sections there are "Self-Assessment Questions and Problems" that allow you to check your knowledge of the primary points presented in the preceding section. The answers to these questions and problems are listed in Appendix A. In this manner, you can check your basic understanding of the material that you have just read before going on to the next section. Also, each time a new term is introduced in this text, it will appear in bold print and in the "Additional Terminology" section at the end of the chapter along with its definition. Therefore, you can review the additional terminology sections for the relevant chapters as part of your preparation for examinations. Finally, at the beginning of each chapter, there is a list of the major objectives for that chapter, which lets you know what you should attain from studying that chapter.

This textbook comes with a set of simulators that can be used for a variety of activities, including open-loop testing, controller tuning and various simulation exercises. The models available in simulators are identical to five of the models developed in detail in Chapter 3, the dynamic modeling chapter. These simulators provide realistic simulations of the processes because they consider the nonlinearity of the process as well as the dynamics of the actuators and sensors. The simulators are available in three different formats: a Fortran version, a MatLab version and a visual basic version. This simulation software can be downloaded from

www.che.ttu.edu/pcoc/software

The visual basic version is the easiest to use because it does not require any programming experience. It is based on a "point-and-click" user interface and the results of each simulation are provided as MS Excel plots directly. Because the execution time for each simulation is less than one second, you can perform exercises requiring a number of simulation (e.g., controller tuning) in a relatively short period of time.

It is our hope that this text will not only make the task of learning the fundamentals and practical aspects of process control easier, but also encourage you to consider a career in process control. Process control can be a very rewarding career path and there is a tremendous need in the profession for creative and dedicated young people.

Note to Instructors

For undergraduate classes, we recommend covering Chapters 1-12 and possibly the SISO parts of Chapter 18. That is, Chapter 18 provides a capstone coverage of the control of heat exchangers, CSTRs and pH systems while emphasizing a number of the principles developed in the text.

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

"Not everything that counts can be counted and not everything that can be counted counts." -Sign hanging in Einstein's office at Princeton University

An effort like this is not possible without the help many colleagues, students, friends and family members. We wish to acknowledge the following people for their discussions and constructive criticisms on our material: Charlie Culter for helpful discussions, Charlie Gooding for feedback on Chapters 1 and 7, John Pittman for feedback on the fieldbus material, Dominique Bonvin for feedback on Chapters 4 and 5 and Michael Shuler for his useful comments on the first three chapters. In particular, we would like to thank Joe Alford from Eli Lilly and Company for his careful and meticulous feedback on the majority of the bio-tech material in this text.

We want to thank all our faculty colleagues and staff who helped us directly and indirectly during the manuscript preparation process. In particular, we wish to thank Lenore Dai, Brandon Weeks and Doir May for patiently reading the manuscript for errors. We are indebted to Ryan Post for help regarding the cover design and other IT help. Our appreciation and thanks go to Mr. Jack Wilson, owner of ABEC, Bethlehem, PA, for providing us with the Bio-related cover photograph.

The draft version of this textbook was used in the process control course at Texas Tech University. We are grateful to all the students in the class, in particular Kevin Ziervogel, Sam Rounday, Amanda Carlson and Cade Hodgson, for providing us with significant feedback. Chris Bettis, a graduate student in our controls program, has helped significantly with editorial feedback.

Finally, it is our families whose encouragement, understanding, patience and love made this a reality. We appreciate their constant support.

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Part I

Introduction

Chapter 1

Introduction to Chemical and Bio-Process Control

Chapter Objectives

- Provide background and justification for the use of process control by industry.
- Introduce the terminology of feedback control using everyday examples.
- Present the format and structure for control diagrams and present control diagrams for several simple industrial control loops.
- Overview the general types of controllers and the responsibilities of process control engineers.
- Introduce process optimization and indicate how process control and process optimization work together.

1.1 Chemical and Bio-Process Control

This text addresses the fundamental and generic aspects of process control, but also focuses on process control applications in the **chemical process industries (CPI)** and the **biotechnology industries**. That is, examples relevant to the CPI and the biotechnology industries are presented throughout the text as well as a discussion of some of the key operational issues associated with these industries. In addition, the major elements of the control hardware associated with these industries is also presented and their effect on control performance is addressed throughout the text.

The CPI represents a range of industries that use processing units to produce a wide range of products, including hydrocarbon fuels, petrochemical products, concrete, pharmaceutical products, paper products, man-made fibers and films, agrochemical products and ceramics[1]. In addition, the CPI also involves processing technologies that provide environmental protection, refrigeration, air conditioning and electric power generation. Two primary examples of the CPI are refineries and chemical plants. Refineries produce fuel products, such as gasoline, jet fuel and diesel fuel, and produce a wide range of high volume chemical intermediates, such as ethylene, benzene and linear paraffins. On the other hand, chemical plants use these chemical intermediates and other feedstock sources to produce a range of chemical products, including plastics, resins, solvents, synthetic fibers and a large number of final chemical products, e.g., gasoline additives, food additives and preservatives, diapers and detergents.

