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Process Control Instrumentation Technology

Curtis D. Johnson

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Introduction to Process Control

INSTRUCTIONAL OBJECTIVES

This chapter presents an introduction to process-control concepts and the elements of a process-control system. After you read this chapter and work through the example problems and chapter problems you will be able to:

- Draw a block diagram of a simple process-control loop and identify each element.
- List three typical controlled variables and one controlling variable.
- Describe three criteria to evaluate the performance of a process-control loop.
- Explain the difference between analog and digital control systems.
- Define supervisory control.
- Explain the concept behind process-control networks.
- Define accuracy, hysteresis, and sensitivity.
- List the SI units for length, time, mass, and electric current.
- Recognize the common P&ID symbols.
- Draw a typical first-order time response curve.
- Determine the average and standard deviation of a set of data samples.

1 INTRODUCTION

Human progress from a primitive state to our present complex, technological world has been marked by learning new and improved methods to control the environment. Simply stated, the term *control* means methods to force parameters in the environment to have specific values. This can be as simple as making the temperature in a room stay at 21°C or as complex as manufacturing an integrated circuit or guiding a spacecraft to Jupiter. In general, all the elements necessary to accomplish the control objective are described by the term *control system.*

The purpose of this book is to examine the elements and methods of control system operation used in industry to control industrial processes (hence the term *process control*). This chapter will present an overall view of process-control technology and its elements, including important definitions.

2 CONTROL SYSTEMS

The basic strategy by which a control system operates is logical and natural. In fact, the same strategy is employed in living organisms to maintain temperature, fluid flow rate, and a host of other biological functions. This is natural process control.

The technology of artificial control was first developed using a human as an integral part of the control action. When we learned how to use machines, electronics, and computers to replace the human function, the term *automatic control* came into use.

2.1 Process-Control Principles

In process control, the basic objective is to regulate the value of some quantity. To regulate means to maintain that quantity at some desired value regardless of external influences. The desired value is called the *reference value* or *setpoint.*

In this section, a specific system will be used to introduce terms and concepts employed to describe process control.

The Process Figure 1 shows the process to be used for this discussion. Liquid is flowing into a tank at some rate, Q_{in}, and out of the tank at some rate, Q_{out}. The liquid in the tank has some height or level, h. It is known that the output flow rate varies as the square root of the height, $Q_{out} = K\sqrt{h}$, so the higher the level, the faster the liquid flows out. If the output flow rate is not exactly equal to the input flow rate, the level will drop, if $Q_{out} > Q_{in}$, or rise, if $Q_{out} < Q_{in}$.

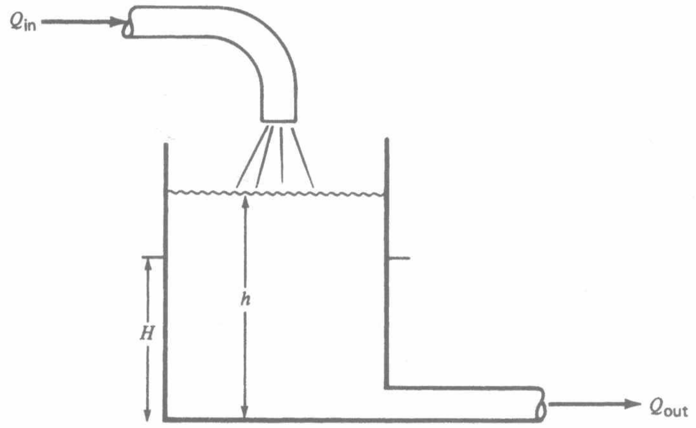


FIGURE 1
The objective is to regulate the level of liquid in the tank, h, to the value H.

This process has a property called *self-regulation*. This means that for some input flow rate, the liquid height will rise until it reaches a height for which the output flow rate matches the input flow rate. A self-regulating system does not provide regulation of a variable to any particular reference value. In this example, the liquid level will adopt some value for which input and output flow rates are the same, and there it will stay. But if the input flow rate changed, then the level would change also, so it is not regulated to a reference value.

