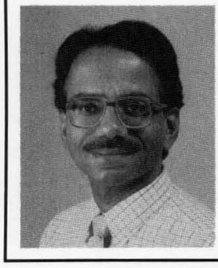
A COMPREHENSIVE PROCESS CONTROL LABORATORY COURSE

P. T. VASUDEVAN
University of New Hampshire
Durham, NH 03824

Process Control and Simulation is a 4-credit course in the department of chemical engineering at the University of New Hampshire. Classroom lectures (three hours per week) are supplemented with a two-and-a-half hour laboratory session held once a week. The course is traditionally taught in the spring semester of the senior year. The topics include, but are not limited to, dynamic behavior of chemical engineering processes described by differential equations, feedback control concepts and techniques, stability analysis, and advanced control techniques.

Students are usually divided into groups of two or three, and each group is required to do six different experiments over the course of the semester. These experiments are designed to expose the students to the practical aspects of almost all the theoretical topics covered in class. The basic materials and equipment are supplied for all the experiments. The students have to assist in designing and building the experiments, decide *a priori* what data they want to collect, perform the experiments, analyze the data, and submit a report. Some of the experiments are designed to permit flexibility in terms of simulating various process configurations (first order, second order, third order) or to demonstrate various process control principles discussed in class. The important features of each experiment will be highlighted in the following paragraphs.

The six experiments are divided into two phases. The first three experiments (phase one) are performed by all the students prior to the spring break, while the remaining three experiments (phase two) are performed after the spring recess.



***P.T. Vasudevan** is a chemical engineering faculty member at the University of New Hampshire. He obtained his PhD from Clarkson University. His research interests are in the area of catalysis and biocatalysis.*

EXPERIMENTS

Two of the three experiments in the first phase deal with determination of time constants of simple processes such as liquid level in a tank or pressure in an air cylinder. The liquid-level process consists of three Plexiglass tanks with interconnecting valves. Water can be pumped to any of the three tanks, and the feed water pressure is maintained constant to avoid any fluctuations in the flow rate. The control valve is located on the feed line. The students are at liberty to select one, two, or all three tanks and set the system up as either an interacting or a noninteracting process. The level is monitored in the third tank by means of a pressure transducer mounted at a height of six inches above the tank bottom, and the signal from the transducer is then sent to a PC equipped with data-acquisition capabilities (in this case, a Metrabyte DAS-8 card). Labtech Notebook is used to set up the various input and output channels. The PC is equipped with additional Metrabyte boards for process control. The students are thus exposed to various features of data acquisition and control, and instrumentation hardware very early in the semester.

In order to determine the time constant of the process, the students have to use both a pulse- and a step-forcing function. These forcing functions are set up in an external file (in ASCII) and can be accessed by Labtech Notebook when needed. Thus, data pertaining to the magnitude of the step or pulse and the type of pulse are stored in this external file.

The controller (output channel) in open loop reads the information from this file and changes the output to the control valve accordingly. The duration of the pulse or the exact moment at which the step change is to be introduced is controlled by adjusting the sampling rate in the output channel. The entire operation is therefore carried out in a precise fashion, with very little human intervention.

The data are recorded in a file and are also continuously monitored on the VGA monitor, so the students can compare the experimentally obtained value for time constant with the theoretical value (knowing the valve resistance and area of the tank). A linear valve is used in the experiment, and the valve resistance can be easily determined experimentally. The determination of time constant for a step-forcing function is straightforward. For the case of a pulse-forcing function, the following method is used for determining the time constant for a first order process (single tank).

