**Process Control: Modeling, Design and Simulation**

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## Preface

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 otherhand, 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.

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. 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.

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. At Rensselaer Polytechnic Institute, we teach the one semester, 4-credit course in a studio-based format, with students attending two 2-hour sessions and a 2-hour recitation (this also provides plenty of "catch-up" time for the students) 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 groups of two students each. 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.

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. The development of fundamental (first-principles material and energy balance) models is covered in Chapter 2, including the steady-state solution and linearization to form state space models. Chapter 3 focusses on the dynamic behavior of linear systems, starting with state space models and then covering transfer function-based models in detail. Finally, in 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. In addition, direct synthesis is presented as an introduction to the model-based techniques presented in Chapters 8 and 9. It is important to realize that no model is perfect, so a controller designed based on a nominal model or operating condition may fail to provide satisfactory results when operating conditions change. Frequency response analysis techniques, important for understanding robustness of control systems, 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 feedforward 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 anti-reset 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 we first review common control strategies for individual unit operations, then discuss strategies for integrated systems (for example a feed/effluent heat exchanger and chemical reactor).

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.

The chapters are followed by a series of learning modules. The modules 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 recommended 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 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 Modules 9 and 10. It is critical to tightly control steam drum level as presented in module 11. Surge drum vessels, on the otherhand, can allow the level to “float” in order to minimize the effect of flowrate changes, as presented in module 10. Challenges associated with jacketed batch reactors are presented in module 11. Some interesting (and 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 problems are presented in module 16.

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. In graduate school, Professor Tom Edgar at the University of Texas provided the “degrees of freedom” to explore a range of control topics. My 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.

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 (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 and Uncle Sam Brewery (try the Porter or Collar City Stout the next time you are in town) led to many interesting education and research discussions (not to mention political and other topics). The Wine Shop in Albany always seemed to have the right Cabernet for performing late night edits on the text.

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.

**Table of Contents**

Chapters



Modules (with associated chapter focus)

13. Distillation (chapters 13 and 14)
14. Case Studies in Multivariable Control (chapters 13, 14 and 15)
15. Flow control
16. Digital control