ChE laboratory

ADVANCED PROCESS CONTROL EXPERIMENTS

PRADEEP B. DESHPANDE,
W. L. S. LAUKHUF and
NANDKISHOR G. PATKE
University of Louisville
Louisville, KY 40208

It has four of the most commonly encountered control loops in process industry, i.e., liquid-level, flow, pressure, and temperature.

In a course on advanced process control a substantial portion of the time is spent in discussing the fundamentals, design, and implementation of advanced control concepts. When the course was first offered several years ago, computer simulations were used to demonstrate the concepts. While simulation is certainly a very valuable tool in the analysis and design of control systems, the students felt that it would have been much more satisfying if they had a physical process to work with. In subsequent years, several laboratory experiments were developed to eliminate this deficiency.

The equipment for the process, around which the present experiments were developed, was constructed from data provided by Exxon Oil Company (then Humble Oil & Refining Co.) on an identical setup at their Bayway refinery. [1] The rig was used by Exxon to train their instrument and process personnel. It has four of the most commmonly encountered control loops in process industry, i.e., liquid-level, flow, pressure and temperature. The equipment was used to demonstrate feedback control concepts for these loops. Additional instrumentation has been added to the apparatus at the University of Louisville in order to demonstrate advanced control concepts.

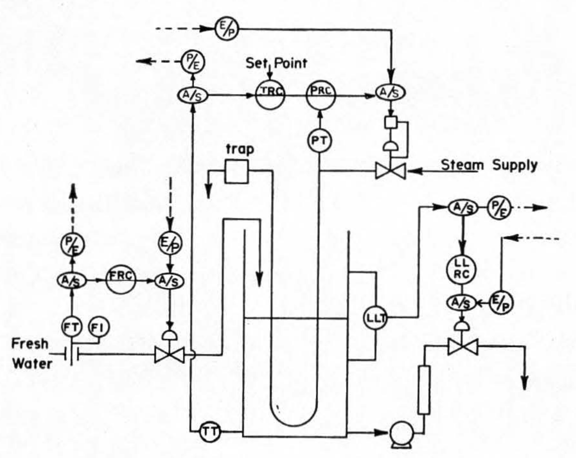


FIGURE 1. Schematic of Process Control System (Arrows indicate Signal transmission between the process and the computer).

EQUIPMENT & INSTRUMENTATION

A schematic of the thermal process unit is shown in Figure 1. The process involves heating of a continuous stream of water by steam. A vertical cylindrical tank approximately one foot in diameter is located in the center of the unit. The tank contains a steam pipe in the form of a vertical U tube. Water flows continuously in and out of the tank where it is heated by steam.

As shown in Figure 1, the process is instrumented with conventional controllers as well as with computer control hardware. Three variables can be controlled in this process: the flow rate of water into the tank, the level of water in the tank, and the temperature of water in the tank.

FLOW CONTROL LOOP

This loop regulates the flow of cold water into the tank. Supply water passes through a 7/16-inch diameter orifice mounted in a 1/2-inch pipe, then through a 1/2-inch control valve made by Uniflow Valve Corporation, and into the top of the tank. The differential pressure across the orifice is transmitted to a mercury manometer (FI in Figure 1) and to a Honeywell flow indicating transmitter (FT). The pneumatic 3-15 psig output of the transmitter is fed to a flow recording controller (FRC). It is also fed to an AMTEK pneumatic to voltage (P/E) transducer. The electrical output of the P/E transducer is connected to one of the analog-to-digital (A/D) converter channels of the control computer. As indicated in Figure 1, the position of a Foxboro air-switch determines whether the transmitter output is fed to the conventional controller or to the control computer.

The conventional flow recording controller is a Honeywell, proportional + reset type, controller which sends a signal to an "air-to-open" control valve on the process unit. Alternately, the signal to the control valve may also come from one of the digital-to-analog converter channels on the control computer, via a Fisher E/P transducer. Again, the position of an air switch determines whether the signal to the valve comes from the conventional controller or from the control computer.

