B.Wayne Bequette

Process Control

Modeling Design and Simulation

过程控制

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Modeling, Design, and Simulation

B. Wayne Bequette

Rensselaer Polytechnic Institute

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To Pat, Brendan, and Eileen
and
my parents, Bill and Ayleen Bequette

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Preface

Background

There are a variety of courses in a standard chemical engineering curriculum, ranging from the introductory material and energy balances course, and culminating with the capstone process design course. The focus of virtually all of these courses is on steady-state behavior; the rare exceptions include the analysis of batch reactors and batch distillation in the reaction engineering and equilibrium stage operations courses, respectively. A concern of a practicing process engineer, on the other hand, is how to best operate a process plant where everything seems to be changing. The process dynamics and control course is where students must gain an appreciation for the dynamic nature of chemical processes and develop strategies to operate these processes.

Textbook Goals

The major goal of this textbook is to teach students to analyze dynamic chemical processes and develop automatic control strategies to operate them safely and economically. My experience is that students learn best with immediate simulation-based reinforcement of basic concepts. Rather than simply present theory topics and develop analytical solutions, this textbook uses "interactive learning" through computer-based simulation exercises (modules). The popular MATLAB software package, including the SIMULINK block-diagram simulation environment, is used. Students, instructors, and practicing process engineers learning new model-based techniques can all benefit from the "feedback" provided by simulation studies.[1]

Depending on the goals of the instructor and the background of the students, roughly one chapter (± 0.5) and one module can be covered each week. Still, it is probably too ambitious to cover the entire text during a typical 15-week semester, so I recommend that instructors carefully choose the topics that best meet their personal objectives. At Rensselaer

[1]It should be noted that I am not a proponent of a solely "simulation-based" control education, where students iteratively adjust parameters in a JavaScript simulation until acceptable responses are obtained. I wish for students to obtain the classic mode of understanding as analyzed so well by Robert Pirsig in *Zen and the Art of Motorcycle Maintenance* (Bantam Books, 1974). This deeper understanding of process control can be obtained by rigorous analysis and by selected simulations where the student plays a direct role in the implementation of an algorithm or strategy of choice.

Polytechnic Institute, we teach the one-semester, 4-credit course in a studio-based format, with students attending two 2-hour sessions and one 2-hour recitation (which also provides plenty of "catch-up" time) each week. During these sessions we typically spend 45 minutes discussing a topic, then have the students spend the remaining hour performing analysis and computer simulation exercises, working in pairs. During the discussion periods the students face the instructor station at the front of the room, and during the simulation periods they swivel in their chairs to the workstations on the countertops behind them. This textbook can also be used in a more traditional lecture-based course, with students working on the modules and solving homework problems on their own.

Chapters

An introduction to process control and instrumentation is presented in Chapter 1. The development and use of models is very important in control systems engineering. Fundamental models are developed in Chapter 2, including the steady-state solution and linearization to form state space models. Chapter 3 focuses on the dynamic behavior of linear systems, starting with state space models and then covering transfer function-based models in detail. Chapter 4 we cover the development of empirical models, including continuous and discrete transfer function models.

Chapter 5 provides a more detailed introduction to feedback control, developing the basic idea of a feedback system, proportional, integral, derivative (PID) controllers, and methods of analyzing closed-loop stability. Chapter 6 presents the Ziegler-Nichols closed-loop oscillation method for controller tuning, since the same basic concept is used in the automatic tuning procedures presented in Chapter 11. Frequency response analysis techniques, important for determining control system robustness, are presented in Chapter 7.

In recent years model-based control has lead to improved control loop performance. One of the clearest model-based techniques is internal model control (IMC), which is presented in Chapter 8. The PID controller remains the most widely used controller in industry; in Chapter 9 we show how to convert internal model controllers to classical feedback (PID) controllers.

In Chapter 10 the widely used cascade and feed-forward strategies are developed. Many control loops suffer from poor performance, either because they were not tuned well originally, or because the process is nonlinear and has changed operating conditions. Two methods of dealing with these problems, automatic tuning and gain scheduling, are presented in Chapter 11. The phenomenon of reset windup and the development of antireset windup strategies are also presented in Chapter 11.

Many control strategies must be able to switch between manipulated inputs or select from several measured outputs. Split-range, selective and override strategies are presented in Chapter 12. Process units contain many control loops that generally do not operate independently. The effects of these control-loop interactions are presented in Chapter 13. The design of multivariable controllers is developed in Chapter 14.

The development of the control instrumentation diagram for an entire chemical process is challenging and remains somewhat of an art. In Chapter 15 recycle systems are shown to cause unique and challenging steady-state and dynamic control problems. In addition, an overview of corporate-wide optimization and control problems is presented. Model predictive control (MPC) is the most widely applied advanced control strategy in industry. The basic step response model-based MPC method is developed in Chapter 16. This is followed by a discussion of the constrained version of MPC, and enhancements to improve disturbance rejection.

