TEACHING ANTIWINDUP, BUMPLESS TRANSFER, AND SPLIT-RANGE CONTROL

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Providing fast and smooth transitions during discrete process changes is of high industrial importance. For example, in polymerization, production runs for a particular polymer are typically of limited duration, and the reactor conditions must be modified to produce a different grade or type of polymer. Another type of discrete process change occurs when a controller output saturates. *Reset windup* is said to occur when the controller continues to integrate the error signal during saturation, causing large overshoots and oscillations.

Discrete process changes also occur during *split-range control,* in which different manipulated variables become active in different operating regimes. Split-range control is useful when more than one manipulated variable is required to span the whole range of setpoints.[1-3] Controllers that provide smooth transitions during discrete process changes are said to provide *bumpless transfer.*

Although industrial control systems must be designed to handle such discrete process changes, students are rarely taught in their undergraduate process control courses how to address such problems. This paper serves to close this gap in the education of undergraduate chemical engineers. The paper is distributed as a reading assignment to students in the undergraduate chemical process control course at the University of Illinois, and the material is discussed during the lecture immediately after the students have covered feedforward, ratio, and cascade control.

. . . students are rarely taught in their undergraduate process control courses how to address such [discrete process change] problems. This paper serves to close this [educational] gap. . .

First, the students are introduced to the process model of a laboratory apparatus for collecting permeation data for thin polymer films.[4] The temperature must be controlled to very high accuracy for the apparatus to provide accurate measurements of diffusion coefficients. The students are taught to control the process using multiple digital Internal-Model-Control-Based Proportional Integral Derivative (IMC-Based PID) controllers in the velocity form.

For homework, the students are required to derive the control algorithm, to simulate closed-loop responses using different controller-tuning parameters, and to propose and discuss potential improvements (see Table 1 for the homework assignment). The students are also required to compare the closed-loop response of their best controller to that obtained by a default controller that was implemented on the real apparatus.[5] Although this paper focuses on IMC-Based PID control, the homework assignment can be readily modified to teach other controller design methods.

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The advantages of using this control problem for training students are

- *The process dynamics and performance specifications are based on a real system.*
- *The two operating conditions are substantially different (there are significant changes in time delay, gain, and time constant).*
- *A practical control algorithm is provided that can be easily implemented in a process control laboratory or in industry.*
- *A MATLAB program simulating the process and the classical control algorithm is available via the Internet.[6]*

PROBLEM STATEMENT

Precise control of the temperature, T, of a sample containing a thin polymer film is required to provide accurate measurements of the diffusion coefficient.[4] The manipulated variable is the power to a heating tape that surrounds the polymer sample. Heat sinks allow the temperature of the sample to be reduced quickly. For temperatures below 30°C, the heat sink is distilled water, and for higher temperatures, the heat sink is gaseous nitrogen. The advantage of the gaseous-nitrogen heat sink over the liquid-water sink is that it allows a wide range of temperatures to be covered by only manipulating the heating power. The distilled-water sink provides a more stable response for temperatures under 30°C.

The heat sinks are at room temperature, which is approximately 21°C with slow variations up to ±1°C. For each heat sink, temperature responses to step changes in heating power were taken at a variety of operating conditions along the desired temperature trajectory in order to estimate the importance of nonlinearity. The process responses were linear for each heat sink, with the transfer functions given by

$$p_1(s) = \frac{1.0\, e^{-2.4s}}{9.5s + 1} \tag{1}$$

for the gaseous-nitrogen heat sink (T > 30°C), and

$$p_2(s) = \frac{0.068\, e^{-1.4s}}{1.7\, s + 1} \tag{2}$$

for the liquid-water heat sink (T < 30°C), where the time constants, τ_i, and time delays, θ_i, are measured in minutes, and the process gains, K_i, are measured in °C/% power. The heating power is constrained between 0 and 100%. At steady state, the sample is at room temperature when the heating power is turned off.

