Practical Application of Feedback Control

CHAPTER 12

12.1 ▫ INTRODUCTION

The major components of the feedback control calculations have been presented in previous chapters in this part. However, much more needs to be done to ensure the successful application of the principles already covered. Practical application of feedback control requires that equipment and calculations provide accuracy and reliability and also overcome a few shortcomings of the basic PID control algorithm. Some of these requirements are satisfied through careful specification and maintenance of equipment used in the control loop. Other requirements are satisfied through modifications to the control calculations.

The application issues will be discussed with reference to the control loop diagram in Figure 12.1, which shows that many of the calculations can be grouped into three categories: input processing, control algorithm, and output processing. As shown in Table 12.1, most of the calculation modifications are available in both analog and digital equipment; however, a few are not available on standard analog equipment, because of excessive cost. The application requirements are discussed in the order of the four major topics given in Table 12.1. A few key equipment specifications are presented first, followed by input processing calculations, performed before the control calculation. Then, modifications to the PID control calculation are explained. Finally, a few issues related to output processing are presented. The topics in this chapter are by no means a complete presentation of practical issues for successful application of control; they are limited to the most important

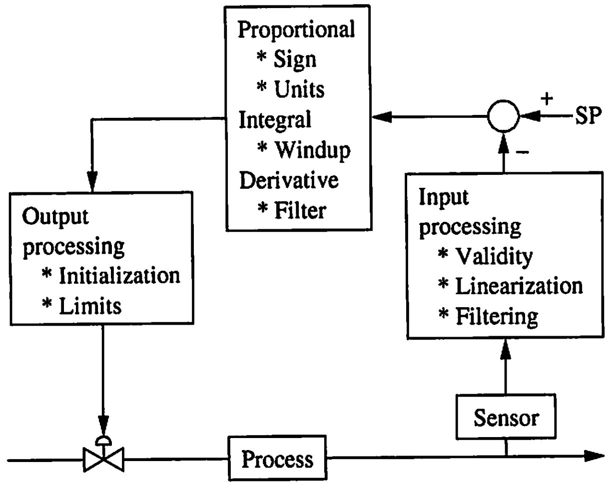


FIGURE 12.1

Simplified control loop drawing, showing application topics.

TABLE 12.1

Summary of application issues

Application topic	Available in either analog or digital equipment	Typically available only in digital equipment
Equipment specification		
Measurement range	†	
Final element capacity	†	
Failure mode	†	
Input processing		
Input validity		X
Engineering units		X
Linearization	X	
Filtering	X	
Control algorithm		
Sign	X	
Dimensionless gain	X	
Anti-reset windup	X	
Derivative filter	X	
Output processing		
Initialization	X	
Bounds on output variable	X	

† Involves field control equipment that is independent of analog or digital controllers.

issues for single-loop control. Further topics, addressing design, reliability, and safety, are covered in Part VI after multiple-loop processes and controls have been introduced.

12.2 ▫ EQUIPMENT SPECIFICATION

Proper specification of process and control equipment is essential for good control performance. In this section, the specification of sensors and final control elements is discussed. Sensors are selected to provide an indication of the true controlled variable and are selected based on accuracy, reproducibility, and cost. The first two terms are defined here as paraphrased from ISA (1979).

Accuracy is the degree of conformity to a standard (or true) value when the device is operated under specified conditions. This is usually expressed as a bound that errors will not exceed when a measuring device is used under these specified conditions, and it is often reported as inaccuracy as a percent on the instrument range.

Reproducibility is the closeness of agreement among repeated sensor outputs for the same process variable value. Thus, a sensor that has very good reproducibility can have a large deviation from the true process variable; however, the sensor is consistent in providing (nearly) the same indication for the same true process variable.

Often, deviations between the true variable and the sensor indication occur as a "drift" or slow change over a period of time, and this drift contributes a bias error. In these situations, the accuracy of the sensor may be poor, although it may provide a good indication of the change in the process variable, since the sensitivity relationship (Δ sensor signal)/(Δ true variable) may be nearly constant. Although a sensor with high accuracy is always preferred because it gives a close indication of the true process variable, cases will be encountered in later chapters in which reproducibility is acceptable as long as the sensitivity is unaffected by the drift. For example, reproducibility is often acceptable when the measurement is applied in enhancing the performance of a control design in which the key output controlled variable is measured with an accurate sensor. The importance of accuracy and reproducibility will become clearer after advanced control designs such as cascade and feedforward control are covered; therefore, the selection of sensors is discussed again in Chapter 24.

Often, inaccuracies can be corrected by periodic calibration of the sensor. If the period of time between calibrations is relatively long, a drift from high accuracy over days or weeks could result in poor control performance. Thus, critical instruments deserve more frequent maintenance. If the period between calibrations is long, some other means for compensating the sensor value for a drift from the accurate signal may be used; often, laboratory analyses can be used to determine the bias between the sensor and true (laboratory) value. If this bias is expected to change very slowly, compared with laboratory updates, the corrected sensor value, equalling measurement plus bias, can be used for real-time control. Further discussion on using measurements that are not exact, but give approximate indications of the process variable over limited conditions, is given in Chapter 17 on inferential control.

Sensor Range

An important factor that must be decided for every sensor is its range. For essentially all sensors, accuracy and reproducibility improve as the range is reduced, which means that a small range would be preferred. However, the range must be large enough to span the expected variation of the process variable during typical conditions, including disturbances and set point changes. Also, the measurement ranges are selected for easy interpretation of graphical displays; thus, ranges are selected that are evenly divisible, such as 10, 20, 50, 100, or 200. Naturally, each measurement must be analyzed separately to determine the most appropriate ranges, but some typical examples are given in the following table.

Variable	Typical set point	Sensor range
Furnace outlet temperature	600°C	550–650°C
Pressure	50 bar	40–60 bar
Composition	0.50 mole %	0–2.0 mole %

Levels of liquids (or solids) in vessels are typically expressed as a percent of the span of the sensor rather than in length (meters). Flows are often measured by pressure drop across an orifice meter. Since orifice plates are supplied in a limited number of sizes, the equipment is selected to be the smallest size that is (just) large enough to measure the largest expected flow. The expected flow is always greater than the design flow; as a result of the limited equipment and expected flow range, the flow sensor can usually measure at least 120 percent of the design value, and its range is essentially never an even number such as 0 to 100 m^3/day.

These simple guidelines do not satisfy all situations, and two important exceptions are mentioned here. The first special situation involves nonnormal operations, such as startup and major disturbances, when the variable covers a much greater range. Clearly, the suppressed ranges about normal operation will not be satisfactory in these cases. The usual practice is to provide an *additional* sensor with a much larger range to provide a measurement, with lower accuracy and reproducibility, for these special cases. For example, the furnace outlet temperature shown in Figure 12.2, which is normally about 600°C, will vary from about 20 to 600°C during startup and must be monitored to ensure that the proper warm-up rate is attained. An additional sensor with a range of 0 to 800°C could be used for this purpose. The additional sensor could be used for control by providing a switch, which selects either of the sensors for control. Naturally, the controller tuning constants would have to be adapted for the two types of operation.

A second special situation occurs when the accuracy of a sensor varies over its range. For example, a flow might be normally about 30 m^3/h in one operating situation and about 100 m^3/h in the other. Since a pressure drop across an orifice meter does not measure the flow accurately for the lower one-third of its range, two pressure drop measurements are required with different ranges. For this example, the meter ranges might be 0 to 40 and 0 to 120 m^3/h, with the smaller range providing good accuracy for smaller flows.

Control Valve

The other critical control equipment item is the final element, which is normally a control valve. The valve should be sized just large enough to handle the maximum

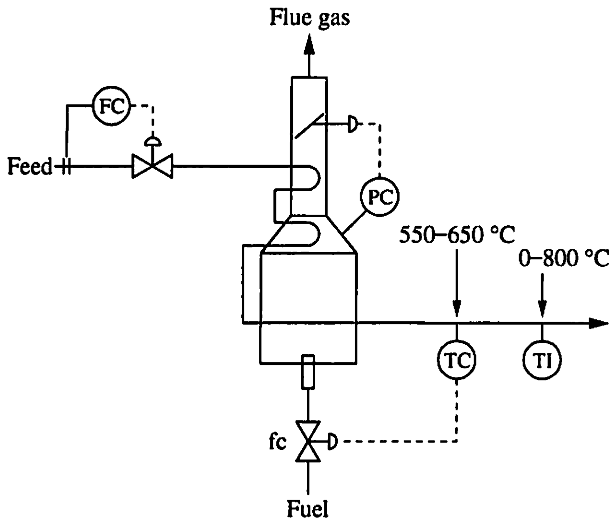


FIGURE 12.2

Fired heater with simple control strategy.

expected flow at the expected pressure drop and fluid properties. Oversized control valves (i.e., valves with maximum possible flows many times larger than needed) would be costly and might not provide precise maintenance of low flows. The acceptable range for many valves is about 25:1; in other words, the valve can regulate the flow smoothly from 4 to nearly 100 percent of its range, with flows below 4 percent having unacceptable variation. (Note that the range of stable flow depends on many factors in valve design and installation; the engineer should consult specific technical literature for the equipment and process design.) Valves are manufactured in specific sizes, and the engineer selects the smallest valve size that satisfies the maximum flow demand. If very tight regulation of small changes is required for a large total flow, a typical approach is to provide two valves, as shown in Figure 12.3. This example shows a pH control system in which acid is adjusted to achieve the desired pH. In this design, the position of the large valve is changed infrequently by the operator, and the position of the small valve is changed automatically by the controller. Strategies for the controller to adjust both valves are presented in Chapter 22 on variable-structure control.