LIQUID-LEVEL CONTROL LOOP

Water level in the tank is controlled by manipulating the flow of water out of the tank. The level sensor infers the liquid level by measuring the pressure required to cause air bubbles to form slowly at the bottom of the tank. This pressure signal is fed into the high pressure side of a Foxboro differential pressure transmitter (LLT), set at a range of 40 inches of water. The low pressure side of the transmitter is vented to the atmosphere as is the surface of the liquid in the tank. Thus, the differential pressure transmitter output is proportional to the liquid level. The signal from the transmitter is fed to a Honeywell proportional + reset controller (LLRC) and to one of the A/D converter channels via an air switch which determines whether the loop will be on conventional control or on computer control.

The outputs of the controller and a D/A converter channel are fed to an air switch and then to a 3/4-inch, "air-to-close" control valve made by the Uniflow Valve Corporation, installed in the drain line from the tank. The air switch selects computer control or conventional control. A 1/4-hp, Barray pump in this line insures sufficient fluid pressure on the upstream side of the valve.

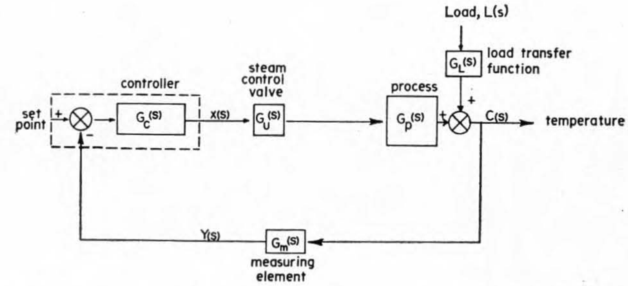


FIGURE 2. Block Diagram of the Temperature Control System

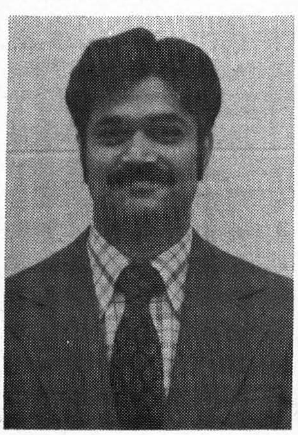
TEMPERATURE CONTROL LOOP

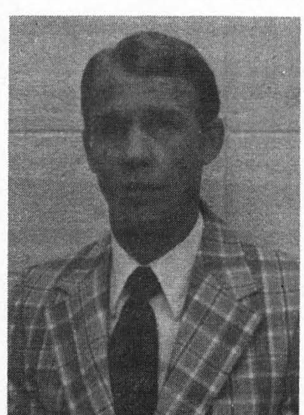
The temperature of water near the bottom of the tank is measured by an iron-constantan thermocouple immersed in an oil-filled well extending into the bottom portion of the tank. The voltage produced by the thermocouple is converted by a Honeywell electropneumatic transducer (TT)

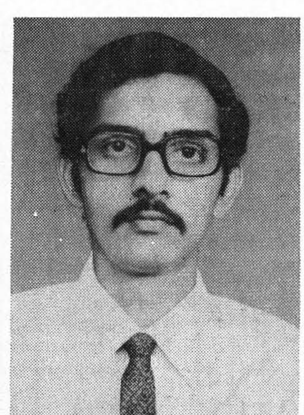
Pradeep B. Deshpande is associate professor of ChE at the University of Louisville. Prior to coming to Louisville, he was with Bechtel, Inc., at San Francisco, CA. He has served as a consultant to Mobil Exploration Norway, Inc., and to other companies in the areas of control systems design and simulation. He has a Ph.D. in ChE from the University of Arkansas and is a registered control systems engineer in California. **(L)**

Walden L. S. Laukhuf is an associate professor of ChE at the University of Louisville. Prior to coming to the University, he was a Captain in the Air Force at the Air Force Materials Laboratory in Dayton, OH. He has a BChE, MSChE and a PhD in ChE from the University of Louisville and is a registered professional engineer in Kentucky. **(C)**

Nandkishor G. Patke is presently working on a Ph.D. in ChE at the University of Louisville. His research interests are process modeling, simulation and control. He has a B.Tech. in ChE from the Indian Institute of Technology, Kanpur, India. **(R)**