EXAMPLE 1 The tank in Figure 1 has a relationship between flow and level given by $Q_{out} = K\sqrt{h}$ where h is in feet and $K = 1.156\ (\text{gal/min})/\text{ft}^{1/2}$. Suppose the input flow rate is 2 gal/min. At what value of h will the level stabilize from self-regulation?

Solution

The level will stabilize from self-regulation when $Q_{out} = Q_{in}$. Thus, we solve for h,

$$h = \left(\frac{Q_{out}}{K}\right)^2 = \left(\frac{2\ \text{gal/min}}{1.156\ (\text{gal/min})/\text{ft}^{1/2}}\right)^2 = 3\ \text{ft}$$

Suppose we want to maintain the level at some particular value, H, in Figure 1, regardless of the input flow rate. Then something more than self-regulation is needed.

Human-Aided Control Figure 2 shows a modification of the tank system to allow artificial regulation of the level by a human. To regulate the level so that it maintains the value H, it will be necessary to employ a sensor to measure the level. This has been provided via a "sight tube," S, as shown in Figure 2. The actual liquid level or height is called the *controlled variable*. In addition, a valve has been added so that the output flow rate can be changed by the human. The output flow rate is called the *manipulated variable* or *controlling variable*.

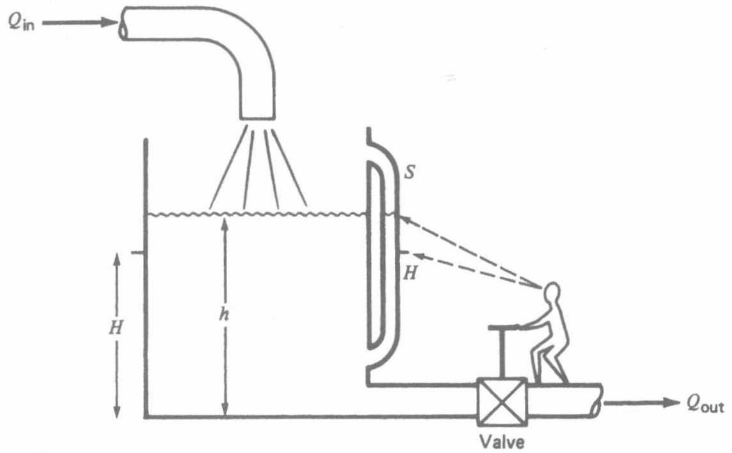


FIGURE 2
A human can regulate the level using a sight tube, S, to compare the level, h, to the objective, H, and adjust a valve to change the level.

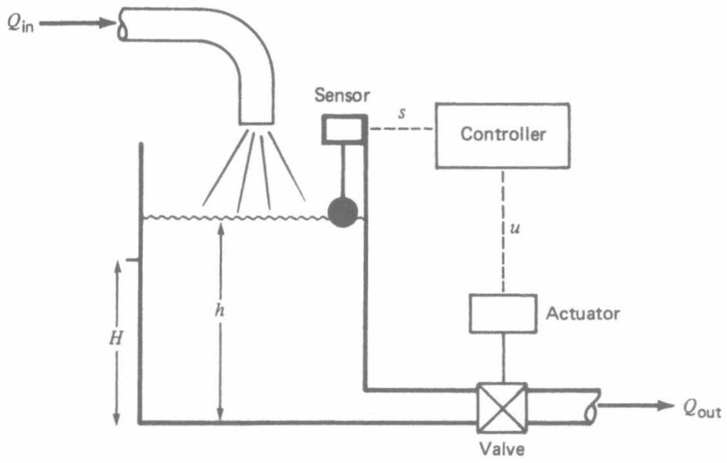


FIGURE 3
An automatic level-control system replaces the human with a controller and uses a sensor to measure the level.

Now the height can be regulated apart from the input flow rate using the following strategy: The human measures the height in the sight tube and compares the value to the setpoint. If the measured value is larger, the human opens the valve a little to let the flow out increase, and thus the level lowers toward the setpoint. If the measured value is smaller than the setpoint, the human closes the valve a little to decrease the flow out and allow the level to rise toward the setpoint.