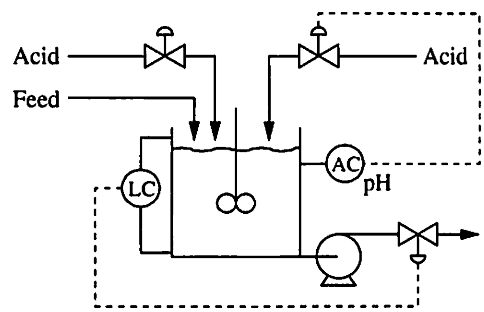


FIGURE 12.3

Stirred-tank pH control system with two manipulated valves, of which only one is adjusted automatically.

> Sensors and final elements are sized to (just) accommodate the typical operating range of the variable. Extreme oversizing of a single element is to be avoided; a separate element with larger range should be provided if necessary.

Another important issue is the behavior of control equipment when power is interrupted. Naturally, a power interruption is an infrequent occurrence, but proper equipment specification is critical so that the system responds safely in this situation. Power is supplied to most final control elements (i.e., valves) as air pressure, and loss of power results from the stoppage of air compressors or from the failure of pneumatic lines. The response of the valve when the air pressure, which

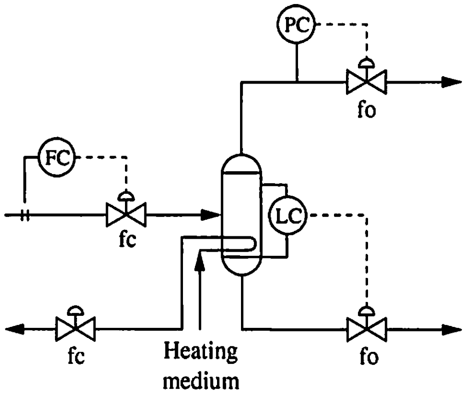


FIGURE 12.4

A flash separation unit with the valve failure modes.

is normally 3 to 15 psig, decreases below 3 psig is called its *failure mode.* Most valves fail open or fail closed, with the selection determined by the engineer to give the safest process conditions after the failure. Normally, the safest conditions involve the lowest pressures and temperatures. As an example, the flash drum in Figure 12.4 would have the valve failure modes shown in the figure, with "fo" used to designate a fail-open valve and "fc" a fail-closed valve. (An alternative designation is an arrow on the valve stem pointing in the direction that the valve takes upon air loss.) The valve failure modes in the example set the feed to zero, the output liquid flow to maximum, the heating medium flow to zero, and the vapor flow to its maximum. All of these actions tend to minimize the possibility of an unsafe condition by reducing the pressure. However, the proper failure actions must consider the integrated plant; for example, if a gas flow to the process normally receiving the liquid could result in a hazardous situation, the valve being adjusted by the level controller would be changed to fail-closed.

The proper failure mode can be ensured through simple mechanical changes to the valve, which can be made after installation in the process. Basically, the failure mode is determined by the spring that directs the valve position when no external air pressure provides a counteracting force. This spring can be arranged to ensure either a fully opened or fully closed position. As the air pressure is increased, the force on the restraining diaphragm increases, and the valve stem (position) moves against the spring.

> The failure mode of the final control element is selected to reduce the possibility of injury to personnel and of damage to plant equipment.

The selection of a failure mode also affects the normal control system, because the failure mode is the position of the valve at 0 percent controller output. As the controller output increases, a fail-open valve closes and a fail-closed valve opens. As a result, the failure mode affects the sign of the process transfer function expressed as $CV(s)/MV(s)$, which is the response "seen" by the controller. As a consequence, the controller gain used for negative feedback control is influenced by the failure mode. If the gain for the process $CV(s)/F(s)$, with $F(s)$ representing the flow through the manipulated valve, is K_p^*, the correct sign for the controller gain is given by

Failure mode	**Sign of the controller gain considering the failure mode**
Fail closed	$\text{Sign}(K_p^*)$
Fail open	$-\text{Sign}(K_p^*)$

This brief introduction to determining sensor ranges, valve sizes, and failure modes has covered only a few of the many important issues. These topics and many more are covered in depth in many references and instrumentation handbooks, which should be used when designing control systems (see references in Chapter 1).

12.3 ▫ INPUT PROCESSING

The general control system, involving the sensor, signal transmission, control calculation, and transmission to the final element, was introduced in Chapter 7. In this section, we will look more closely at the processing of the signal from the completion of transmission to just before the control algorithm. The general objectives of this signal processing are to (1) improve reliability by checking signal validity, (2) perform calculations that improve the relationship between the signal and the actual process variable, and (3) reduce the effects of high-frequency noise.

Validity Check

The first step is to make a check of the validity of the signal received from the field instrument via transmission. As we recall, the electrical signal is typically 4 to 20 mA, and if the measured signal is substantially outside the expected range, the logical conclusion is that the signal is faulty and should not be used for control. A faulty signal could be caused by a sensor malfunction, power failure, or transmission cable failure. A component in the control system must identify when the signal is outside of its allowable range and place the controller in the manual mode *before the value is used for control.* An example is the furnace outlet temperature controller in Figure 12.2. A typical cause of a sensor malfunction is for the thermocouple measuring the temperature to break physically, opening the circuit and resulting in a signal, after conversion from voltage to current, below 4 mA. If this situation were not recognized, the temperature controller would receive a measurement equal to the lowest value in the sensor range and, as a result, increase the fuel flow to its maximum. This action could result in serious damage to the process equipment and possible injury to people. The input check could quickly identify the failure and interrupt feedback control. An indication should be given to the operators, because the controller mode would be changed without their intervention. Because of the logic required for this function, it is easily provided as a preprogrammed feature in many digital control systems, but it is not a standard feature in analog control because of its increased cost.

Conversion for Nonlinearity

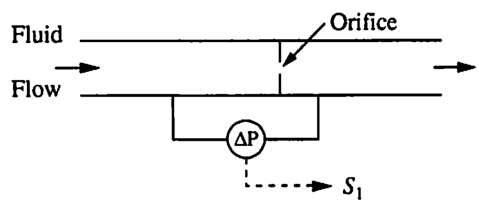


FIGURE 12.5

Flow measurement by sensing the pressure difference about an orifice in a pipe.

The next step in input processing is to convert the signal to a better measure of the actual process variable. Naturally, the physical principles for sensors are chosen so that the signal gives a "good" measure of the process variable; however, factors such as reliability and cost often lead to sensors that need some compensation. An example is a flow meter that measures the pressure drop across an orifice, as shown in Figure 12.5. The flow and pressure drop are ideally related according to the equation

$$F = K\sqrt{\frac{\Delta P}{\rho}} \tag{12.1}$$

with $F =$ volumetric flow rate
$\rho =$ density
$\Delta P =$ pressure difference across the orifice

Typically, the sensor measures the pressure drop, so that

$$F = \frac{K}{\sqrt{\rho}}\sqrt{(S_1 - S_{10})(R_1) + Z_1} \tag{12.2}$$

with $S_1 =$ signal from the sensor
$S_{10} =$ lowest value of the sensor signal
$R_1 =$ range of the true process variable measured by the sensor
$Z_1 =$ value of the true process variable when the sensor records its lowest signal (S_{10})
$\rho =$ constant

Thus, using the sensor signal directly (i.e., without taking the square root) introduces an error in the control loop. The accuracy would be improved by using the square root of the signal, as shown in equation (12.2), for control and also for process monitoring. In addition, the accuracy could be improved further for important flow measurements by automatically correcting for fluid density variations as follows:

$$F = K\sqrt{\frac{(S_1 - S_{10})(R_1) + Z_1}{(S_2 - S_{20})(R_2) + Z_2}} \tag{12.3}$$

with the subscript 1 for the pressure difference sensor signal and 2 for the density sensor signal. By far the most common flow measurement approach used commercially is equation (12.2), with equation (12.3) used only when the accurate flow measurement is important enough to justify the added cost of the density analyzer.

Another common example of sensor nonlinearity is the thermocouple temperature sensor. A thermocouple generates a millivolt signal that depends on the temperature difference between the two junctions of the bimetallic circuit. The signal transmitted for control is either in millivolts or linearly converted to milliamps. However, the relationship between millivolts and temperature is not linear. Usually, the relationship can be represented by a polynomial or a piecewise linear approximation to achieve a more accurate temperature value; the additional calculations are easily programmed as a function in the input processing to achieve a more accurate temperature value.

These orifice flow and thermocouple temperature examples are only a few of the important relationships that must be considered in a plantwide control system. Naturally, each relationship should be evaluated based on the physics of the sensor and the needs of the control system. Standard handbooks and equipment supplier manuals provide invaluable information for this analysis. The importance of the analysis extends beyond control to monitoring plant performance, which depends on accurate measurements to determine material balances, reactor yields, energy consumption, and so forth. Thus, many sensor signals are corrected for nonlinearities even when they are not used for closed-loop control.

Engineering Units

Another potential input calculation expresses the input in engineering units, which greatly simplifies the analysis of data by operations personnel. This calculation is possible only in digital systems, as analog systems perform calculations using voltage or pressure. Recall that the result of the transmission and any correction for nonlinearity in digital systems is a signal in terms of the instrument range expressed as a percent (0 to 100) or a fraction (0 to 1). The variable is expressed in engineering units according to the following equation:

$$\mathrm{CV} = Z + R(S_3 - S_{30}) \tag{12.4}$$

with S_3 the signal from the sensor after correction for nonlinearity.