Biotechnology[2] is the technology that uses **microbial species** or any other living organisms or part of them to produce useful products. Biotechnology is used to produce high-volume products such as ethanol (bio-fuel) and citric acid from renewable resources, e.g., corn. High-value products, such as pharmaceutical and **recombinant drugs** for combating various diseases, are the main emphasis of modern biotechnology. Some portion of bio-processes use typical unit operations that are found in the CPI, such as mixers, reactors, heat exchangers, distillation columns, liquid/liquid separation, membrane separation, crystallizers, etc. The difference is that a specific **microorganism** is grown to produce a desired product, which could be the cell mass itself, and contamination may not be allowed in the process. Thus, maintenance of sterility is a key factor that separates many bio-processes from traditional chemical processes. In addition, in certain cases local hydrodynamic shear rates must be kept below specific levels or cell damage to the microbial species can result. Another key factor for human therapeutics is that every process, piece of instrumentation, control configuration and the computer software used to produce these products needs to be FDA (Federal Drug Administration) "validated", which requires extensive certification and documentation. Also, the processes that produce pharmaceutical and recombinant drugs have much smaller-scale production rates than those typically used in the CPI because bio-processes typically use batch reactors instead of the continuous processes used extensively in the CPI.

Bio-processes usually involve a bio-reactor and bio-separation systems. Bio-reactors are usually batch reactors, i.e., the reactor is filled with microbial species and food and **nutrients** for the microbial species and after the reactions attain the desired degree of completion, the reactor is emptied and the process is repeated. For "bio-separations", unit operations that are not common in chemical industries, such as chromatographic columns, ultra-filtration and micro-filtration, are used. In summary, **the primary differences between processes from the CPI and biotechnology systems are (1) many bio-systems must maintain sterile conditions throughout the system, (2) stagnant regions need to be eliminated from bio-systems to enhance cleanability, sterilizability and to maintain a uniform environment for the microorganisms, (3) limits on local shear rates occur for many bio-processes, (4) bio-processes that produce products for human consumption must have FDA validation, (5) bio-separations tend to be different separation technologies than used in the CPI and (6) most bio-systems tend to have much smaller production rates than CPI processes.**

Chemical Process Control. Chemical process control (**CPC**) is concerned with operating a processing 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 conditions. CPC is part of the larger field of automatic control, which ranges from controlling aircraft to controlling robots to controlling the operation of the critical systems in a computer.

Automatic control was first applied to refineries and chemical plants due to their large processing rates and complex configurations of unit operations. The first refineries and chemical plants were designed with large holding tanks between processing units, allowing each unit to be operated more or less independently. Because of the holding tanks, the plant operators were able to perform most of the control functions for these early processing systems. Holding tanks are an expensive approach for simplifying the control of a process because these tanks require significant additional capital, require significant space for installation, represent additional safety risks and result in an increase in inventory costs. Intermediate holding tanks have largely been removed from large-scale processing systems as the capability and reliability of process control has improved. That is, modern process control systems have allowed operating companies to remove these intermediate holding tanks for economic reasons while, in fact, improving the overall safety of their operations and the quality of their products. In addition, the rapid increase in oil prices in the 1970s resulted in more complex and integrated

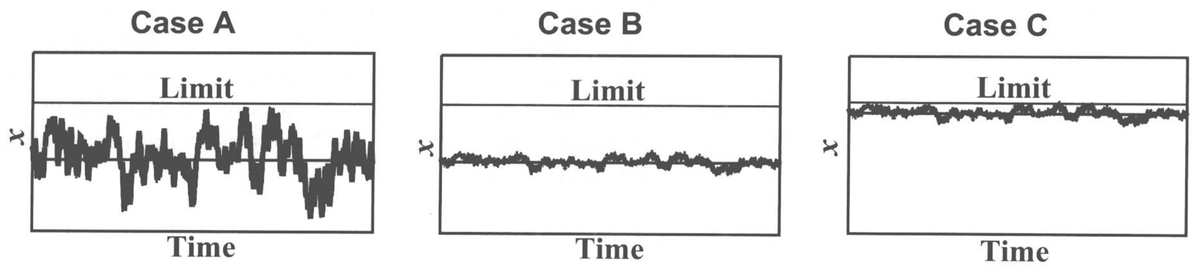

Figure 1.1.1 Comparison between impurity measurements (x) and the upper limit on the impurity in a product for the original control system (case A), the improved control system with the original impurity target (case B) and the improved control system with a new impurity target (case C).

process designs in an effort to conserve energy. These design modifications produced processes that rely more on process control for effective operation.

Over the past 20 to 25 years, the CPI 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. Today, technological breakthroughs are relatively rare in the CPI. On the other hand, companies in the CPI can attain significant economic advantage by optimizing the performance of their existing processes. CPC is an integral part of attaining the most efficient operation of processes in the CPI.

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 a product is often 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 1.1.1 shows the measurement of the impurity in a product for the original control system (case A). Case B represents the performance of a new and improved 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 target 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.

Summarizing, the benefits of improved control in the CPI 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 by improving the performance of the control systems.

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