2.9 Feedback and Feedforward Control

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Feedback control is the action of moving a manipulated variable m in response to a deviation or error e between the controlled variable c and its set point r in such a way as to reduce, or if possible, to eliminate the error. Feedback control cannot anticipate and thereby prevent errors, because it can only initiate its corrective action *after* an error has already developed. Because of dynamic lags and delays in the response of the controlled variable to manipulation, some time will elapse before the correction will take effect. During this interval, the deviation will tend to grow, before eventually diminishing. Feedback control cannot therefore achieve perfect results; its effectiveness is limited by the responsiveness of the process to manipulation. By contrast, feedforward correction can be initiated as soon as any change is detected in a load variable as it enters the process; if the feedforward model is accurate and the load dynamics are favorable, the upset caused by the load change is canceled before it affects the controlled variable. Because feedforward models and sensors are both imperfect, feedforward loops are usually corrected by feedback trimming.

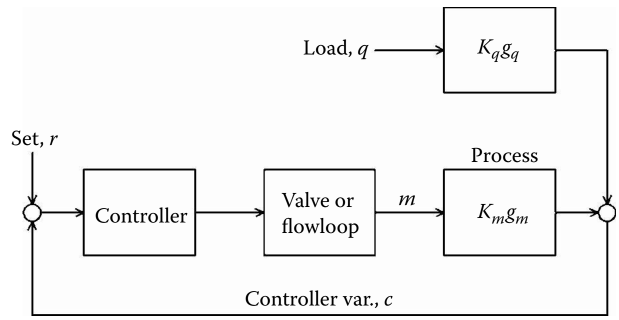

FIG. 2.9a
Load changes can enter through different gain and dynamics from the controller output.

FEEDBACK CONTROL

The purpose of any process control system is to maintain the controlled variable at a desired value, the set point, in the face of disturbances. The control system regulates the process by balancing the variable load(s) with equivalent changes in one or more manipulated variables. For the controlled variable to remain stationary, the controlled process must be in a balanced state.

Regulation through feedback control is achieved by acting on the change in the controlled variable that was induced by a change in load. Deviations in the controlled variable are converted into changes in the manipulated variable and sent back to the process to restore the balance. Figure 2.9a shows the backward flow of information from the output of the process back to its manipulated input. The load q is a flow of mass or energy entering or leaving a process, which must be balanced by an equal flow leaving or entering. It may have more than one component—for example in a temperature loop, both the flow and temperature of a stream are components of its energy demand, but they may be balanced by a single manipulated variable such as steam flow. The steady-state gain K and dynamic gain vector $\mathbf{g}$ in the paths of the manipulated and load variables may differ, and therefore have been given different subscripts m and q.

Limitations of Feedback Control

Feedback, by its nature, is incapable of correcting a deviation in the controlled variable at the time of detection. In any process, a finite delay exists between a changing of the manipulated variable and the effect of the change on the controlled variable. Perfect control is not even theoretically attainable because a deviation in the controlled variable must appear before any corrective action can begin. In addition, the value of the manipulated variable needed to balance the load must be sought by trial and error, with the feedback controller observing the effect of its output on the controlled variable.

Best-Possible Feedback Control

An absolute limitation to the performance of a feedback control loop is imposed by any deadtime in the loop. Figure 2.9b describes the results of a step-load change applied to a process whose dynamics consist of deadtime and a single lag in both the load path $\mathbf{g}_q$ and the manipulated-variable path $\mathbf{g}_m$. The time scale is given in units of deadtime τ_d in the path of the manipulated variable. To simplify the illustration, the deadtimes in both paths are identical (this is not essential—*any*