Filtering

An important feature in input processing is filtering. The transmitted signal represents the result of many effects; some of these effects are due to the process, some are due to the sensor, and some are due to the transmission. These contributions to the signal received by the controller vary over a wide range of frequencies, as presented in Figure 12.6. The control calculation should be based on only the responses that can be affected by the manipulated variable, because very high-frequency components will result in high-frequency variation of the manipulated variable, which will not improve and may degrade the performance of the controlled system.

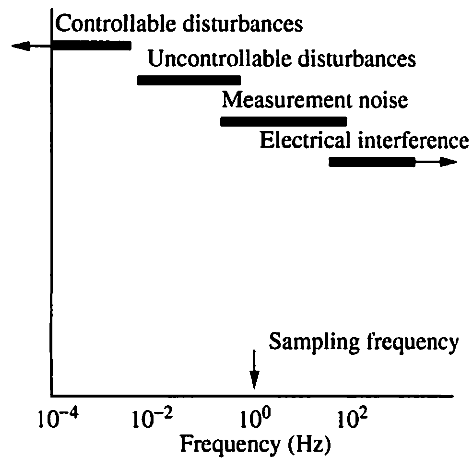


FIGURE 12.6

Example frequency ranges for components in the measurement. (Reprinted by permission. Copyright ©1966, Instrument Society of America. From Goff, K., "Dynamics of Direct Digital Control, Part I," *ISA J., 13, 11,* 45–49.)

Some noise components are due to such factors as electrical interference and mechanical vibration, which have a much higher frequency than the process response. (This distinction may not be so easy to make in controlling machinery or other very fast systems.) Other noise components are due to changes such as imperfect mixing and variations in process input variables such as flows, temperatures, and compositions; some of these variations may be closer to the critical frequency of the control loop. Finally, some measurement variations are due to changes in flows and compositions that occur at frequencies much below the critical frequency; the effects of these slow disturbances can be attenuated effectively by feedback control.

The very high-frequency component of the signal cannot be influenced by a process control system, and thus is considered "noise"; the goal, therefore, is to remove the unwanted components from the signal, as shown in Figures 12.7 and 12.8. The filter is located in the feedback loop, and dynamics involved with the filter, like process dynamics, will influence the stability and control performance of the closed-loop system. This statement can be demonstrated by deriving the following transfer function, which shows that the filter appears in the characteristic equation.

$$\frac{\mathrm{CV}(s)}{\mathrm{SP}(s)} = \frac{G_p(s)G_v(s)G_c(s)}{1 + G_p(s)G_v(s)G_c(s)G_f(s)G_s(s)} \tag{12.5}$$

If it were possible to separate the signal ("true" process variable) from the noise, the perfect filter in Figure 12.8 would transmit the unaltered "true" process variable value to the controller and reduce the noise amplitude to zero. In addition, the perfect filter would do this without introducing phase lag! Unfortunately, there is no clear distinction between the "true" process variable, which can be influenced by adjusting the manipulated variable, and the "noise," which cannot be influenced and should be filtered. Also, no filter calculation exists that has the features of a perfect filter in Figure 12.8.

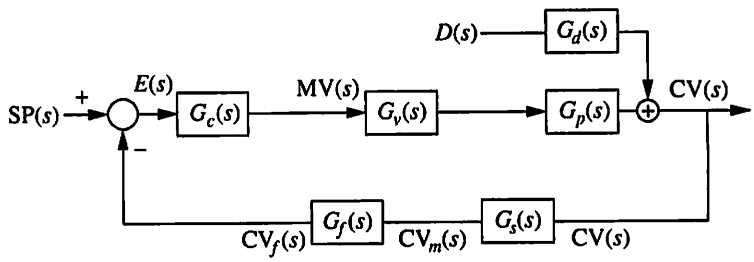


FIGURE 12.7

Block diagram of a feedback loop with a filter on the measurement.

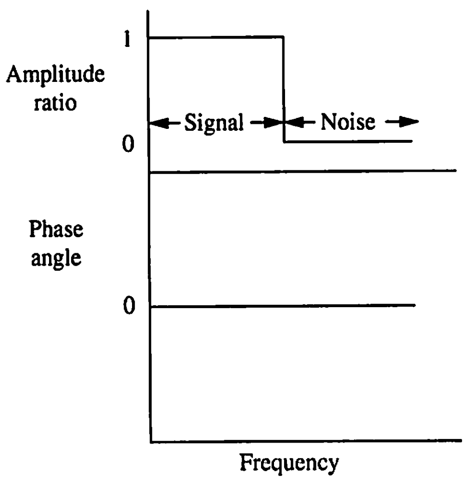


FIGURE 12.8

The amplitude ratio and phase angle of a perfect filter, which *cannot* be achieved exactly.

The filter calculation usually employed in the chemical process industries is a first-order transfer lag:

$$CV_f(s) = \frac{1}{\tau_f s + 1} CV_m(s) \tag{12.6}$$

with $CV_f(s)$ = value after the filter
$CV_m(s)$ = measured value before the filter
τ_f = filter time constant

The gain is unity because the filter should not alter the actual signal at low frequency, including the steady state. The frequency response of the continuous filter was derived in Section 4.5, is repeated in the following equations, and is shown in Figure 12.9.

$$\begin{aligned} AR &= \frac{1}{\sqrt{1+\omega^2\tau_f^2}} \\ \phi &= \tan^{-1}(-\omega\tau_f) \end{aligned} \tag{12.7}$$

The filter time constant, τ_f, is a tuning parameter that is selected to approximate the perfect filter shown in Figure 12.8; this goal requires that it be small with respect to the dominant process dynamics so that feedback control performance is not significantly degraded. Also, it should be large with respect to the noise period (inverse of frequency) so that noise is attenuated. These two requirements cannot usually be satisfied perfectly, because the signal has components of all frequencies and the cutoff between process and noise is not known. As seen in Figure 12.9, the amplitude of high-frequency components decreases as the filter time constant is increased. In the example, signal components with a frequency smaller than $0.5/\tau_f$ are essentially unaffected by the filter, while components with a much higher frequency have their magnitudes reduced substantially. This performance leads to the name *low-pass filter,* which is sometimes used to describe the filter that does not affect low frequencies—lets them pass through—while attenuating the high-frequency components of a signal. A simple case study has been performed to demonstrate the trade-off between filtering and performance. The effect of filtering on a first-order-with-dead-time plant is given in Figure 12.10. The controlled-variable performance, measured simply as IAE in this example, degrades as the filter time

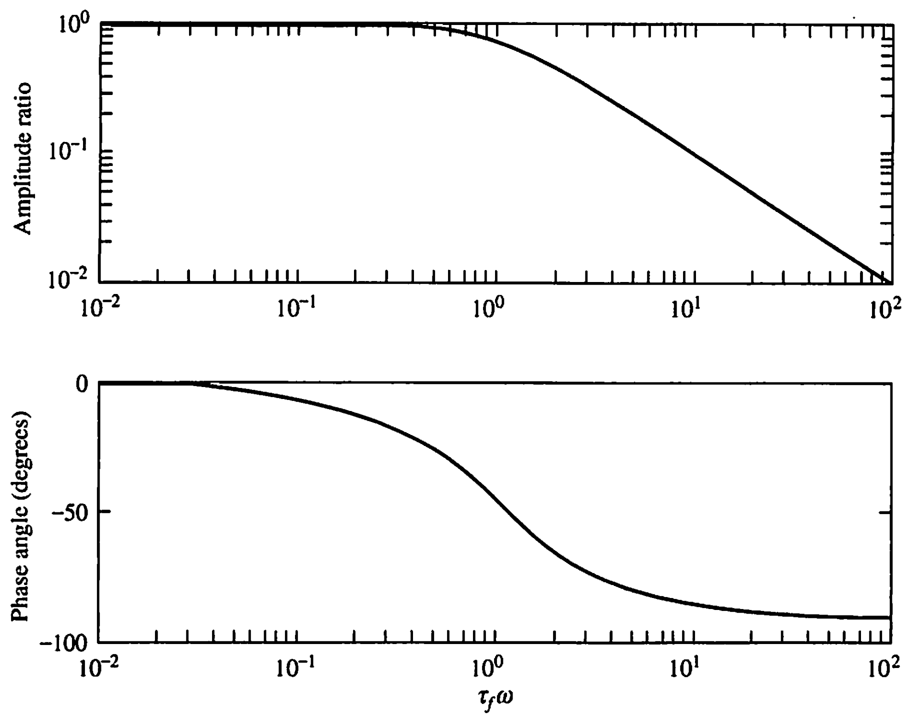


FIGURE 12.9

Bode plot of first-order filter.

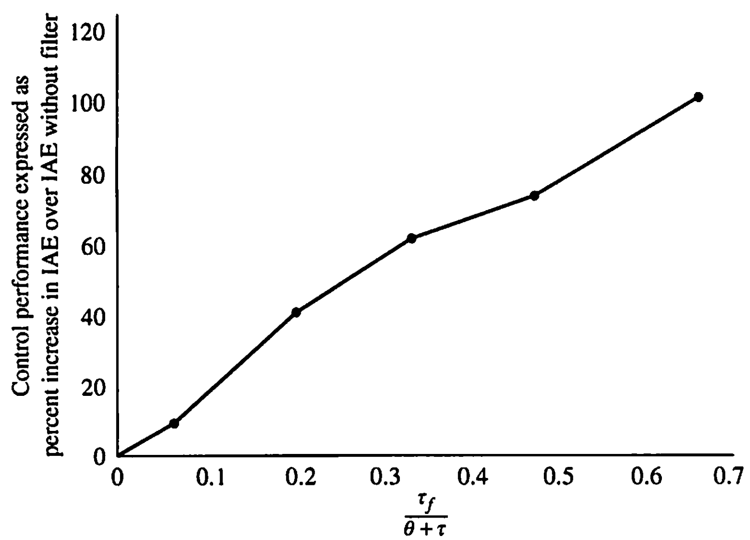


FIGURE 12.10

The effect of measurement filtering on feedback control performance ($\theta/(\theta + \tau) = 0.33$).

constant is increased. The results are given in Figure 12.10, which shows the percent increase in IAE over control without the filter as a function of the filter time constant. This case study was calculated for a plant with fraction dead time of 0.33 under a PI controller with tuning according to the Ciancone correlations. Thus, the results are *typical but not general;* similar trends can be expected for other systems.