The goal of the closed-loop system is to smoothly ramp the temperature from stable operations at 120°C to 25°C (see Figure 1a). For reproducible collection of diffusion data, the temperature must stay within 0.5°C of the setpoint 70 min utes before and 50 minutes after the ramp, and within 1.5°C throughout the ramp. The control algorithm must provide bumpless transfer between the radically different process

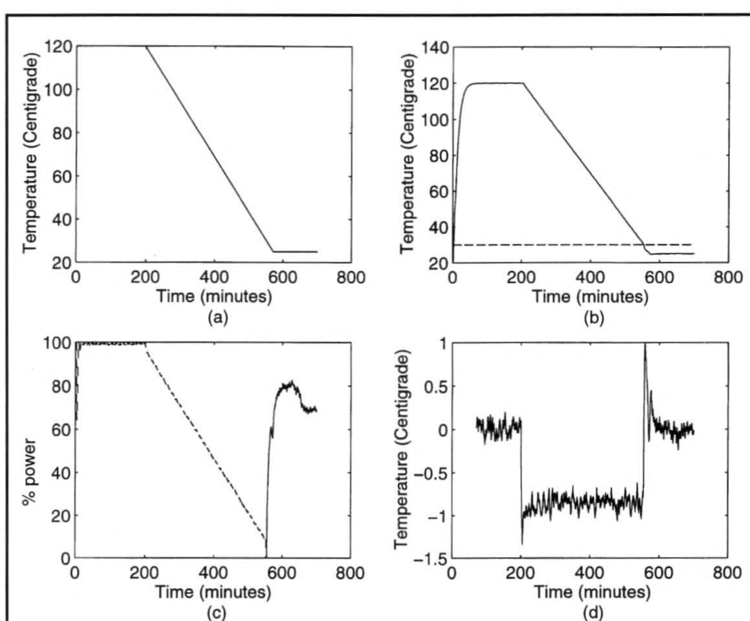

Figure 1. *(a) Setpoint; (b) closed-loop temperature tracking (-) and transition line between heat sinks (--); (c) power output from the nitrogen (--) and water (-) heat sinks; (d) difference between setpoint and controlled variable.*

TABLE 1
Homework Assignment
Antiwindup, Bumpless Transfer, and Split-Range Control
(The textbook referred to in Problem 2 is Ref. [1], Handout A is Ref. [5], Handout B is this paper.)

Problem 1. In Handout B, derive Equations (7) and (8) from Equation (6).

Problem 2. Draw a block diagram for the split-range control problem described on page 583 of the textbook. Describe the differences and similarities between this control problem and the control problem described in Handout B.

Problem 3. Use Netscape to download the MATLAB program bump.m from http://brahms.scs.uiuc.edu/~erp/lssrl/software. This program implements the two IMC-based PID controllers and the process models described in Handout B. Implement several values of the IMC tuning parameter λ, and select the λ that gives the best overall performance. Justify your selection.

Problem 4. Implement the IMC-tuning parameters listed in Equation (20) of Handout A in the MATLAB program. Select λ to give the best overall performance. Compare the performance for this controller with the best performance reported in Problem 3. List conditions for which the IMC tuning parameters in Handout A are expected to provide superior performance. Propose and discuss modifications that could improve your best control algorithm.

Problem 5. Compare your best closed-loop response to that in Figure 1 of Handout B. Discuss.

behaviors, Eqs. (1) and (2), that result when the temperature crosses 30°C, while satisfying the constraints on heating power. This control problem is referred to in industry as a *split-range control problem.*[1]

CONTROL ALGORITHM

One strategy is to design an Internal-Model-Control (IMC)-Based Proportional-Integral-Derivative Controller (PID) with a filter for each process transfer function, implement the controllers in digital velocity form, and switch controllers when the heat sinks are changed. Figure 2 is the block diagram of the system. The continuous-time transfer function for an IMC-Based PID controller is[7-9]

$$k(s) = K_c\left(1 + \tau_D s + \frac{1}{\tau_I s}\right)\frac{1}{\tau_F s + 1} \quad (3)$$

where

$$K_c = \frac{2\tau+\theta}{2K(\lambda+\theta)};\quad \tau_I = \tau + \frac{\theta}{2};\quad \tau_D = \frac{\tau\theta}{2\tau+\theta};\quad \tau_F = \frac{\lambda\theta}{2(\lambda+\theta)} \quad (4)$$

The IMC tuning parameter λ provides a trade-off between speed of response and the robustness of the closed-loop system to measurement noise and inaccuracy in the model.