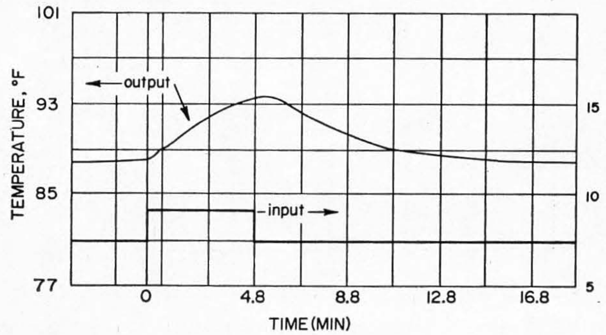


FIGURE 3. Input/Output Records From Pulse Test

into a pneumatic signal. This air signal is fed to a Foxboro three-mode controller (TRC). When conducting cascade control experiments, this controller serves as the master controller. The transmitter output is also fed to an A/D converter channel via an air switch. The output of the three-mode controller is fed to the set-point input of the Honeywell, proportional + reset, pressure recording controller (PRC). In cascade control experiments PRC serves as the slave controller.

The coil-side steam pressure is fed to a Honeywell transmitter. The output of the transmitter is fed to the pressure controller. The output of the controller operates a 1/2-in. Uniflow pressure control valve. The signal to the valve may alternately come from a D/A converter channel of the control computer.

In conventional control experiments, cascade control is achieved if both, master and slave controllers, are placed in automatic. If the pressure (slave) controller is switched to manual, the input to the control valve comes from the temperature controller. The temperature control loop is then a simple closed-loop rather than a cascade system.

The control computer used in some of the experiments is a PDP 1103 microcomputer system manufactured by the Digital Equipment Corporation. It has 24K words of memory and is equipped with an 8-channel D/A converter and a 16-channel A/D converter. The computer comes with a dual disk drive. A floppy disk, containing systems programs (e.g. Fortran support programs, real-time subroutines) resides in one of the drives while a second floppy disk, containing user-developed control programs, resides in the other drive. Communication with the computer is via a teletypewriter (LA 36 DECWRITER).

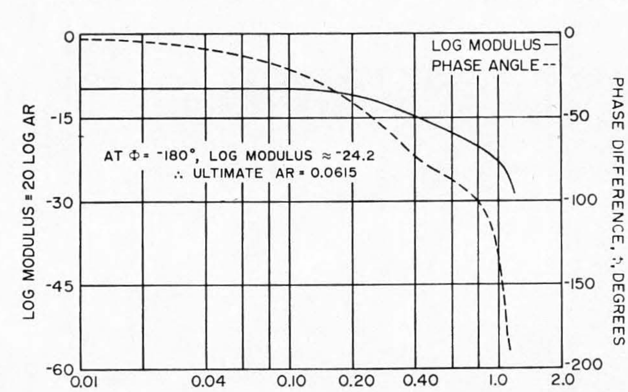


FIGURE 4. Frequency Response Diagram Frequency ω, Radians/min.

EXPERIMENT 1: Process Identification

This experiment is concerned with dynamic identification of an open-loop process by pulse testing. The resulting information is used to find (1) suitable tuning constants for a feedback controller or (2) to develop an approximate process model which is useful in designing advanced control strategies. The pulse testing technique [2, 3] has been applied to the temperature control loop whose block diagram is shown in Figure 2.

The input and output records from the pulse test are shown in Figure 3. Numerous data points from these records are entered into a computer program [3, 4] which generates frequency response data as shown in Figure 4.

From Figure 4, the ultimate AR, which refers to the amplitude ratio for which the phase lag equals 180 degrees, is 0.0615. Also, the crossover frequency, which is the frequency corresponding to the phase lag of 180 degrees, is 1.1 radians per minute. Therefore, the ultimate gain, Ku, and the ultimate period, Pu, are

$$\mathrm{Ku} = \frac{1}{0.0615} = 16.23 \text{ psi}/{}^\circ\mathrm{F} \qquad (1)$$

$$\mathrm{Pu} = \frac{2\pi}{1.1} = 5.71 \text{ min.}$$

Since the gain of the transmitter, K_T, is 0.06 psi/°F, the Ziegler-Nichols tuning constants for a PI controller are

$$\text{Gain, } K_c = 0.45\ \mathrm{Ku}/K_T = (0.45)\ (16.23)/0.06 = 121 \text{ psi/psi}$$

$$\text{Integral Time, } \tau_I = \mathrm{Pu}/1.2 = 5.71/1.2 = 4.75 \text{ min.} \qquad (2)$$

To assess the adequacy of the controller settings found in this section, a closed-loop control experiment was conducted. The response of the system to a step change in set point and load is shown in

Figure 5. This plot shows that the tuning constants found through pulse testing are adequate.