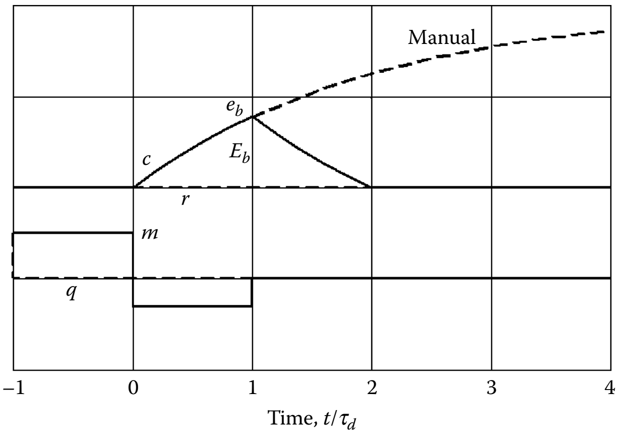

FIG. 2.9b
The best-possible load response for a process having deadtime and a single lag.

deadtime in the load path, or none, will produce the same response, simply shifting its location in time). Also for simplification, the steady-state gains in both paths are made equal.

At time −1, a step decrease in load q enters the process. After the deadtime in the load path expires, at time zero, the controlled variable c responds, beginning to rise along an exponential curve determined by the gain and lag in the load path. If the controller were left in Manual, it would continue to a new steady state. In this example, K_q is 2.0, leaving the final value of c in Manual having changed twice as much as load q; the time constant τ_q of the load lag in this example is $2.0\tau_d$.

Also shown is the possible return trajectory of c to set point r if the manipulated variable m were to step as soon as any deviation is detected, i.e., at time zero, by an amount

$$\Delta m = \Delta q(K_q/K_m)(1+\varepsilon^{-\tau_d/\tau_q}) \qquad \textbf{2.9(1)}$$

where ε is the exponential operator 2.718. This move turns out to be the best that is possible by a feedback controller,[1] as it causes the deviation to decay to zero during the next deadtime. The peak deviation reached during this excursion is

$$e_b = \Delta q K_q(1-\varepsilon^{-\tau_d/\tau_q}) \qquad \textbf{2.9(2)}$$

At the time the peak is reached, the controller output must be stepped to match the new steady-state load.

The leading edge of the curve, i.e., up to time 1.0, is determined completely by the load step and the gain and dynamics in its path; the trailing edge is determined by the controller and its tuning. The leading and trailing edges of the best response are complementary, so that the area that they enclose is

$$E_b = e_b\tau_d = \Delta q K_q \tau_d(1-\varepsilon^{-\tau_d/\tau_q}) \qquad \textbf{2.9(3)}$$

These values of e_b and E_b are the *best* that can be obtained for any feedback controller on a process whose dynamics consist of deadtime and a single lag. A real controller will yield a somewhat larger peak deviation and an area at least twice as great, depending on its modes and their tuning. If the process contains two or more lags, the value of E_b remains the same as estimated above but is more difficult to approach with a real controller.

Integrated Error

The actual effectiveness of feedback control depends on the dynamic gain of the controller, which is a function of its control modes and their tuning. Although a high controller gain is desirable, the dynamic gain of the closed loop at its period of oscillation must be less than unity if the loop is to remain stable. In effect, then, the dynamic gain of the process dictates the allowable dynamic gain of the controller.

For each process and controller, optimum settings exist that minimize some objective function such as Integrated Absolute Error (IAE). However, most controllers are not tuned optimally, for various reasons, such as process nonlinearities. Therefore, controller performance needs to be stated in terms of the actual settings being used. As an example, the integrated error produced by a load change to a process under ideal Proportional-Integral-Derivative (PID) control will be evaluated based only on its mode settings. The controller output m_1 at time t_1 is related to the deviation e_1 between the controlled variable and its set point by

$$m_1 = \frac{100}{P}\left(e_1 + \frac{1}{I}\int_{t_0}^{t_1} e\,dt + D\frac{de_1}{dt}\right) + C \qquad \textbf{2.9(4)}$$

where P, I, and D are the percent Proportional Band, Integral time and Derivative time, respectively, and C is the output of the controller at time, t_0 when it was first placed in Automatic. Let t_1 be a steady state, so that $e_1 = 0$ and its derivative is also zero.

Then a load change arises, causing the controller to change its output to return the deviation to zero. When a new steady state is reached, the controller will have an output m_2:

$$m_2 = \frac{100}{P}\left(e_2 + \frac{1}{I}\int_{t_0}^{t_2} e\,dt + D\frac{de_2}{dt}\right) + C \qquad \textbf{2.9(5)}$$

where e_2 and its derivative are again zero.