By a succession of incremental opening and closing of the valve, the human can bring the level to the setpoint value, H, and maintain it there by continuous monitoring of the sight tube and adjustment of the valve. The height is regulated.

Automatic Control To provide automatic control, the system is modified as shown in Figure 3 so that machines, electronics, or computers replace the operations of the human. An instrument called a *sensor* is added that is able to measure the value of the level and convert it into a proportional signal, s. This signal is provided as input to a machine, electronic circuit, or computer called the *controller.* The controller performs the function of the human in evaluating the measurement and providing an output signal, u, to change the valve setting via an *actuator* connected to the valve by a mechanical linkage.

When automatic control is applied to systems like the one in Figure 3, which are designed to regulate the value of some variable to a setpoint, it is called *process control.*

2.2 Servomechanisms

Another commonly used type of control system, which has a slightly different objective from process control, is called a *servomechanism.* In this case, the objective is to force some parameter to vary in a specific manner. This may be called a tracking control system. In-

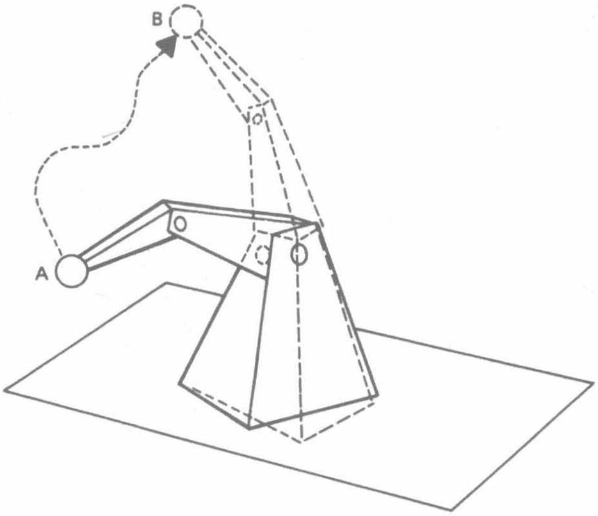


FIGURE 4
Servomechanism-type control systems are used to move a robot arm from point *A* to point *B* in a controlled fashion.

stead of regulating a variable value to a setpoint, the servomechanism forces the controlled variable value to follow variation of the reference value.

For example, in an industrial robot arm like the one shown in Figure 4, servomechanisms force the robot arm to follow a path from point *A* to point *B*. This is done by controlling the speed of motors driving the arm and the angles of the arm parts.

The strategy for servomechanisms is similar to that for process-control systems, but the dynamic differences between regulation and tracking result in differences in design and operation of the control system. This book is directed toward process-control technology.

2.3 Discrete-State Control Systems

This is a type of control system concerned with controlling a *sequence of events* rather than regulation or variation of individual variables. For example, the manufacture of paint might involve the regulation of many variables, such as mixing temperature, flow rate of liquids into mixing tanks, speed of mixing, and so on. Each of these might be expected to be regulated by process-control loops. But there is also a sequence of events that must occur in the overall process of manufacturing the paint. This sequence is described in terms of events that are timed to be started and stopped on a specified schedule. Referring to the paint example, the mixture needs to be heated with a regulated temperature for a certain length of time and then perhaps pumped into a different tank and stirred for another period.

The starting and stopping of events is a discrete-based system because the event is either *true* or *false,* (i.e., started or stopped, open or closed, on or off). This type of control system can also be made automatic and is perfectly suited to computer-based controllers.

These discrete-state control systems are often implemented using specialized computer-based equipment called programmable logic controllers (PLCs).

3 PROCESS-CONTROL BLOCK DIAGRAM

To provide a practical, working description of process control, it is useful to describe the elements and operations involved in more generic terms. Such a description should be independent of a particular application (such as the example presented in the previous section) and thus be applicable to *all* control situations. A model may be constructed using blocks to represent each distinctive element. The characteristics of control operation then may be developed from a consideration of the properties and interfacing of these elements. Numerous models have been employed in the history of process-control description; we will use one that seems most appropriate for a description of modern and developing technology of process control.