We let

R = linear valve resistance
H = magnitude of the pulse
T = duration of the pulse
$h_d(s)$ = height in the tank in terms of deviation variables

Then, in the Laplace domain

$$h_d(s) = \frac{RH}{\tau s + 1}\left(\frac{1 - e^{-sT}}{s}\right) \tag{1}$$

In the time domain, for $t > T$,

$$h_d(t) = RH\left(e^{-(t-T)/\tau} - e^{-t/\tau}\right) \tag{2}$$

We now define a function, f, equal to the product of $h_d(t)$ and time, t. A plot of f versus time t will go through a maximum. By differentiating Eq. (2) with respect to time and equating it to zero, we can show that the maximum occurs when $t = \tau$. Thus, this method gives a simple procedure for estimating the time constant for a first-order process. Alternately, a plot of $\ell n\ h_d(t)$ vs. time is a straight line with a slope equal to the reciprocal of τ. However, Eq. (2) does not take into consideration the response of the process for values of $t < T$. If the duration of the pulse is sufficiently long, it is necessary to consider the complete solution.

This problem is easily solved in the following manner. It is possible to delay the storage of information by specifying a time delay equal to the duration of the pulse, T. By setting up a "calculated channel" it is therefore possible to monitor and store time in an external file as (t - T), (referred to hereafter as "adjusted time"). In the next channel, the data are stored or displayed as the product of height (in deviation variables, also easily set up in notebook through the use of "calculated channels" once the initial steady-state height is known), and adjusted time. The product of height and adjusted time (function f) versus the adjusted time is continuously displayed on the screen (and also stored in an external file) so that the information can be plotted later on.

Such a plot is shown in Figure 1. (Since the sampling rate is 1 Hz, the data points are not shown.) From this plot the time constant can be determined as the value on the abscissa corresponding to the value on the ordinate where the function f goes through a maximum. Or, to obtain an accurate estimate, a differential analysis of the data (function f with respect to time) can be performed.

The value of the time constant from the plot is about 210 seconds. This compares very well (within 5%) with the value of time constant obtained using a step change. For this particular experiment, the duration of the pulse was 100 seconds and the magnitude of the pulse (change in flow rate) was 0.32 ft³/min. It is interesting to note that the valve resistance can easily be determined once the time constant for the process is known. Setting $t = t$ is Eq. (2), we get

$$h_d(\tau) = \frac{f}{\tau} = 0.368\, RH\left(e^{T/\tau} - 1\right)$$

The only unknown in this equation is R, and it can be determined.

The same experimental setup is used to introduce concepts such as transmitter gain and dead time. For instance, since a pressure transducer is used to measure the height in the tank or the pressure in the cylinder (in the air-pressure process experiment), the students are required to calculate the

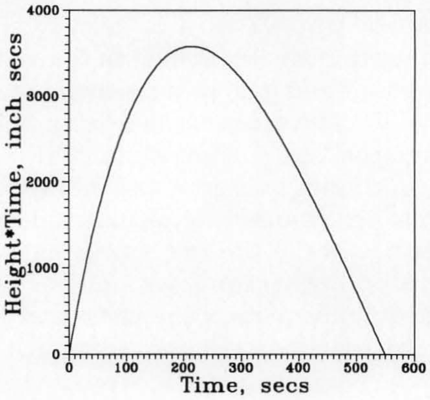


***Figure 1.** Determination of time constant from a pulse test. Sampling rate = 1 Hz*

transmitter gain. This information is then entered into the input channel. The students thus gain an understanding of how a transducer works and the range of the output signal for electrical and pneumatic transducers.

The first fifteen to twenty minutes of each laboratory period is spent in demonstrating the process-control principles discussed in class the previous week. For example, the liquid-level experiment is used to demonstrate types of controller action and how to set up the right action (reverse or direct) in the output channel. The PC is equipped with a Metrabyte DDA-06 controller card. The phenomenon of reset windup and the concept of stability are also demonstrated soon after the theoretical material is presented in class. Since Labtech Notebook uses the position form of the controller equation, reset windup is demonstrated very effectively.

The students also develop a good understanding of the dynamics of PID control and the effect each element (P, I, D) has on the overall control process. Important concepts such as offset, or how a simple first-order process with PI control can behave in an oscillatory manner, or how a second-order overdamped process with simple proportional control can become underdamped, are demonstrated with ease.