Based on the goals of filtering, the guidelines in Table 12.2 are recommended for reducing the effects of high-frequency noise for a typical situation. These steps should be implemented in the order shown until the desired control performance is achieved. Normally, step 2 will take priority over step 3, because the controlled-variable performance is of greater importance. If reducing the effects of high-frequency noise is an overriding concern, the guidelines can be altered accordingly, such as achieving step 3 while allowing some degradation of the controlled-variable control performance.

The final issue in filtering relates to digital implementation. A digital filter can be developed by first expressing the continuous filter in the time domain as a differential equation:

$$\tau_f \frac{d\mathrm{CV}_f(t)}{dt} + \mathrm{CV}_f(t) = \mathrm{CV}_m(t) \tag{12.8}$$

leading to the digital form of the first-order filter,

$$(\mathrm{CV}_f)_n = A(\mathrm{CV}_f)_{n-1} + (1 - A)(\mathrm{CV}_m)_n \qquad \text{with } A = e^{-\Delta t/\tau_f} \tag{12.9}$$

This equation can be derived by solving the differential equation defined by equation (12.8) and assuming that the measured value $(\mathrm{CV}_m)_n$ is constant over the filter execution period Δt. The digital filter also has to be initialized when the calculations are first performed or when the computer is restarted. The typical filter initialization sets the initial filtered value to the value of the initial measurement.

$$(\mathrm{CV}_f)_1 = (\mathrm{CV}_m)_1 \tag{12.10}$$

As is apparent, the first-order filter can be easily implemented in a digital computer. However, the digital filter does not give exactly the same results as the continuous version, because of the effects of sampling. As discussed in Chapter 11 on digital control, sampling a continuous signal results in some loss of information. Shannon's theorem shows us that information in the continuous signal at frequencies above about one-half the sample frequency cannot be reconstructed from the sampled data. For example, sampled data taken at a period of one minute could not

TABLE 12.2
Guidelines for reducing the effects of noise

Step	Action	Justification
1. Reduce the amplification of noise by the control algorithm	Set derivative time to zero $T_d = 0$	Prevent amplification of high-frequency component by controller
2. Allow only a slight increase in the IAE of the controlled variable	Select a small filter τ_f, e.g., $\tau_f < 0.05(\theta + \tau)$	Do not allow the filter to degrade control performance
3. Reduce the noise effects on the manipulated variable	Select filter time constant to eliminate noise, e.g., $\tau_f > 5/\omega_n$ where ω_n is the noise frequency	Achieve a small amplitude ratio for the high-frequency components

be used to determine a sinusoidal variation in the continuous signal with a period of one second. As a result, the *digital filter cannot attenuate higher-frequency noise.*

This is potentially a serious problem, because very high-frequency noise is possible due to mechanical vibrations of the sensor and electrical interference in signal transmission, as shown in Figure 12.6. Since a digital filter alone at a relatively long period cannot provide adequate filtering, most commercial digital control equipment has *two filters in series:* an analog filter before the analog-to-digital (A/D) conversion and an (optional) digital filter after the conversion, as shown in Figure 12.11. The purpose of the analog filter is to reduce high-frequency components of the signal substantially, and typically, it has a time constant on the order of the sample period. The analog filter in this configuration is sometimes referred to as an *antialiasing* filter, since it reduces potential errors resulting from slowly sampling a signal with high-frequency components. The digital filter in the design, if needed, would be tuned according to the guidelines in Table 12.2 to further attenuate variations at higher frequencies.

There is a tendency to overfilter signals used for control. Thus, the following recommendation should be considered:

> Since the filter is a dynamic element in the feedback loop, signals used for control should be filtered no more than the minimum required to achieve good control performance.

Not all measurements are used for control; in fact, a rough estimate is that less than one-third of the signals transmitted to a central control room are used for control. The other signals serve the important purpose of enabling plant personnel to monitor the process. For displaying the current status of the process, these signals should not be filtered, except for the analog filter before the A/D converter, because any filter would delay the information display, which could confuse the plant operator.

Much of this information is also stored for later process analysis. Since high-frequency data is usually not required, a typical approach is to store data consisting of averages of several samples of the measured variable within meaningful time periods such as hour, shift (8 hours), day, and week. This data concentration approach represents a *filter* that reduces the effects of high-frequency noise and short-term

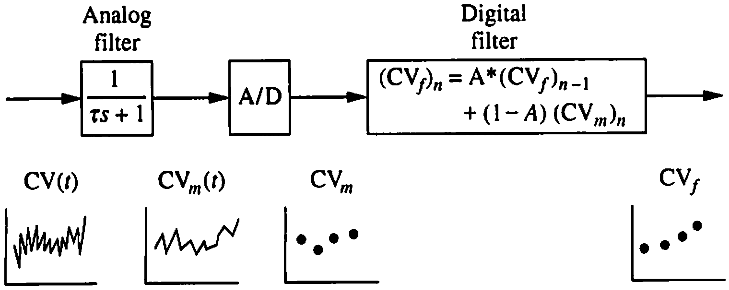


FIGURE 12.11

Schematic of the effects of analog and digital filters in series.

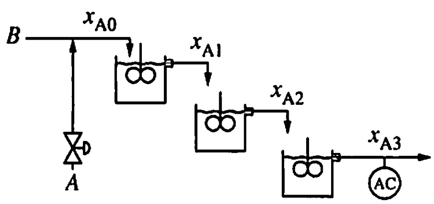
plant variations. Assuming that the values used to calculate the average are taken infrequently enough to be independent, the effect of the number of values used in the average on the standard deviation is given as

$$\sigma_{\text{aver}} = \frac{\sigma_m}{\sqrt{n}} \tag{12.11}$$

with σ_{aver} = standard deviation of the average
σ_m = standard deviation of the individual measurements used in calculating the average
n = number of measurements used to calculate the average

This filtering is desired for the purpose of long-term process analysis, such as detecting slow changes in heat transfer coefficients or catalyst activity, which in many cases change slowly over weeks or months.

EXAMPLE 12.1.



The measurement of the controlled variable in the three-tank mixer feedback control system in Example 7.2 is modified to have higher-frequency sensor noise. Determine how a filter affects (*a*) the open-loop response of the controlled variable after the filter and (*b*) the control performance of the feedback system. Recall that the feedback process is third-order with all time constants equal to 5 minutes.

Typical dynamic data of the controlled variable without control is shown in Figure 12.12, along with the responses of the signal after filters with two different time constants; the mean values are the same, but the plots are displaced for clearer comparison. As expected, the filters reduce the high-frequency variation in the unfiltered signal. The other key issue is the effect of the filter on the control performance. The dynamic responses of the control system with and without the derivative mode for various filter time constants are shown in Figure 12.13*a* through *c*; in all of these figures, the value of the controlled variable plotted is *before* the

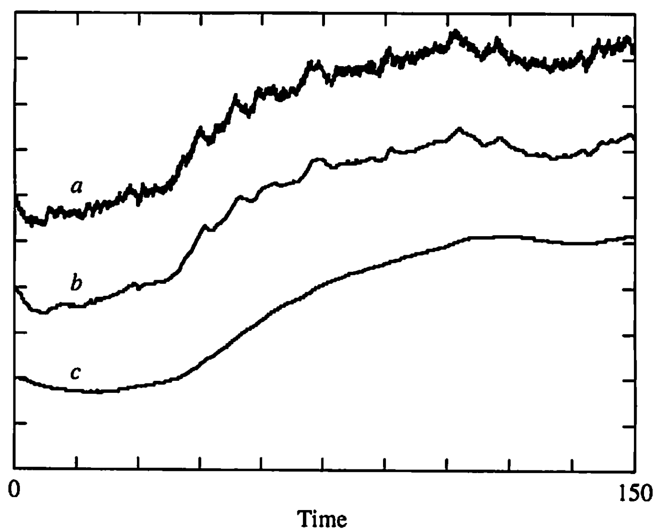


FIGURE 12.12

Open-loop dynamic data for Example 12.1 with τ_f equal to: (*a*) 0.0; (*b*) 3.0; and (*c*) 10.0 min.

filter; thus, this signal is modulated before being used in the controller. The amplification of the measurement noise by the derivative mode is apparent by comparing Figure 12.13*a* and Figure 12.13*b*. In fact, simply eliminating the derivative might be sufficient in this case. The addition of the filter further smooths the manipulated variable but worsens the performance of the controlled variable. A measure of the controlled-variable performance is summarized in Table 12.3, which includes the need to change the controller tuning because of the addition of the filter in the control loop. The results are in general agreement with the guidelines shown in Figure 12.10.