3.1 Identification of Elements

The elements of a process-control system are defined in terms of separate functional parts of the system. The following paragraphs define the basic elements of a process-control system and relate them to the example presented in Section 2.

Process In the previous example, the flow of liquid in and out of the tank, the tank itself, and the liquid all constitute a process to be placed under control with respect to the fluid level. In general, a process can consist of a complex assembly of phenomena that relate to some manufacturing sequence. Many variables may be involved in such a process, and it may be desirable to control all these variables at the same time. There are *single-variable* processes, in which only one variable is to be controlled, as well as *multivariable* processes, in which many variables, perhaps interrelated, may require regulation. The process is often also called the *plant.*

Measurement Clearly, to effect control of a variable in a process, we must have information about the variable itself. Such information is found by measuring the variable. In general, a *measurement* refers to the conversion of the variable into some corresponding *analog* of the variable, such as a pneumatic pressure, an electrical voltage or current, or a digitally encoded signal. A sensor is a device that performs the initial measurement and energy conversion of a variable into analogous digital, electrical, or pneumatic information. Further transformation or *signal conditioning* may be required to complete the measurement function. The result of the measurement is a representation of the variable value in some form required by the other elements in the process-control operation.

In the system shown in Figure 3, the controlled variable is the level of liquid in the tank. The measurement is performed by some sensor, which provides a signal, *s,* to the controller. In the case of Figure 2, the sensor is the sight tube showing the level to the human operator as an actual level in the tank.

The sensor is also called a *transducer.* However, the word *sensor* is preferred for the initial measurement device because "transducer" represents a device that converts any signal from one form to another. Thus, for example, a device that converts a voltage into a proportional current would be a transducer. In other words, all sensors are transducers, but not all transducers are sensors.

Error Detector In Figure 2, the human looked at the difference between the actual level, h, and the setpoint level, H, and deduced an error. This error has both a magnitude and polarity. For the automatic control system in Figure 3, this same kind of error determination must be made before any control action can be taken by the controller. Although the error detector is often a physical part of the controller device, it is important to keep a clear distinction between the two.

Controller The next step in the process-control sequence is to examine the error and determine what action, if any, should be taken. This part of the control system has many names, such as *compensator* or *filter,* but *controller* is the most common. The evaluation may be performed by an operator (as in the previous example), by electronic signal processing, by pneumatic signal processing, or by a computer. In modern control systems, the operations of the controller are typically performed by microprocessor-based computers. The controller requires an input of both a *measured indication* of the controlled variable and a representation of the *reference value* of the variable, expressed in the same terms as the measured value. The reference value of the variable, you will recall, is referred to as the setpoint. Evaluation consists of determining the action required to drive the controlled variable to the setpoint value.

Control Element The final element in the process-control operation is the device that exerts a direct influence on the process; that is, it provides those required changes in the controlled variable to bring it to the setpoint. This element accepts an input from the controller, which is then transformed into some proportional operation performed on the process. In our previous example, the control element is the valve that adjusts the outflow of fluid from the tank. This element is also referred to as the *final control element.*

Often an intermediate operation is required between the controller output and the final control element. This operation is referred to as an *actuator* because it uses the controller signal to actuate the final control element. The actuator translates the small energy signal of the controller into a larger energy action on the process.

3.2 Block Diagram

Figure 5 shows a general block diagram constructed from the elements defined previously. The controlled variable in the process is denoted by c in this diagram, and the measured representation of the controlled variable is labeled b. The controlled variable setpoint is labeled r, for reference. The controller uses the error input to determine an appropriate output signal, p, which is provided as input to the control element. The control element operates on the process by changing the value of the controlling process variable, u.

The error detector is a *subtracting-summing point* that outputs an *error signal,* $e = r - b$, to the controller for comparison and action.