EXPERIMENT 2: Multivariable Control

Most large processes have many controlled variables and many manipulated variables. Ideally, a change in a given manipulated variable should affect only its own controlled variables and no others. Unfortunately, in many cases, this is not the case. The interaction among different loops can lead to poor control and even instability.

Since interaction can be a problem in multivariable control systems, it is important to know the extent of interaction and to be able to develop criteria for proper pairing of manipulated and controlled variables.

A measure of the extent of interaction in multivariable control is obtained by Bristol's method [5]. The method is based on steady-state input-output relationships for the process. It yields a measure of steady-state gain between a given input-output pairing. By using the most sensitive input-output connections, interaction is minimized.

Since Bristol's method does not take systems

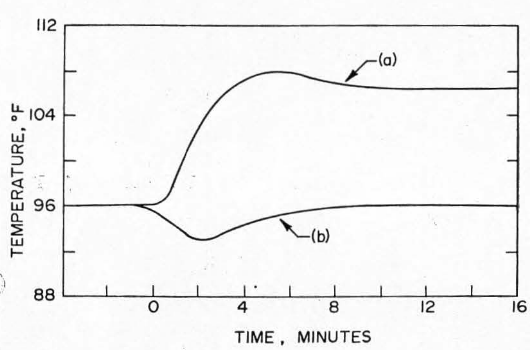


FIGURE 5. Transient Closed-Loop Response to (a) Set Point Change (b) Load Change

dynamics into account, it would be very useful to evolve an experiment which assesses the beneficial effects of proper pairing upon the dynamic response of the multivariable system. The present experiment [6] is designed to accomplish this objective.

The hardware for this experiment is essentially that shown in Figure 1 with the exception that the steam line is replaced by a pipe which introduces hot water into the tank. The air switches must be in the computer control position for this experiment.

Since interaction can be a problem in multivariable control systems, it is important to know the extent of interaction and to be able to develop criteria for proper pairing of manipulated and controlled variables.

The process objective is to control the level (in effect, total flow) and temperature of water in the tank. There are two inputs to the process, namely, the flow of cold water and the flow of hot water into the tank. So, the controlled variables are temperature and total flow and the manipulated variables are cold water flow rate and hot water flow rate. The question is, should the temperature be controlled by manipulating hot water flow and level (i.e. total flow) by cold water flow or vice versa? Bristol's method provides the answer.

Bristol's Relative Gains Analysis

The functional steady-state relationship between temperature, total flow and the flow streams is

$$\begin{aligned} T &= f(m_c, m_h) = (m_c T_c + m_h T_h)/m_t \\ m_t &= f(m_c, m_h) = m_c + m_h \end{aligned} \tag{3}$$

Around some steady-state operating point, these relationships can be expressed as

$$\begin{aligned} \Delta T &= \frac{\partial T}{\partial m_c}\Delta m_c + \frac{\partial T}{\partial m_h}\Delta m_h \\ &= K_{11}\Delta m_c + K_{12}\Delta m_h \end{aligned}$$

and (4)

$$\begin{aligned} \Delta m_t &= \frac{\partial m_t}{\partial m_c}\Delta m_c + \frac{\partial m_t}{\partial m_h}\Delta m_h \\ &= K_{21}\Delta m_c + K_{22}\Delta m_h \end{aligned}$$

The K's are the open-loop steady-state gains which quantitatively describe how the m's affect T and m_t. They can be determined from a mathematical model of the process or by experimental step or pulse-testing on the plant. To evaluate K_{11} and K_{21} for example, a small change in the flow of cold water is made, while the process is operating under steady state conditions (under manual control with the flow of hot water maintained constant). When the temperature and level reach their new steady-state values, K_{11} and K_{21} can be evaluated by

$$K_{11} = \left(\frac{\Delta T}{\Delta m_c}\right)_{m_h = \text{constant}} \tag{5}$$

and

$$K_{21} = \left(\frac{\Delta m_T}{\Delta m_c}\right)_{m_h = \text{constant}} \qquad (6)$$