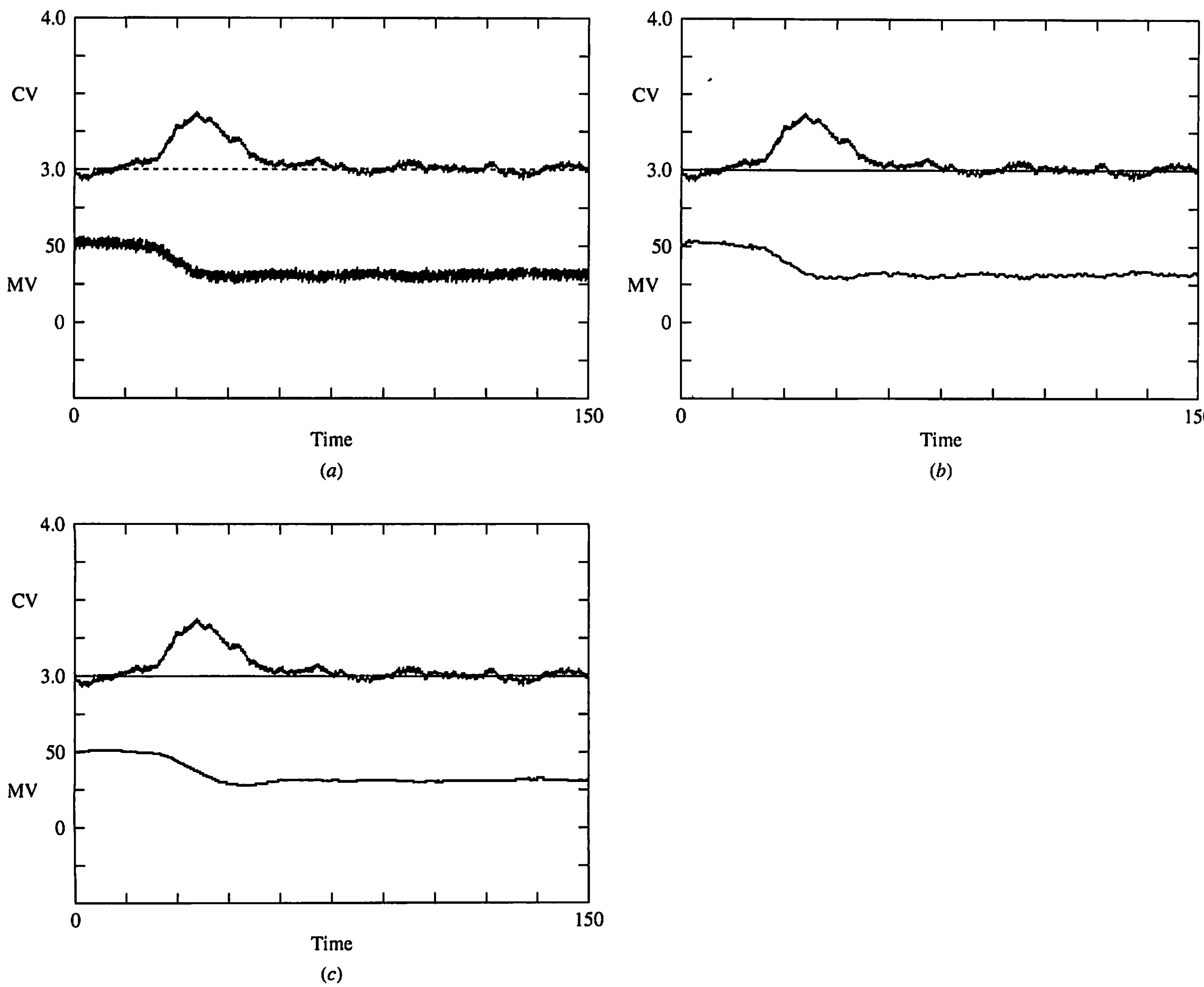


FIGURE 12.13

Closed-loop dynamic data for the system in Example 12.1: (*a*) PID without filtering; (*b*) PI without filtering; (*c*) PI with filtering (τ_f = 3.0 min).

TABLE 12.3

Results from Example 12.1

K_c	T_I	T_d	τ_f	IAE	
30	11	0.88	0	9.4	No filter
30	11	0	0	9.5	No filter
29	12	0	1	10.3	Generally acceptable, $\tau_f/(\theta+\tau) \approx 0.066$
26	14	0	3	12.5	Generally too much filtering, $\tau_f/(\theta+\tau) \approx 0.20$
22	23	0	10	21.2	Too much filtering, $\tau_f/(\theta+\tau) \approx 0.66$

Set-Point Limits

Often, limits are placed on the set point. Without a limit, the set point can take any value in the controlled-variable sensor range. Since the controlled-variable sensor range is selected to provide information during upsets and other atypical operations, it may include values that are clearly undesirable but not entirely preventable. Limits on the set point prevent an incorrect value being introduced (1) inadvertently by the operator or (2) by poor control of a primary in a cascade control strategy (see Chapter 14).

12.4 ▫ FEEDBACK CONTROL ALGORITHM

Many features and options are included in commercial PID control algorithms. In this section, some selected features are introduced, because they are either required in many systems or are optional features used widely. The features are presented according to the mode of the PID controller that each affects.

Controller Proportional Mode

Throughout the previous chapters, we have allowed the controller gain to be either positive or negative as required to achieve *negative feedback*. In many control systems that use preprogrammed algorithms, the controller gain is required to be *positive*. Naturally, another option must be added; this is a "sense switch" that defines the sign of the controller output. The effect of the sense switch is

$$\mathrm{MV}(t) = (K_{\text{sense}})K_c\left(E + \frac{1}{T_I}\int_0^t E\,dt' - T_d\frac{d\mathrm{CV}}{dt}\right) + I \qquad (12.12)$$

The sense switch has two possible positions, which are defined in the following table using two common terminologies.

Value of K_{sense}	Position	Position
+1	Direct-acting	Increase/increase
−1	Reverse-acting	Increase/decrease

This approach is not necessary, but it is used so widely that control engineers should be aware of the practice. We will continue to use controller gains of either sign in subsequent chapters unless otherwise specified.

EXAMPLE 12.2.

What is the correct sense switch position for the temperature feedback controller in Figure 12.2?

Note that the process gain and failure mode of the control valve must be known to determine the proper sense of the controller. In this example, the valve failure mode is fail-closed. Therefore, an increase in the controller output signal results in (1) the valve opening, (2) the fuel flow increasing, (3) the heat transferred increasing, and (4) the temperature increasing. The overall process loop gain is the product of all gains in the system, which must be positive to provide the desired (negative) feedback control.

$$\text{Sign(loop gain)} = \text{sign}(K_v)\,\text{sign}(K_p)\,\text{sign}(K_s) K_{\text{sense}} K_c = +1$$

The sensor gain is always positive, and when using the convention that the controller gain is positive, the loop gain can be simplified to

$$\text{Sign(loop gain)} = \text{sign}(K_v)\,\text{sign}(K_p)\,\overset{+1}{\cancel{\text{sign}(K_s)}} K_{\text{sense}} \overset{+1}{\cancel{K_c}} = +1$$

giving $$K_{\text{sense}} = \text{sign}(K_v)\,\text{sign}(K_p)$$

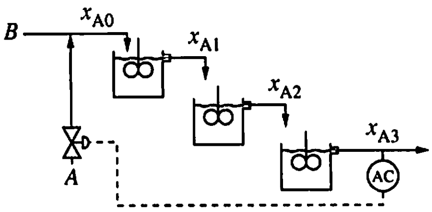
In this example, $K_{\text{sense}} = (+1)(+1) = +1$; thus, the sense is direct-acting.

Another convention in commercial control systems is the use of dimensionless controller gains. This is required for analog systems, which perform calculations in scaled voltages or pressures, and it is retained in most digital systems. The scaling in the calculation is performed according to the following equation:

$$\frac{\text{MV}}{\text{MV}_r} = (K_c)_s \left(\frac{E}{\text{CV}_r} + \frac{1}{T_I} \int_0^t \frac{E}{\text{CV}_r}\, dt' - T_d \frac{d\left(\dfrac{\text{CV}}{\text{CV}_r}\right)}{dt} \right) + I'' \tag{12.13}$$

with	$(K_c)_s$ = dimensionless (scaled) controller gain = $K_c(\text{CV}_r/\text{MV}_r)$
	MV_r = range of the manipulated variable [100% for a control valve]
	CV_r = range of the sensor measuring the controlled variable in engineering units

The range of values for the unscaled controller gain K_c is essentially unlimited, because the value can be altered by changing the units of the measurement. For example, a controller gain of 1.0 (weight%)/(% open) is the same as 1.0×10^6(ppm)/(% open). However, the scaled controller gain has a limited range of values, because properly designed sensors and final elements have ranges that give good accuracy. For example, a very small dimensionless controller gain indicates that the final control element would have to be moved very accurately for small changes to control the process. In this case, the final element should be changed to one with a smaller capacity. A general guideline is that the scaled controller gain should have



a value near 1.0. Scaled controller gains outside the range of 0.01 to 10 suggest that the range of the sensor or final element may have been improperly selected.

Some commercial controller algorithms include a slight modification in the proportional tuning constant term that does not influence the result of the controller calculation. The controller gain is replaced with the term 100/PB, with the symbol PB representing the *proportional band.*

> The proportional band is calculated as $PB = 100/(K_c)_s$. Proportional band is dimensionless.