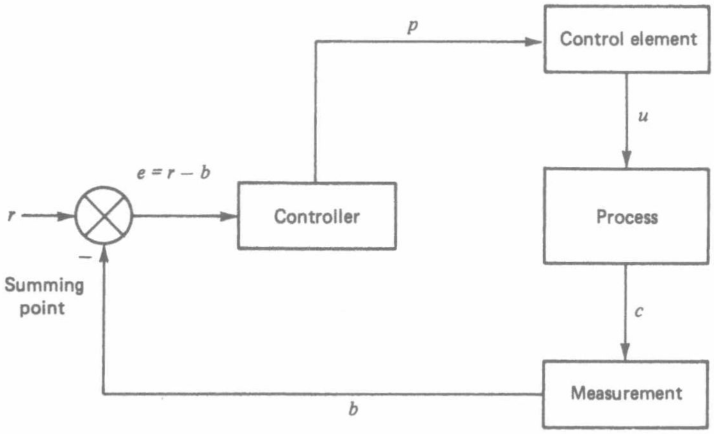


FIGURE 5
This block diagram of a control loop defines all the basic elements and signals involved.

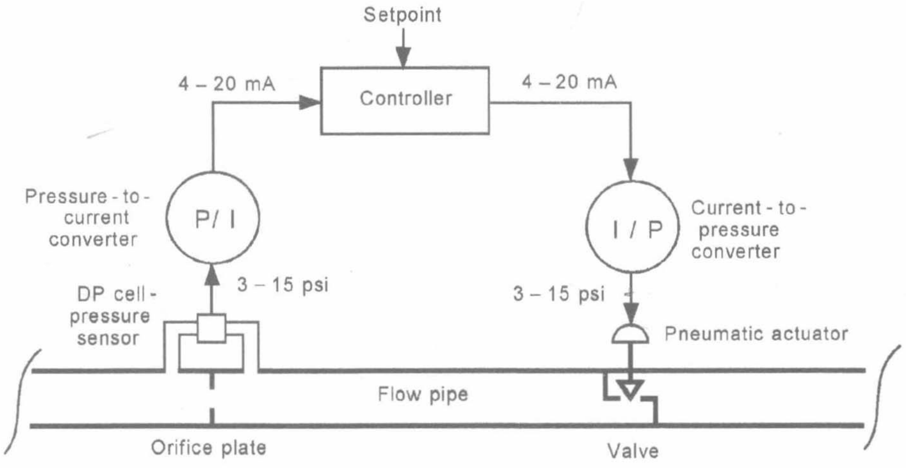
Figure 6 shows how a physical control system is represented as a block diagram. The physical system for control of flow through a pipe is shown in Figure 6. Variation of flow through an obstruction (the orifice plate) produces a pressure-difference variation across the obstruction. This variation is converted to the standard signal range of 3 to 15 psi. The P/I converter changes the pressure to a 4- to 20-mA electric current, which is sent to the controller. The controller outputs a 4- to 20-mA control signal to signify the correct valve setting to provide the correct flow. This current is converted to a 3- to 15-psi pressure signal by the I/P converter and applied to a pneumatic actuator. The actuator then adjusts the valve setting.

Figure 6 shows how all the control system operations are condensed to the standard block diagram operations of measurement, error detection, controller, and final control element.

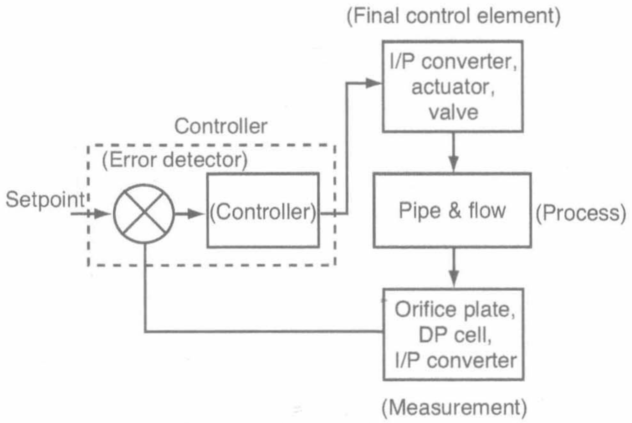
The purpose of a block diagram approach is to allow the process-control system to be analyzed as the interaction of smaller and simpler subsystems. If the characteristics of each element of the system can be determined, then the characteristics of the assembled system can be established by an analytical marriage of these subsystems. The historical development of the system approach in technology was dictated by this practical aspect: first, to specify the characteristics desired of a total system, and then, to delegate the development of subsystems that provide the overall criteria.