The time domain expression for the controller is

$$\tau_F\frac{du}{dt} + u(t) = u(0) + K_c\left(e(t) + \tau_D\frac{de}{dt} + \frac{1}{\tau_I}\int_0^t e(\tilde{t})d\tilde{t}\right) \quad (5)$$

where e is the difference between the setpoint r and measured variable m. To avoid *derivative kick,*[2] the derivative of the error e=r-m is replaced with the derivative of the measured variable m to give

$$\tau_F\frac{du}{dt} + u(t) = u(0) + K_c\left(e(t) - \tau_D\frac{dm}{dt} + \frac{1}{\tau_I}\int_0^t e(\tilde{t})d\tilde{t}\right) \quad (6)$$

By approximating the integral by a summation and the derivatives by a first-order backward difference, and rearranging, we arrive at the control algorithm in digital form

$$u_n = \frac{u_0}{1+\tau_F/\Delta t} + \frac{\tau_F/\Delta t}{1+\tau_F/\Delta t}u_{n-1} + \frac{K_c}{1+\tau_F/\Delta t}\left(e_n - \tau_D\frac{m_n - m_{n-1}}{\Delta t} + \frac{\Delta t}{\tau_I}\sum_{k=1}^{n} e_k\right) \quad (7)$$

where

$\Delta t = t_n - t_{n-1}$ sampling time

u_n value of the manipulated variable (% Power) that is held constant between times t_n and t_{n+1}

m_n, e_n defined similarly.

Writing Eq. (7) for the n-1 sampling instance and subtracting gives what is referred to as the velocity form of the algorithm:

$$u_n = u_{n-1} + \frac{\tau_F/\Delta t}{1+\tau_F/\Delta t}(u_{n-1} - u_{n-2}) + \frac{K_c}{1+\tau_F/\Delta t}\left(e_n - e_{n-1} - \tau_D\frac{m_n - 2m_{n-1} + m_{n-2}}{\Delta t} + \frac{\Delta t}{\tau_I}e_n\right) \quad (8)$$

The main advantage of implementing the controller in this form is that it will not integrate the controller error when the manipulated variable reaches a constraint (for example, 0 or 100% power). For this reason, the controller will also perform better during transitions between different operating conditions—that is, it will provide *bumpless transfer.* The sampling time was selected as $\Delta t = 0.1$ minute, which is consistent with well-known rules-of-thumb.[1] The IMC tuning parameter was selected to be $\lambda = 1.0$ minute to give fast uniform closed-loop response throughout the temperature ramp. Disturbances on the output were modeled as integrated white noise, given by

$$d_o = \beta\gamma_o \quad (9)$$

and

$$d_k = d_{k-1} + \beta\gamma_k \quad (10)$$

where the γ_k's are normally distributed random numbers.