The net PID controller calculation in equation (12.13) is unchanged because the controller gain is calculated as $(K_c)_s = 100/PB$. Thus, the use of gain or proportional band is arbitrary; either gives the same control loop performance. However, the engineer must know which convention is used in the controller and enter the appropriate value. Note that in fine-tuning, the controller is modified to be less aggressive by *decreasing* the controller gain or *increasing* the proportional band.

Integral Mode

Usually, the tuning constant associated with the integral mode is expressed in time units, minutes or seconds. Some commercial systems use a PID algorithm that calculates the same output as equation (12.13) but replaces the inverse of the integral time with an alternate parameter termed the *reset time.*

> The reset time is the inverse of the integral time, $T_R = 1/T_I$. The units for reset time are repeats per time unit, e.g., *repeats per minute.*

EXAMPLE 12.3.

For the three-tank mixing process, the concentration sensor has a range of 5%A, and the control valve is fail-closed. Determine the dimensionless controller gain, proportional band, controller sense, and reset time.

Recall that the process reaction curve identification and Ciancone tuning were applied to determine values for the controller gain in engineering units and the integral time, 30 (% opening/%A) and 11 minutes, respectively (see Example 9.2 for a refresher). Therefore, the dimensionless controller gain and proportional band are

$$(K_c)_s = K_c(\mathrm{CV}_r/\mathrm{MV}_r) = 30(\%\ \text{opening}/\%\text{A})(5\ \%\text{A})/(100\%\ \text{open}) = 1.5$$

$$\mathrm{PB} = 100/(K_c)_s = 100/1.5 = 66.6$$

The controller sense is determined by

$$K_{\text{sense}} = \text{sign}(K_v)\ \text{sign}(K_p) = \text{sign}\ (1)\text{sign}\ (0.039) = +1$$

Therefore, the controller sense is direct-acting. The reset time is the inverse of the integral time,

$$T_R = 1/T_I = 1/11 = 0.919\ \text{repeats per minute}$$

The integral mode is included in the PID controller to eliminate steady-state offset for steplike disturbances, which it does satisfactorily as long as it has the ability to adjust the final element. If the final element cannot be adjusted because it is fully open or fully closed, the control system cannot achieve zero offset. This situation is not a deficiency of the control algorithm; it represents a shortcoming of the process and control equipment. The condition arises because the equipment capacity is not sufficient to compensate for the disturbance, which is presumably larger than the disturbances anticipated during the plant design. The fundamental solution is to increase the equipment capacity.

However, when the final element (valve) reaches a limit, an additional difficulty is encountered that is related to the controller algorithm and must be addressed with a modification to the algorithm. When the valve cannot be adjusted, the error remains nonzero for long periods of time, and the standard PID control algorithm [e.g., equation (12.12) or (11.6)] continues to calculate values for the controller output. Since the error cannot be reduced to zero, the integral mode integrates the error, which is essentially constant, over a long period of time; the result is a controller output value with a very large magnitude. Since the final element can change only within a restricted range (e.g., 0 to 100% for a valve), these large magnitudes for the controller output are meaningless, because they do not affect the process, and should be prevented.

The situation just described is known as *reset* (integral) *windup*. Reset windup causes very poor control performance when, because of changes in plant operation, the controller is again able to adjust the final element and achieve zero offset. Suppose that reset windup has caused a very large positive value of the calculated controller output because a nonzero value of the error occurred for a long time. To reduce the integral term, the error must be negative for a very long time; thus, the controller maintains the final element at the limit for a long time simply to reduce the (improperly "wound-up") value of the integral mode.

The improper calculation can be prevented by many modifications to the standard PID algorithm that do not affect its good performance during normal circumstances. These modifications achieve *anti-reset windup*. The first modification explained here is termed *external feedback* and is offered in many commercial analog and digital algorithms. The external feedback PI controller is shown in Figure 12.14. The system behaves exactly like the standard algorithm when the limitation is not active, as is demonstrated by the following transfer function, which can be derived by block diagram manipulation based on Figure 12.14.

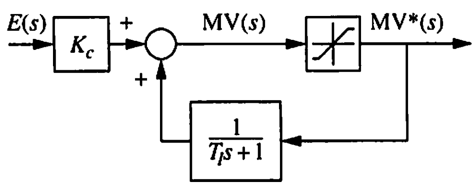


FIGURE 12.14

Block diagram of a PI control algorithm with external feedback.

$$\frac{MV^*(s)}{E(s)} = K_c\left(1 + \frac{1}{T_I s}\right) \qquad (12.14)$$

$$MV^*(s) = MV(s)$$

However, the system with external feedback behaves differently from the standard PI controller when a limitation is encountered. When a limitation is active in Figure 12.14, the following transfer function defines the behavior:

$$MV^*(s) = \text{constant}$$

$$MV(s) = K_c E(s) + \frac{MV^*(s)}{T_I s + 1} \qquad (12.15)$$

with $MV^*(s)$ being the upper or lower MV limit. In this case, the controller output approaches a finite, reasonable limiting value of $K_c E(s) + \text{MV}^*(s)$. Thus, external feedback is successful in providing anti-reset windup. These calculations can be implemented in either analog or digital systems.

The second, alternative anti-reset windup modification can be implemented in digital systems. Reset windup can be prevented by using the velocity form of the digital PID algorithm, which is repeated here.

$$\Delta \text{MV}_n = K_c \left[E_n - E_{n-1} + \frac{\Delta t E_n}{T_I} - \frac{T_d}{\Delta t}(\text{CV}_n - 2\text{CV}_{n-1} + \text{CV}_{n-2}) \right]$$
$$\text{MV}_n = \text{MV}_{n-1} + \Delta \text{MV}_n \tag{12.16}$$

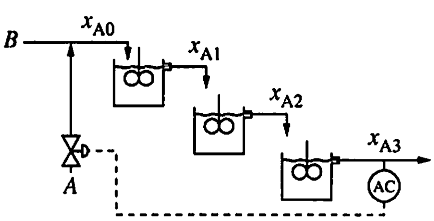
This algorithm does not accumulate the integral as long as the past value of the manipulated variable, MV_{n-1}, is evaluated *after* the potential limitation. When this convention is observed, any difference between the previously calculated MV and the MV actually implemented (final element) is not accumulated.

Many other methods are employed to prevent reset windup. The two methods described here are widely used and representative of the other methods. The key point of this discussion is that

> Anti-reset windup should be included in every control algorithm that has integral mode, because limitations are encountered, perhaps infrequently, by essentially all control strategies due to large changes in operating conditions.

Reset windup is relatively simple to recognize and correct for a single-loop controller outputting to a valve, but it takes on increasing importance in more complex control strategies such as cascade and variable-structure systems, which are covered later in this book. Also, the general issue of reset windup exists for any controller that provides zero offset when no limitations exist. For example, reset windup is addressed again when the predictive control algorithms are covered in Chapter 19.

EXAMPLE 12.4.



The three-tank mixing process in Examples 7.2 and 9.2 initially is operating in the normal range. At a time of about 20 minutes, it experiences a large increase in the inlet concentration that causes the control valve to close and thus reach a limit. After about 140 minutes, the inlet concentration returns to its original value. Determine the dynamic responses of the feedback control system with and without anti-reset windup.

The results of simulations are presented in Figure 12.15*a* and *b*. In Figure 12.15*a* the dynamic response of the system without anti-reset windup is shown. As usual, the set point, controlled variable, and manipulated variable are plotted. In addition, the calculated controller output is plotted for assistance in analysis, although this variable is not normally retained for display in a control system. After the initial disturbance, the valve position is quickly reduced to 0 percent open. Note that the calculated controller output continues to decrease, although it has no additional effect on the valve. During the time from 20 to 160 minutes, the controlled variable does not return to its set point because of the limitation in

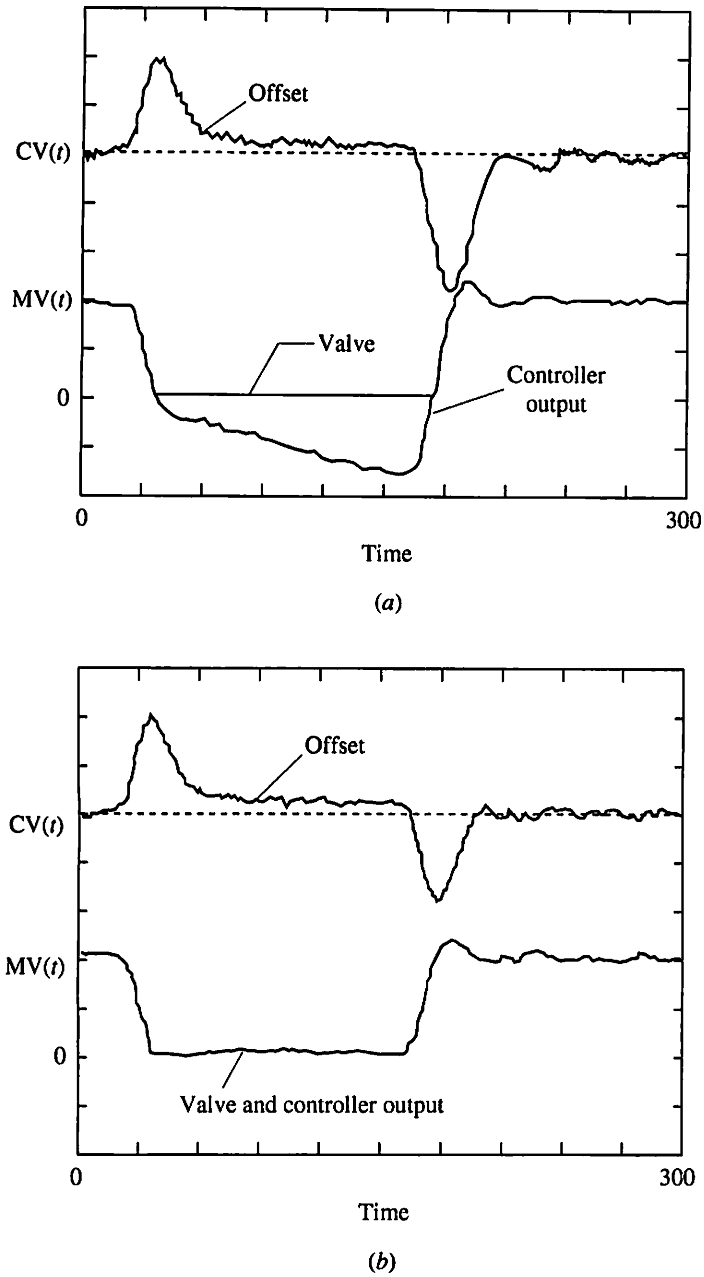


FIGURE 12.15

Dynamic response of the three-tank mixing system: (*a*) without anti-reset windup; (*b*) with anti-reset windup. Note that CV(t) = x_{A3} and MV(t) is the controller output.