The gain K_{11}, then, determines the change in temperature, T, due to a change in m_c when m_h is held constant. Now, suppose instead of holding m_h constant, while a small change in m_c is being made, m_h is manipulated so as to bring m_t back to the original value it had before the change in m_c was made. Then, another gain A_{11} can be defined as

$$A_{11} = \left(\frac{\Delta T}{\Delta m_c}\right)_{m_t = \text{constant}} \qquad (7)$$

A_{11} is a measure of how m_c affects temperature T, if level were under closed-loop control (i.e. held constant). The ratio of K_{11} to A_{11} is called the relative gain λ_{11}. Thus,

$$\lambda_{11} = \frac{K_{11}}{A_{11}} = \frac{(\Delta T/\Delta m_c)_{m_h = \text{constant}}}{(\Delta T/\Delta m_c)_{m_t = \text{constant}}} \qquad (8)$$

By comparing the relative gains for each manipulated variable, it is possible to assess which m has the most effect on a given controlled variable

The equipment for the process, around which the present experiments were developed, was constructed from data provided by Exxon Oil Company . . . on an identical setup at their Bayway refinery.

and therefore how to pair the manipulated and the controlled variables.

While K's can be determined easily, the experimental determination of A's is not so easy. However, they can be evaluated from the K's as follows:
By definition

$$A_{11} = \left(\frac{\Delta T}{\Delta m_c}\right)_{m_t = \text{constant}}$$

The open-loop relationships (Equation (4) become

$$\Delta m_t = 0 = K_{21}\Delta m_c + K_{22}\Delta m_h \qquad (9)$$

Thus,

$$\Delta m_h = -\frac{K_{21}}{K_{22}}\Delta m_c$$

Also in view of Equation (4)

$$\Delta T = K_{11}\Delta m_c - \frac{K_{12}K_{21}}{K_{22}}\Delta m_c \qquad (10)$$

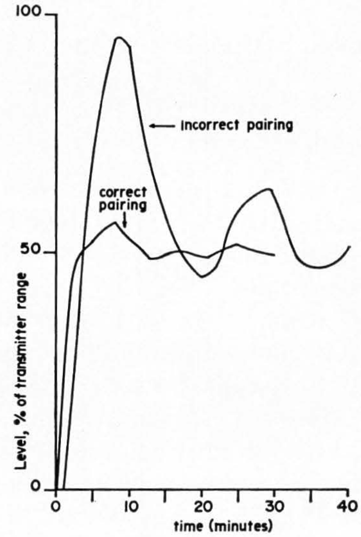


FIGURE 6. Transient Response of Level

Therefore,

$$\Delta T = \frac{K_{11}K_{22} - K_{12}K_{21}}{K_{22}}\Delta m_c \qquad (11)$$

and,

$$A_{11} = \left(\frac{\Delta T}{\Delta m_c}\right)_{m_t = \text{constant}} = \frac{K_{11}K_{22} - K_{12}K_{21}}{K_{22}} \qquad (12)$$

The relative gain λ_{11} is then

$$\lambda_{11} = \frac{K_{11}}{A_{11}} = \frac{K_{11}K_{22}}{K_{11}K_{22} - K_{12}K_{21}} \qquad (13)$$

Similar analysis yields the remaining relative gains. Thus,

$$\lambda_{12} = \frac{K_{12}K_{21}}{K_{12}K_{21} - K_{11}K_{22}} \qquad (14)$$

$$\lambda_{21} = \frac{K_{12}K_{21}}{K_{12}K_{21} - K_{11}K_{22}} \qquad (15)$$

$$\lambda_{22} = \frac{K_{11}K_{22}}{K_{11}K_{22} - K_{12}K_{21}} \qquad (16)$$

To facilitate the pairing of manipulated and controlled variables, it is convenient to present the relative gains in a matrix form as shown in Equation (17).

$$\begin{array}{c|cc} & m_c & m_h \\ \hline T & \lambda_{11} & \lambda_{12} \\ m_t & \lambda_{21} & \lambda_{22} \end{array} \qquad (17)$$

For each controlled variable, the manipulated variable selected is the one which has the largest positive relative gain. Since a property of this matrix is that each row and column sums to one, only one λ need by explicitly computed in a 2 x 2 system.