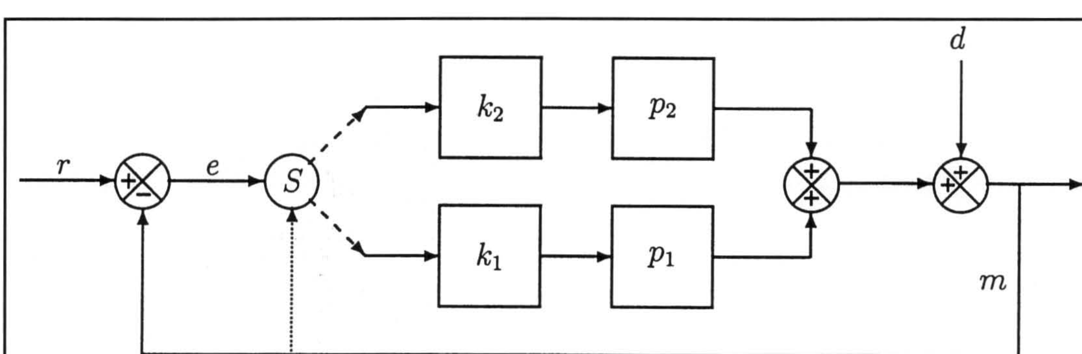

Figure 2. *Block diagram. The setpoint signal is r, the error signal is e, the measured temperature is m, and the effect of the disturbances on the temperature is d. The selector S switches between the controllers k_1 and k_2, depending on the value of the measured temperature.*

The coefficient β was set to 0.013, to be consistent with the open-loop step tests for the apparatus.[4]

CLOSED-LOOP RESPONSE

A simulation of the closed-loop temperature response to programmed step and ramp trajectories is shown in Figure 1 (the program producing the plot is available from the World Wide Web[6]). The simulated response is very similar to the experimental response shown in Figure 3.6 of Drake.[4] If disturbances had been better modeled as entering the process input, then the alternative IMC-Based PID controllers derived in [5,7] would provide improved performance. A slightly more complex IMC controller would be used [7,9] if zero offset in tracking the ramp had been required.

CONCLUSIONS

The model of a polymer-film-diffusion apparatus was used to teach the design of controllers that can handle discrete process changes. An available MATLAB code[6] demonstrates that two digital IMC-Based PID controllers, implemented in velocity form that switch during transitions between operating regimes, provide high performance for this problem. This paper and the MATLAB program are provided with the hope it will encourage teaching the design of such controllers in undergraduate courses in process control.

ACKNOWLEDGMENTS

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ChE book review

CHEMICAL ENGINEERING THERMODYNAMICS

by Y.V.C. Rao
Sangam Books Limited; 601 pages (1997)

Reviewed by
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This beginning intermediate text is a welcome addition to the limited number of texts appropriate to entry-level chemical engineering courses. While the major emphasis of the book is for use in the classroom, employment by more advanced students and practitioners is suggested and is justified by the breadth of material included.

Each chapter of the book begins with a set of learning objectives that is more helpful than the usual one-or-two paragraph introduction informing the reader of a chapter's content. At the end of each chapter, a quantitative summary reviews the material, including the important definitions and equations. A set of review questions (primarily qualitative but sometimes requiring a calculation) and a set of problems pertinent for class use complete each chapter.

The fourteen chapters of the book proceed logically from basic definitions and concepts to more complex topics, but do not become lost in esoteric arguments of little use to undergraduates. Chapters 1 and 2 give the basic definitions of both thermodynamics itself and primary concepts such as systems, processes, properties, energy types, and equilibrium, together with the units used for thermodynamic calculations. Review questions and problems support the text in prompting the student to make sure they understand the material.

Chapter 3, on PvT relations of fluids, discusses real fluids together with ideal gases as a preparation to their use for later application to calculations using the first and second laws. The selection of relations includes the progression of cubic equations from van der Waals to the various modified Redlich-Kwong equations, as well as the virial equation and Pitzer corresponding states. The selection is in line with current industrial use and what I myself would recommend.

The first law treatment is classical, beginning with calculations of various types of processes for ideal and nonideal gases as well as steam. Treatment of control mass and control volume analysis for transient flow processes is much more thorough, but also more understandable than most treatments. Standard thermochemical calculation methods are also included.

The second law treatment in Chapter 5 is again classical, with a good comparison of heat engines and heat pumps and methods for calculation of entropy. Control volume analysis and efficiency calculations are brief, but unusually clear.

In Chapter 6, the mathematical analysis of the state principle, the criteria for equilibrium, the Gibbs-Duhem equation, and the derived energy properties, in my opinion, need not be as difficult as they are presented. This is the only chapter that absolutely needs its summary for understanding and relevance.

Relations among properties and their manipulation by Jacobeans

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