the range of the manipulated variable. When the inlet concentration returns to its normal value, the outlet concentration initially falls below its set point. The controller detects this situation immediately, but it cannot adjust the valve until the calculated controller output increases to the value of zero. This delay, which would be longer had the initial disturbance been longer, is the cause of a rather large disturbance. Finally, the PI controller returns the controlled variable to its set point, since the manipulated variable is no longer limited.

The case with anti-reset windup is shown in Figure 12.15*b*. The initial part of the process response is the same. However, the calculated controller output does not fall below the value of 0 percent; in fact, it remains essentially equal to the true valve position. When the inlet concentration returns to its normal value, the controller output is at zero percent and can rapidly respond to the new operating conditions. The second disturbance is much smaller than in Figure 12.15*a*, showing the advantage of anti-reset windup.

Derivative Mode

An additional modification of the PID algorithm addresses the effect of noise on the derivative mode. It is clear that the derivative mode will amplify high-frequency noise present in the measured controlled variable. This effect can be reduced by decreasing the derivative time, perhaps to zero. Unfortunately, this step also reduces or eliminates the advantage of the derivative mode. A compromise is to filter the derivative mode by using the following equation:

$$\frac{T_d s}{\alpha_d T_d s + 1} \tag{12.17}$$

The result of this modification is to reduce the amplification of noise while retaining some of the good control performance possible with the derivative mode. As the factor α_d is increased from 0 to 1, the noise amplification is decreased, but the improvement in control performance due to the derivative mode decreases. This parameter has typical values of 0.1 to 0.2 and is not normally tuned by the engineer for each individual control loop. Since the PID control algorithm has been changed when equation (12.17) is used for the derivative mode, the controller tuning values must be changed, with the Ciancone correlations no longer being strictly applicable. Tuning correlations for the PID controller with $\alpha_d = 0.1$ are given by Fertik (1974).

Initialization

The PID controller requires special calculations for initialization. The specific initialization required depends upon the particular form of the PID control algorithm; typical initialization for the standard digital PID algorithm is as follows:

$$\Delta \mathrm{MV}_n = K_c\left[E_n - E_{n-1} + \frac{\Delta t\, E_n}{T_I} - \frac{T_d}{\Delta t}(\mathrm{CV}_n - 2\mathrm{CV}_{n-1} + \mathrm{CV}_{n-2})\right]$$

$$\mathrm{MV}_n = \mathrm{MV}_{n-1} + \Delta \mathrm{MV}_n$$

$$\mathrm{MV}_1 = \mathrm{MV}_0 \quad \text{that is, } \Delta\mathrm{MV}_1 = 0 \quad \text{for } n = 1 \quad \text{for initialization}$$

$$\begin{aligned} E_{n-1} &= E_n && \text{for } n = 1 \\ \mathrm{CV}_{n-2} = \mathrm{CV}_{n-1} &= \mathrm{CV}_n && \text{for } n = 1 \end{aligned} \tag{12.18}$$

This initialization strategy ensures that no large initial change in the manipulated variable will result from outdated past values of the error or controlled variables.

12.5 OUTPUT PROCESSING

The standard PID controller has no limits on output values, nor does it have special considerations when the algorithm is first used, as when the controller is switched from manual to automatic. As already described, the calculated controller output is initialized so that the actual valve position does not immediately change on account of the change in controller mode.

In addition to initialization, the PID algorithm can be modified to limit selected variables. The most common limitation is on the manipulated variable, as is done when certain ranges of the manipulated variable are not acceptable. Thus, the manipulated variable is maintained within a restricted range less than 0 to 100 percent.

$$\mathrm{MV}_{\min} < \mathrm{MV}(t) < \mathrm{MV}_{\max} \tag{12.19}$$

An example of limiting the manipulated variable is the damper (i.e., valve), position in the stack of a fired heater as shown in Figure 12.2. The stack damper is adjusted to control the pressure of the combustion chamber. Since the stack is the only means for the combustion product gases to leave the combustion chamber, it should not be entirely blocked by a closed valve. However, the control system could attempt to close the damper completely due to a faulty pressure measurement or poor controller tuning. In this case, it is common to limit the controller output to prevent a blockage in the range of 0 to 80 percent (not 20 to 100 percent, because the damper is fail-open, so that a signal of 100 percent would close the valve).

Sometimes the rate of change of the manipulated variable is limited using the following expression:

$$\Delta \mathrm{MV}_n = \min(|\Delta \mathrm{MV}|, \Delta \mathrm{MV}_{\max}) \left(\frac{\Delta \mathrm{MV}}{|\Delta \mathrm{MV}|} \right) \tag{12.20}$$

This modification is appropriate when a rapid adjustment of the manipulated variable can disturb the operation of a process.

12.6 CONCLUSIONS

Clearly, the simple, single PID equation, while performing well under limited conditions, is not sufficient to provide feedback control under the various conditions experienced in realistic plant operation. Some of the most important modifications have been presented in this chapter, and many more modifications are described in publications noted in the references and additional resources.

To complete this chapter, the flowchart for a PID controller that includes the modifications described in this chapter is given in Figure 12.16. The added complexity is apparent. However, the computations are readily packaged in preprogrammed algorithms and performed rapidly by powerful microprocessor-based instrumentation. A wise and productive engineer uses these programs and does not attempt to develop all real-time calculations from scratch, although doing limited algorithm programming is a useful learning exercise for the student.

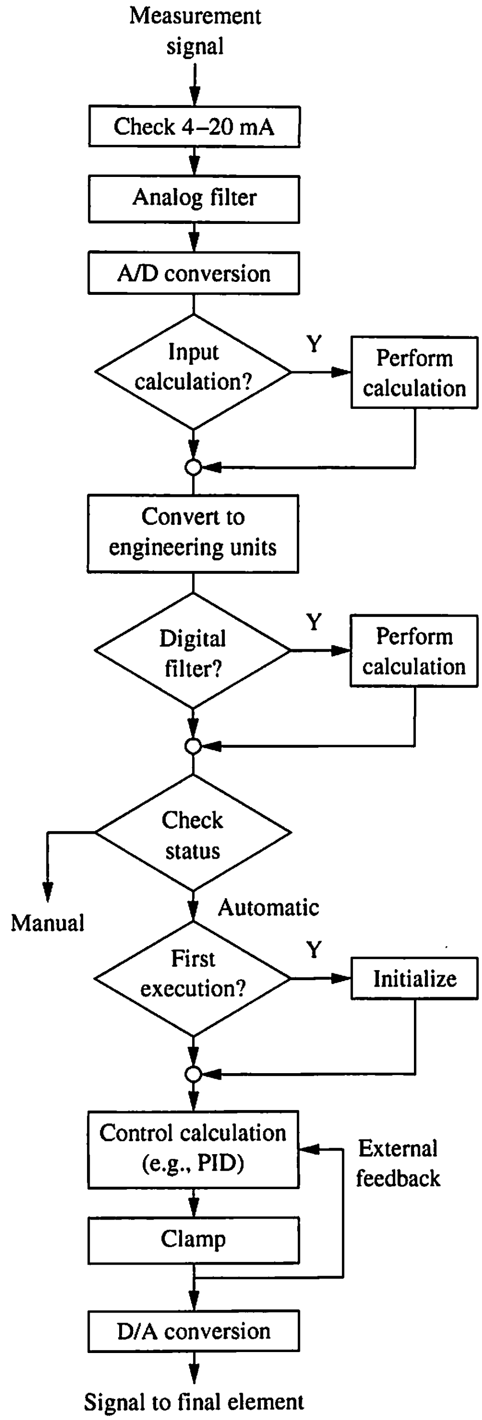


FIGURE 12.16

PID calculation flowchart.

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Fertik, H., "Tuning Controllers for Noisy Processes," *ISA Trans., 14, 4,* 292–304 (1974).

Goff, K.W., "Dynamics in Direct Digital Control, Part I," *ISA J., 13, 11,* 45–49 (November, 1966); "Part II," *ISA J., 13, 12,* 44–54 (December 1966).

ISA, *Process Instrumentation Terminology,* ISA-S51.1-1979, Instrument Society of America, Research Triangle Park, NC, 1979.

Mellichamp, D., *Real-Time Computing,* Van Nostrand, New York, 1983.