It becomes evident that the specification of a process-control system to regulate a variable, c, within specified limits and with specified time responses, determines the characteristics the measurement system must possess. This same set of system specifications is reflected in the design of the controller and control element.

From this concept, we conclude that the analysis of a process-control system requires an understanding of the overall system behavior and the reflection of this behavior in the properties of the system elements. Most people find that an understanding of



(a) Physical diagram of a process-control loop



(b) Block diagram of the process-control loop

FIGURE 6
The physical diagram of a control loop and its corresponding block diagram look similar. Note the use of current- and pressure-transmission signals.

the parts leads to a better understanding of the whole. We will proceed with this assumption as a guiding concept.

The Loop Notice in Figure 5 that the signal flow forms a complete circuit from process through measurement, error detector, controller, and final control element. This is called a *loop,* and in general we speak of a process-control loop. In most cases, it is called a *feedback loop,* because we determine an error and feed back a correction to the process.

4 CONTROL SYSTEM EVALUATION

A process-control system is used to regulate the value of some process variable. When such a system is in use, it is natural to ask, How well is it working? This is not an easy question to answer, because it is possible to adjust a control system to provide different kinds of response to errors. This section discusses some methods for evaluating how well the system is working.

The variable used to measure the performance of the control system is the error, $e(t)$, which is the difference between the constant setpoint or reference value, r, and the controlled variable, $c(t)$.

$$e(t) = r - c(t) \tag{1}$$

Since the value of the controlled variable may vary in time, so may the error. (Note that in a servomechanism, the value of r may be forced to vary in time also.)

Control System Objective In principle, the objective of a control system is to make the error in Equation (1) exactly zero, but the control system responds only to errors (i.e., when an error occurs, the control system takes action to drive it to zero). Conversely, if the error were zero and stayed zero, the control system would not be doing anything and would not be needed in the first place. Therefore, this objective can never be perfectly achieved, and there will always be some error. The question of evaluation becomes one of how large the error is and how it varies in time.

A practical statement of control system objective is best represented by three requirements:

1. The system should be stable.
2. The system should provide the best possible steady-state regulation.
3. The system should provide the best possible transient regulation.

4.1 Stability

The purpose of the control system is to regulate the value of some variable. This requires that action be taken on the process itself in response to a measurement of the variable. If this is not done correctly, the control system can cause the process to become unstable. In fact, the more tightly we try to control the variable, the greater the possibility of instability.

Figure 7 shows that, prior to turning on a control system, the controlled variable drifts in a random fashion and is not regulated. After the control system is turned on, the variable is forced to adopt the setpoint value, and all is well for awhile. Notice that some time later, however, the variable begins to exhibit growing oscillations of value—that is, an instability. This occurs even though the control system is still connected and operational; in fact, it occurs *because* the system is connected and operational.

The first objective, then, simply means that the control system must be designed and adjusted so that the system is stable. Typically, as the control system is adjusted to give better control, the likelihood of instability also increases.

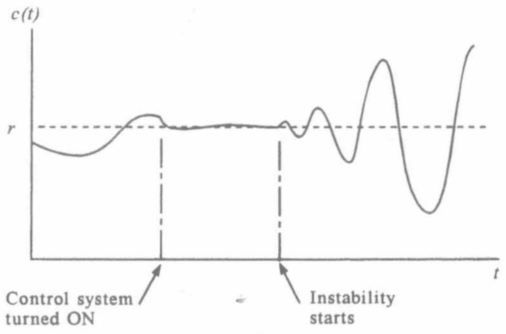


FIGURE 7
A control system can actually cause a system to become unstable.