Learning Modules

The chapters are followed by a series of learning modules that serve several purposes; some focus on the software tools, while others focus on particular control problems. The first two provide introductions to MATLAB and SIMULINK, the simulation environment for the modules that follow. The third module demonstrates the solution of ordinary differential equations using MATLAB and SIMULINK, while the fourth shows how to use the MATLAB Control Toolbox to create and convert models from one form to another. The modules that follow focus on a particular unit operation, to provide a detailed demonstration of various control system design, analysis or implementation techniques. Module 5 develops a simple isothermal CSTR model that is used in a number of the chapters. Module 6 details the robustness analysis of processes characterized by first-order + deadtime (FODT) models.

Module 7 presents a biochemical reactor with two possible desired operating points; one stable and the other unstable. The controller design and system performance is clearly different at each operating point. The classic jacketed CSTR with an exothermic reaction is studied in Module 8. Issues discussed include recirculation heat transfer dynamics, cascade control, and split-range control. Level control loops can be tuned for two different extremes of closed-loop performance, as shown in Module 9 (steam drum, requiring tight level control) and Module 10 (surge drum, allowing loose level control to minimize outflow variation). Challenges associated with jacketed batch reactors are presented in Module 11. Some motivating biomedical problems are presented in Module 12. Challenges of control loop interaction are demonstrated in the distillation application of Module 13. Module 14 provides an overview of several case study problems in multivariable control.

Here the students can download SIMULINK .mdl files for the textbook web page and perform complete modeling and control system design. These case studies are meant to tie together many concepts presented in the text. Issues particular to flow control are discussed in Module 15, and digital control techniques are presented in Module 16.

Textbook Web Page

MATLAB and SIMULINK files, as well as additional learning material and errata, can be found on the textbook web page:

www.rpi.edu/dept/chem-eng/WWW/faculty/bequette/books/Process_Control/

or

www.rpi.edu/~bequeb/Control

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A few acknowledgments are in order. First of all, Professor Jim Turpin at the University of Arkansas stimulated my interest in process dynamics and control when I took his course as an undergraduate. As a neophyte process engineer for American Petrofina I had the opportunity to serve as a process operator during two work-stoppages. A newfound respect for control loop interaction led me to graduate study at the University of Texas, where Professor Tom Edgar provided the "degrees of freedom" for me to explore a range of control topics. Collaborations at Merck, Inc., led to the presentation of modeling and control of batch reactors in Module 11. Research sponsored by the Whitaker Foundation and the National Science Foundation resulted in material presented in Modules 12 and 14.

My own graduate students have served as teaching assistants in the dynamics and control courses, and have provided me with valuable feedback on various versions of this textbook. In particular, Lou Russo, now at ExxonMobil, helped me understand what works and what does not work in the classroom and in homework assignments. He certainly had a major positive impact on the education of many Rensselaer undergraduates.

Professor Robert Parker at the University of Pittsburgh classroom tested this textbook, and made a number of valuable suggestions. In addition, Brian Aufderheide (now at the Keck Graduate Institute) critiqued Chapter 16.

My colleagues at Rensselaer have promoted an environment that provides an optimum mix of teaching and research; our department has published four textbooks during the past two years. Various educational initiatives at Rensselaer have allowed me to

develop an interactive learning approach to dynamics and control. In particular, the Control Engineering Studio environment gives me immediate feedback on the level of practical understanding on a particular topic and allows me to give immediate feedback to students. A Curriculum Innovation grant from P&G led to the development of experiments and learning modules for the dynamics and control course, and for other courses using the Control Engineering Studio classroom.

Various Troy and Albany establishments have served to "gain schedule" my personal regulatory system and allowed me to obtain a better understanding of the pharmacokinetics and pharmacodynamics of caffeine and ethanol. The Daily Grind (www.dailygrind.com; you won't find a better coffee roaster in Seattle) in Albany provided beans for the many espressos that "kick started" numerous sections of this textbook. Group meetings at the Troy Pub & Uncle Sam Brewery (www.troypub.com; try the Harwood Porter the next time you are in town) led to many interesting education and research[2] discussions (not to mention political and other topics).

Naturally, completing this text would have been a struggle without the support of my wife, Pat Fahy, and the good sleeping habits of my kids, Brendan and Eileen. They have done their best to convince me that not all systems are controllable.

[2]The important interplay of research and education should not be overlooked. Seemingly innocuous problems assigned in the control class have led to interesting graduate research projects. Similarly, graduate research results have been brought into the undergraduate classroom.

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