ADDITIONAL RESOURCES

There are many technical references available for determining the performance of sensors and final control elements, including the references in Chapter 1. Also, equipment manufacturers provide information on the performance of their equipment. The following references, along with the references for Chapter 18 on level control, provide additional information on key sensors.

DeCarlo, J., *Fundamentals of Flow Measurement,* Instrument Society of America, Research Triangle Park, NC, 1984.

Miller, R., *Flow Measurement Engineering Handbook,* McGraw-Hill, New York, 1983.

Pollock, D., *Thermocouples, Theory and Practice,* CRC Press, Ann Arbor, 1991.

The following references discuss many options for anti-reset windup.

Gallun, S., C. Matthews, C. Senyard, and B. Slater, "Windup Protection and Initialization for Advanced Digital Control," *Hydrocarbon Proc., 64,* 63–68 (1985).

Khandheria, J., and W. Luyben, "Experimental Evaluation of Digital Control Algorithms for Anti-reset-windup," *IEC Proc. Des. Devel., 15, 2,* 278–285 (1976).

Many calculations in commercial instrumentation use scaled variables, because they are performed in analog systems using voltages or pressures. For an introduction to scaling, see

Gordon, L., "Scaling Converts Process Signals to Instrument Ones," *Chem. Engr., 91,* 141–146 (June 25, 1984).

For an introduction to some of the causes of high-frequency noise and means of its prevention, see

Hazlewood, L., "Getting the Noise Out," *Chem. Engr., 95,* 105–108 (November 21, 1988).

For a very clear discussion of filtering, in addition to Goff (1966) noted above, see

Corripio, A., C. Smith, and P. Murrill, "Filter Design for Digital Control Loops," *Instr. Techn.,* 33–38 (January 1973).

For a concise description of many PID controller enhancements in analog and digital form, see

Clark, D., "PID Algorithms and Their Computer Implementation," *Trans. Inst. Meas. and Cont.*, *6*, *6*, 305–316 (1984).

QUESTIONS

12.1. Many filtering algorithms are possible. For each of the algorithms suggested below, describe its open-loop frequency response and sketch its Bode plot. Also, discuss its advantages and disadvantages as a filter in a closed-loop feedback control system.

(*a*) $\dfrac{1}{\tau^2 s^2 + 0.4\tau s + 1}$

(*b*) $\dfrac{1}{(\tau s + 1)^n}$ with n = positive integer

(*c*) Averaging filter with m values in average

$$(\mathrm{CV}_f)_n = \frac{\mathrm{CV}_n + \mathrm{CV}_{n-1} + \cdots + \mathrm{CV}_{n-m+1}}{m}$$

(*d*) $\dfrac{0.707}{\tau_f s + 1}$

12.2. Answer the questions in Table Q12.2 for each PID controller mode or tuning constant associated with each mode. Explain every entry completely, giving theoretical justification as well as the brief answer indicated. Answer this question on the basis of a commercial control system in which all control calculations are performed in scaled variables.

12.3. You have been given three control systems to analyze. Each has the *dimensionless* controller gain given below. From this information alone, what can you determine about each control system? $(K_c)_s$ = (*a*) 0.02, (*b*) 0.75, and (*c*) 123.00.

12.4. The control systems with the processes given below are to be tuned (1) without a filter and with a first-order filter with (2) $\tau_f = 0.5$ min and (3) $\tau_f = 3.0$ min. Determine the PI tuning constants for all three cases using the Bode stability analysis and Ziegler-Nichols correlations. Also, state whether you expect the control performance, as measured by IAE, to be better or worse with the filter (after retuning). Why?

(*a*) The empirical model derived in question 6.1 for the fired heater.

(*b*) The empirical model for the packed-bed reactor in Figure 6.3 from the data in Figure Q6.4*c*.

(*c*) The linearized, analytical model for the stirred-tank heater in Example 8.5.

12.5. For the process in Figure 2.2, answer the following questions.

(*a*) Determine the proper failure modes for all valves. Also, give the proper controller sense for each controller, assuming that commercial controllers are being used ($K_c > 0$).

TABLE Q12.2

	P	I	D
(*a*) Which modes eliminate offset?			
(*b*) Describe the speed of response for an upset (fastest, middle, slowest).			
(*c*) Compare the propagation of high-frequency noise from controlled to manipulated variable (most, middle, least).			
(*d*) As process dead time increases (with $\theta + \tau$ constant), the tuning constant (increases, decreases, unchanged)?			
(*e*) Does the mode cause windup (Y, N)?			
(*f*) Should tuning constant be changed when filter is added to loop (Y, N)?			
(*g*) Is tuning constant affected by limits on the manipulated variable (Y, N)?			
(*h*) Should tuning constant be altered if the sensor range is changed (Y, N)?			
(*i*) Does tuning constant depend on the failure mode of the final element (Y, N)?			
(*j*) Does tuning constant depend on the linearization performed in the input processing (Y, N)?			
(*k*) Should tuning constant be altered if the final element capacity is changed (Y, N)?			
(*l*) Should tuning constant be changed if the digital controller execution period is changed (Y, N)?			

(*b*) What type of input processing would be appropriate for each measurement? Why?

(*c*) The following alterations are made after the process has been operating successfully. Determine any other changes that must be made as a consequence of each alteration. Your answers should be as specific and quantitative as possible. (1) The control valve for a steam heat exchanger is increased to accommodate a flow 50 percent greater than the original. (2) The failure mode of the control valve in the liquid product stream changed from fail-open to fail-closed. (3) The range of the temperature sensor is changed from 50–100°C to 75–125°C.

12.6. Answer questions 12.5 (*a*) and (*b*) for the CSTR in Figure 2.14.

12.7. Answer questions 12.5 (*a*) and (*b*) for the boiler oxygen control in Figure 2.6.

12.8. In the discussion on external feedback, equations (12.14) and (12.15) were given to prove that reset windup would not occur.

(*a*) Derive these equations based on the block diagram and explain why reset windup does not occur.

(*b*) Prepare the equations in their proper sequence for the digital implementation of external feedback.

12.9. An alternative anti-reset windup method is to use logic to prevent "inappropriate" integral action. This logic is based on the status of the manipulated variable. Develop a flowchart or logic table for this type of anti-reset windup and explain how it would work.

12.10. The goal of initializing the PID controller is to prevent a "bump" when the mode is changed and to prepare the controller for future calculations. Determine the proper initialization for the full-position digital PID controller algorithm in equation (11.6) and explain each step.

12.11. A process uses infrequent laboratory analyses for control. The period of the analyses is much longer than the dynamics of the process. Due to the lack of accuracy in the laboratory method, the reported value has a relatively large standard deviation, resulting in noise in the feedback loop. Describe steps you would take to reduce this noise by a factor of 2. (For the purposes of this problem, you may not change the frequency for collecting one or a group of samples from the process.)

12.12. A signal to a digital controller has considerable high-frequency noise in spite of the analog filter before the A/D converter. The controller is being executed according to the rule that $\Delta t/(\theta + \tau) = 0.05$, and the manipulated variable has too large a standard deviation. Explain what steps you would take in the digital PID control system to reduce the effects of noise on the manipulated variable and yet to have minimal effect on the control performance as measured by IAE of the controlled variable.

12.13. Answer the following questions regarding filtering.

(*a*) Confirm the transfer function in equation (12.5).

(*b*) The equation for the digital first-order filter is presented in equation (12.9). Confirm this equation by deriving it from equation (12.8).

(*c*) Discuss the behavior of a low-pass filter and give examples of its use in process control.

(*d*) A *high-pass* filter attenuates the low-frequency components. Describe an algorithm for a high-pass filter and give examples of its use.

12.14. Consider an idealized case in which process data consists of a constant true signal plus purely random (white) noise with a mean of 0 and a standard deviation of 0.30.

(*a*) Determine the value of the parameter A in the digital filter equation (12.9) that reduces the standard deviation of the filtered value to 0.1. You might have to build a simulation in a spreadsheet with several hundred executions and try several values of A.

(*b*) Determine the number of duplicate samples of the variable to be taken every execution so that the average of these values will have a standard deviation of 0.10.

12.15. Consider the situation in which the measured controlled variable consisted of nearly all noise, with very infrequent changes in the true process variable due to slowly varying disturbances. Suggest a feedback control approach, not a PID algorithm, that would reduce unnecessary adjustments of the manipulated variable.

12.16. Many changes have been proposed to the standard digital PID controller, and we have considered several, such as the derivative on measured variable rather than error. For each of the following proposed modifications in the PID algorithm, suggest a reason for the modification (that is, what possible benefit it would offer and under what circumstances) and any disadvantages.

(*a*) The proportional mode is calculated using the measured variables rather than the error.

$$\mathrm{MV}_n = K_c \left[\mathrm{CV}_n + \frac{\Delta t}{T_I} \sum_{i=0}^{n} (\mathrm{SP}_i - \mathrm{CV}_i) - \frac{T_d}{\Delta t} (\mathrm{CV}_n - \mathrm{CV}_{n-1}) \right] + I$$

(*b*) The controller gain is nonlinear; for example,

$$\text{For} \quad (\mathrm{SP}_n - \mathrm{CV}_n) > 0 \qquad K_c = K'$$
$$\text{For} \quad (\mathrm{SP}_n - \mathrm{CV}_n) < 0 \qquad K_c = K' + K'' \,|\mathrm{SP}_n - \mathrm{CV}_n|$$

(*c*) The rate of change of the manipulated variable is limited, $|\Delta \mathrm{MV}| <$ max.

(*d*) The allowable set point is limited, $\mathrm{SP}_{\min} < \mathrm{SP} < \mathrm{SP}_{\max}$.