4.2 Steady-State Regulation

The objective of the best possible steady-state regulation simply means that the steady-state error should be a minimum. Generally, when a control system is specified, there will be some allowable deviation, $\pm\Delta c$, about the setpoint. This means that variations of the variable within this band are expected and acceptable. External influences that tend to cause drifts of the value beyond the allowable deviation are corrected by the control system.

For example, a process-control technologist might be asked to design and implement a control system to regulate temperature at 150°C within ±2°C. This means the setpoint is to be 150°C, but the temperature may be allowed to vary within the range of 148° to 152°C.

4.3 Transient Regulation

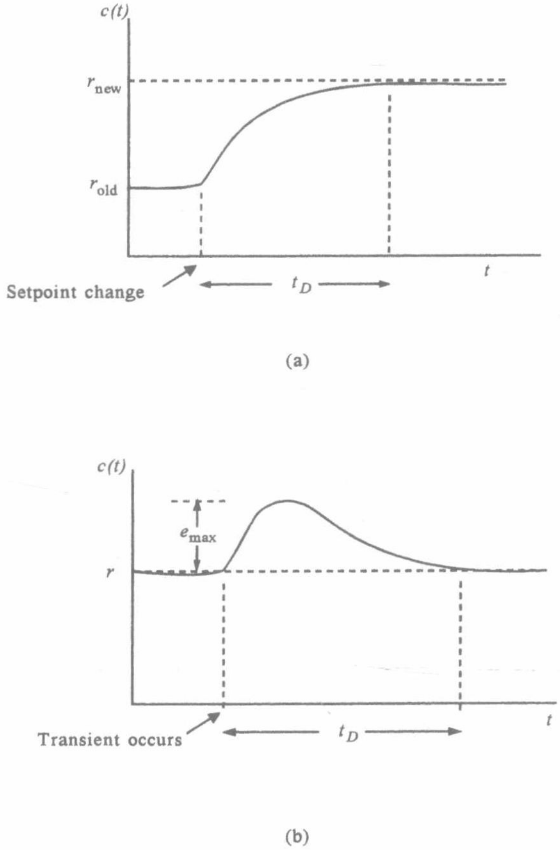
What happens to the value of the controlled variable when some sudden transient event occurs that would otherwise cause a large variation? For example, the setpoint could change. Suppose the setpoint in the aforementioned temperature case were suddenly changed to 160°C. Transient regulation specifies how the control system reacts to bring the temperature to this new setpoint.

Another type of transient influence is a sudden change of some other process variable. The controlled variable depends on other process variables. If one of them suddenly changes value, the controlled variable may be driven to change also, so the control system acts to minimize the effect. This is called *transient response.*

4.4 Evaluation Criteria

The question of how well the control system is working is thus answered by (1) ensuring stability, (2) evaluating steady-state response, and (3) evaluating the response to setpoint changes and transient effects. There are many criteria for gauging the response. In general, the term *tuning* is used to indicate how a process-control loop is adjusted to provide the best control.

FIGURE 8
One of the measures of control system performance is how the system responds to changes of setpoint or a transient disturbance.



Damped Response One type of criterion requires that the controlled variable exhibit a response such as that shown in Figure 8 for excitations of both setpoint changes and transient effects. Note that the error is of only one polarity (i.e., it never oscillates about the setpoint). For this case, measures of quality are the duration, t_D, of the excursion and, for the transient, the maximum error, e_{max}, for a given input. The duration is usually defined as the time taken for the controlled variable to go from 10% of the change to 90% of the change following a setpoint change. In the case of a transient, the duration is often defined as the time from the start of the disturbance until the controlled variable is again within 4% of the reference.

Different tuning will provide different values of e_{max} and t_D for the same excitation. It is up to the process designers to decide whether the best control is larger duration with smaller peak error, or vice versa, or something in between.

Cyclic Response Another type of criterion applies to those cases in which the response to a setpoint change or transient is as shown in Figure 9. Note that the controlled variable oscillates about the setpoint. In this case, the parameters of interest are the maximum error,