The pressure experiment is similar to the liquid-level experiment. Students are required to determine both the experimental and the theoretical time constants and to compare the two. They must determine the transmitter gain (scale factor) and offset and set up various channels in the Notebook.

The third experiment deals with control-valve calibration for both liquid and gas service. Here the students gain a practical understanding of concepts such as inherent and installed characteristics, valve coefficient, and valve flow characteristics. Once again, Notebook is used to set up various channels. A Metrabyte DAC-02 card is used to change the signal to the transducers located on the control valves for both liquid and gas, in increments of 1V (range is -5 to +5V). The students take data of flow rate, valve stem position, current signal to transducer (4-20 mA), upstream pressure, and downstream pressure. They are required to calculate and report the valve coefficients of the two valves as well as the type of valve (linear, equal percentage, quick opening) from suitable plots of the valve characteristics. In their report, the students are required to comment on the phenomenon of hysterisis observed in a plot of valve coefficient versus valve stem position.

The second phase of the laboratory deals with controller tuning based on Ziegler-Nichols closed-loop settings, Cohen-Coon open-loop tuning setting, or data from a pulse test. The liquid-level experimental setup or the air-pressure process can be used again. In the case of the liquid-level experiment, the students can choose any configuration they like. From the process reaction curve generated (here again, Labtech Notebook is used to set up the channels and store the information), the students use Cohen-Coon setting to determine the controller settings. They select a controller (P, PI, or PID) and determine the response to both servo and load changes. The controller settings obtained from the process reaction curve serve as preliminary estimates, and the students are required to obtain the optimum settings using a dynamic criterion such as IAE, ISE, or ITAE. This is easily done through the use of various "calculated channels" of Notebook, and IAE, ISE, and ITAE are set up in different channels.

The display window for the monitor is divided into four sections, and the students can observe the actual height in the tank, the error, IAE, ISE, or ITAE. They are required to select one of the integral criteria and try to obtain the optimum controller settings. This is done by keeping the reset time constant, for instance, and changing the proportional gain and determining the response to a unit step change in the set point (always from the same value). The students then change the integral time (keeping the gain constant) and observe the response. In each case the integral value is reported.

The second experiment also deals with controller tuning. This is done using the Ziegler-Nichols closed-loop tuning method. The second half of this experiment consists of using a pulse test to generate a Bode plot. The objective of the experiment is to determine the open-loop transfer function and calculate the overall gain, time constant, and dead time, if any. The students have to decide on a proper pulse duration and magnitude.

The pulse is introduced by changing the position of the control valve, and hence the flow rate to the system, for a known duration. This is achieved by setting the output channel in "open loop," which in turn accesses an external file to obtain values of the controller output. Care is taken to ensure that the system returns to its original steady state. The input and output data are then Fourier-transformed and divided to give the system transfer function in the frequency domain, G(iw). From the amplitude ratio and phase angle, Bode plots are constructed and the various parameters determined. The calcu-

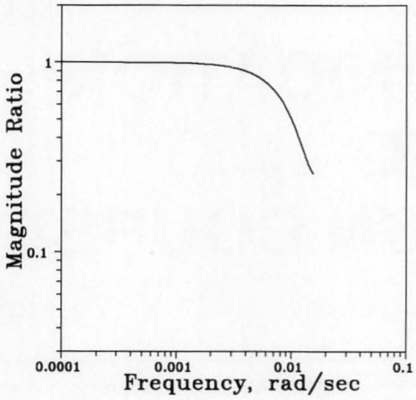


Figure 2. *Bode plot generated from a pulse test: magnitude ratio versus frequency.*