Results

The relative gains matrix for the current process is shown in Equation (18).

$$\begin{array}{c|cc} & m_c & m_h \\ \hline T & \dfrac{m_c}{m_t} & \dfrac{m_h}{m_t} \\ m_t & \dfrac{m_h}{m_t} & \dfrac{m_c}{m_t} \end{array} = \begin{array}{c|cc} & m_c & m_h \\ \hline T & 0.172 & 0.828 \\ m_t & 0.828 & 0.172 \end{array} \qquad (18)$$

This equation shows that: T should be controlled by manipulating m_h and m_t by manipulating m_c. Both loops use a proportional + integral control algorithm on the digital computer as the control element. The algorithm was tuned by trial and

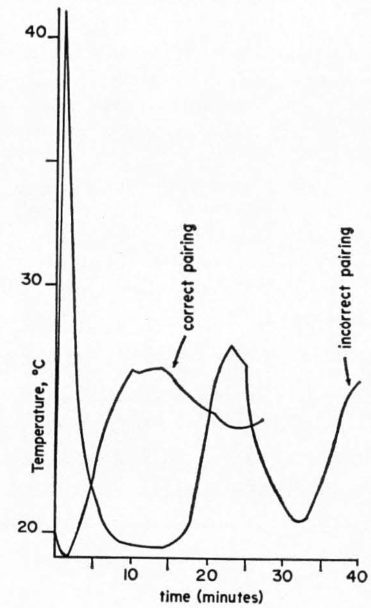


FIGURE 7. Transient Response of Temperature

error. The steady-state operating conditions were: level set point, 50% (which corresponded to total outlet flow of 11.6 lit/min); temperature set point, 24.4°C; cold water flow, 9.61 lit/min; hot water flow, 1.99 lit/min. The process was operated with correct pairing as well as with incorrect pairing. The benefits of proper pairing are clearly evident in the set-point responses shown in Figures 6 and 7. These results show that Bristol's approach is a simple and powerful tool in the control systems design of multivariable processes.

If the relative gains in Equation (18) had turned out to be numerically close to each other, interaction ("fighting loops") would have been a problem, particularly if the response times of the two loops were comparable. Severe cross-coupling can drive the multivariable system to instability. In such cases decoupling will be required. Interested readers may consult reference 7 to obtain further information on the various techniques currently available for decoupling a multivariable control system. □

NOMENCLATURE

AR	=	amplitude ratio
A's	=	closed-loop gains
$G_p(s)$	=	process transfer function
K_T	=	temperature transmitter gain, psi/°F
K_c	=	proportional gain on temperature controller, psi/psi
K_P	=	steady-state gain of process, °F/psi
K's	=	open-loop gains
Ku	=	ultimate gain, psi/°F
m_c	=	cold water flow, lb/hr
m_h	=	hot water flow, lb/hr
m_t	=	total flow $m_c + m_h$, lb/hr
Pu	=	ultimate period, min.
T	=	temperature of the mixture, °F
T_c	=	temperature of cold water, °F
T_h	=	temperature of hot water, °F

Greek

ϕ	=	phase angle
θ_d	=	process dead-time, minutes
τ_P	=	time constant, minutes
τ_I	=	integral time, minutes
$\lambda_{i,j}$	=	relative gain
ω	=	frequency, radians/minute

REFERENCES CITED

1. Alper, William S., *A Laboratory Demonstration of Closed-loop Automatic Process Control,* Master of Chemical Engineering Thesis, University of Louisville, 1963.
2. Hougen, Joel O., *Experiences and Experiments with Process Dynamics,* Chemical Engineering Progress Monograph Series, Vol. 60, No. 4, 1964.
3. Luyben, W. L., *Process Modeling, Simulation and Control for Chemical Engineers,* McGraw-Hill Book Co., New York, NY, 1973.
4. Dynamic Response Testing of Process Control Instrumentation, *ISA-S26 Standard,* Instrument Society of America, 400 Stanwix Street, Pittsburgh, PA 15222, October 1968.
5. Bristol, E. H., *On a New Measure of Interaction for Multivariable Process Control,* Trans. IEEE, 1966.
6. Knabel, E. A., *Multi Variable Control System for Fluidized Bed Coal-gasification Units,* Master of Engineering Thesis, University of Louisville, 1978.
7. Foss, A. S., Denn, M. M. Ed., Chemical Process Control, A.I.Ch.E. Symposium Series, No. 159, Vol. 72, 1976.