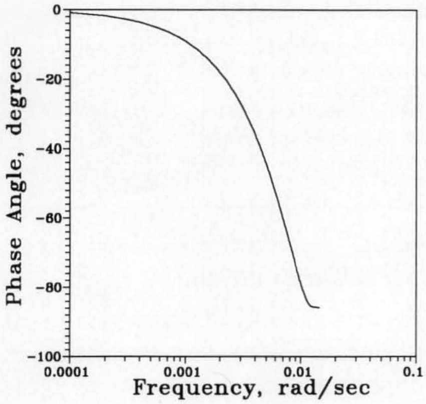


Figure 3. *Bode plot generated from a pulse test: phase angle versus frequency.*

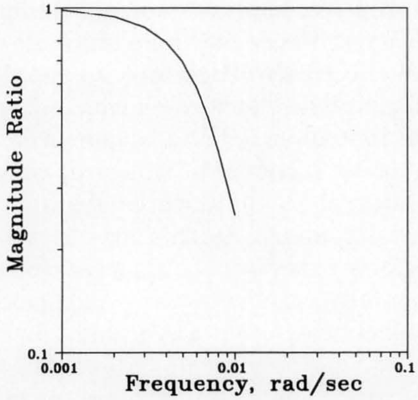


Figure 4. *Bode plot generated from a pulse test: second-order system.*

lation of G(iw) from the pulse data is achieved by representing the transfer function as

$$G(iw) = \frac{\int_0^\infty y(t)\cos(wt)\,dt - i\int_0^\infty y(t)\sin(wt)\,dt}{\int_0^\infty x(t)\cos(wt)\,dt - i\int_0^\infty x(t)\sin(wt)\,dt}$$

where x(t) and y(t) are the input and output functions.

Then

$$G(iw) = \frac{(AC + BD) + i(AD - BC)}{C^2 + D^2}$$

where

$$A = \int_0^{T_y} y(t)\cos(wt)\,dt \qquad B = \int_0^{T_y} y(t)\sin(wt)\,dt$$

$$C = \int_0^{T_x} x(t)\cos(wt)\,dt \qquad D = \int_0^{T_x} x(t)\sin(wt)\,dt$$

The duration of the input pulse and the time it takes the response to return to the original steady state, are T_x and T_y, respectively. The integrals are evaluated numerically by picking different values for the frequency, w. The students do this on a mainframe computer after up-loading the data from the PC to the mainframe. The experiment yields reasonably accurate frequency response curves. Numerical integration becomes a problem because of the oscillatory behavior of the sine and cosine terms at high values of frequency.

Since there is practically no human input necessary while performing this experiment, and because of the resolution and sampling rate used, data noise is not a problem. The Bode plots generated for a first-order liquid-level process are shown in Figures 2 and 3. The magnitude ratio and phase angle at higher values of frequency are not shown because of the problems associated with integration. Figure 3 indicates that the phase angle reaches an asymptotic value around -90°, which is indicative of a first-order system without dead time. It is also evident from Figure 2 that the transfer function of the system is exactly first order.

These observations are not surprising considering the fact that the process is first order and there is no measurement lag. The time constant for the process can be easily determined from Figure 2 once the corner frequency is known. The time constant is found to be about 200 seconds and is within 5% of the value previously reported.

The magnitude ratio for a second-order process (two interacting tanks) is shown in Figure 4. It is clear from the slope of the high-frequency asymptote that the system is exactly second order. Labtech Notebook also has a Fast Fourier Transform (FFT) capability that can be used to generate a power spectrum. In the above experiments, the students are also required to study the effect of sampling rate on data acquisition and on the control characteristics.

Continued on page 193.

technical background. Although the oral and written reports are addressed to a technical audience, when working individually with the CI the students must express technical ideas to a non-technical audience. This actually helps to develop a better understanding of the material and is a challenging communicative exercise in itself.

Finally, we recognize that integrating communication training into existing courses does not allow for as much instruction as could be offered in a separate communication course. There is not enough time to require helpful reading materials on speaking and writing, or to evaluate and discuss published articles, or to offer workshops on writing and speaking. Many students would benefit from more intense instruction—particularly on technical writing. But, acknowledging that good communication skills are never "learned" once and for all, we feel that by providing some limited instruction and significant practice and evaluation, we are at least helping students to improve their skills. As one student remarked, his writing improved partly "because [he was] actually writing for a change." An integrative approach is certainly a step in the right direction. We also still encourage students to take communication courses outside the department and to use campus resources such as the "Writer's Workshop," a writing tutorial center sponsored by the Center for Writing Studies.

As we work to provide our students with better communication skills, we must remember that developing expertise in writing and speaking is a lifelong process. Integrating communication training into existing chemical engineering courses may not be extensive enough for some students, but it does provide a significant amount of practice in both speaking and writing, leaving students with some professional experience and, hopefully, with an awareness of the value of communication.

ACKNOWLEDGMENT

The communication work reported in this article was developed by a number of individuals in addition to the authors: Dr. Charles A. Eckert, who initiated our emphasis on communication in collaboration with Marsha Bryant and Wayne Howell; Drs. Edward W. Funk, Thomas J. Hanratty, Douglas A. Lauffenburger, Richard I. Masel, Mark A. Stadtherr, K. Dane Wittrup, and Charles F. Zukoski, who all taught the courses; and Dr. Ruth Yontz, former Communication Instructor.

REFERENCES

1. Caruana, Claudia M., "More ChE Departments Stress Communications Skills," *Chem. Eng. Prog.*, **87**, 10 (1991)
2. Gieselman, Robert D., and Ruth A. Yontz, in "Writing Across the Curriculum: The Case of Engineering," *ASEE Spring Conf. Papers, Illinois/Indiana Section* (1991)
3. Emig, Janet, "Writing as a Mode of Learning," *The Web of Meaning: Essays on Writing, Teaching, and Thinking,* Baynton/Cook, Portsmouth, NH (1983)
4. Griffin, C.W., "Using Writing to Teach Many Disciplines," *Improving Coll. and Univ. Teaching,* **31**, 121 (1983)
5. Debs, Mary Beth, "Collaborative Writing in Industry," *Technical Writing: Theory and Practice,* Bertie E. Fearing and W. Keats Sparrow, eds., MLA, New York, 33 (1989)
6. Forman, Janis, and Patricia Katsky, "The Group Report: A Problem in Small Group or Writing Processes?" *J. of Bus. Comm.*, **23**, 23 (1986)
7. Some of the ideas for this checklist were adapted from Clark, David G., and Donald E. Zimmerman, *The Random House Guide to Technical and Scientific Communication,* Random House, New York, Chap. 10 (1987) ❐

Process Control Lab Course

Continued from page 187.

The last experiment in the second phase is called "Hardware." In it, the students are required to study the features of Metrabyte cards such as DAS-8, DAC-02, DDA-06, PIO-12, and to hard-wire a data acquisition system for monitoring temperature in six polymer reactors with different initiators or different initiator concentrations. A multiplexer board (Metrabyte EXP-16) is used to connect the different thermocouples. The students thus learn about multiplexers, thermocouples (how the cold junction is set up on the EXP-16), A/D converters, D/A converters, electro-pneumatic transducers, and other important features in data acquisition and digital control. The reaction is then started, and the students monitor the temperature change in each reactor simultaneously. The students study the effect of changing sampling rate on data acquisition since six different temperatures are monitored simultaneously.

CONCLUSIONS

These six laboratory experiments are an effective supplement to classroom lectures. Students gain hands-on experience in controller tuning, data acquisition, and control. Various process control concepts are emphasized, and the students develop a thorough understanding of the practical meaning of the concepts. The laboratory sessions cover almost all the topics discussed in class except certain advanced control strategies such as feedforward control or cascade control. Some of the available computer simulation packages are used to illustrate a few of these advanced control strategies. Interested readers may obtain complete information on the equipment or writeups of the experiment by contacting the author. ❐