The difference in output values between the two steady states is

$$\Delta m = m_2 - m_1 = \frac{100}{PI}\int_{t_1}^{t_2} e\,dt \qquad \textbf{2.9(6)}$$

Solving for the integrated error:

$$E = \int_{t_1}^{t_2} e\,dt = \Delta m\frac{PI}{100} \qquad \textbf{2.9(7)}$$

For any sustained load change, there must be a corresponding change in the controller output, and in fact the current load is often reported as the steady-state controller output. The wider the proportional band and the longer the integral time, the greater will be the integrated error per unit load change. (While the derivative setting does not appear in the integrated-error function, its use allows a lower integral time than is optimum for a PI controller.) Therefore, loops with controllers having large PI products are candidates for feedforward control.

FEEDFORWARD CONTROL

Feedforward provides a more direct solution to the control problem than finding the correct value of the manipulated variable by trial and error, as occurs in feedback control. In the feedforward system, the major components of load are entered into a model to calculate the value of the manipulated variable required to maintain control at the set point. Figure 2.9c shows how information flows forward from the load to the manipulated variable input of the process. The set point is used to give the system a command. (If the controlled variable were used in the calculation instead of the set point, a positive feedback loop would be formed.)

A system, rather than a single control device, is normally used for feedforward loops because it is not always convenient to provide the computing functions required by the forward loop with a single device or function. Instead, the feedforward system consists of several devices if implemented in hardware or several blocks of software if implemented digitally. The function of these blocks is to implement a mathematical model of the process.

Load Balancing

A dynamic balance is required to keep the control variable at set point. It is achieved by solving the process material- and/or energy-balance equations continuously. When a change in load is sensed, the manipulated variable is automatically adjusted to the correct value at a rate that keeps the process continually in balance. Although it is theoretically possible to achieve such perfect control, in practice the system cannot be made to duplicate the process balance exactly.

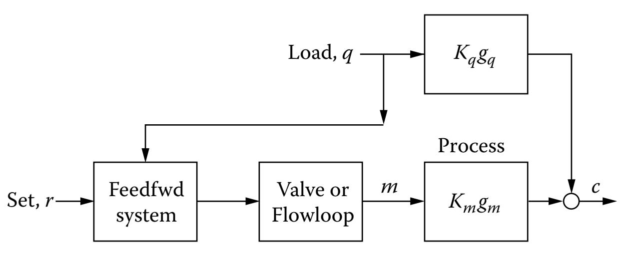

FIG. 2.9c
Feedforward calculates the value of the manipulated variable based on current load and set point.

The material- and energy-balance equations are not usually difficult to write for a given process. Variations in nonstationary parameters such as heat-transfer and mass-transfer coefficients do not ordinarily affect the performance of a feedforward system. The load components are usually inflow or outflow when level or pressure is to be controlled, feed flow and feed composition where product composition is to be controlled, and feed flow and temperature where product temperature is to be controlled. Flow is the primary component of load in almost every application because it can change widely and rapidly. Composition and temperature are less likely to exhibit such wide excursions, and their rate of change is usually limited by upstream capacity. In most feedforward systems these secondary load components are left out; their effects are accommodated by the feedback controller.

The output of a feedforward system should be an accurately controlled flow rate, if possible. This controlled flow rate cannot usually be obtained by manipulating the control valve directly, since valve characteristics are nonlinear and inconsistent, and the delivered flow is subject to such external influences as upstream and downstream pressure variations. Therefore, most feedforward systems depend on some measurement and feedback control of flow to obtain an accurate manipulation of the flow rate. Only when the range of the manipulated variable exceeds that which is available in flowmeters, or the required speed of response exceeds that of a flow loop, should one consider having the valves positioned directly, and in such cases care must be taken to obtain a reproducible response.

Steady-State Model

The first step in designing a feedforward control system is to form a steady-state mathematical model of the process. The model equations are solved for the manipulated variable, which is to be the output of the system. Then the set point is substituted for the controlled variable in the model.

This process will be demonstrated by using the example of temperature control in a heat exchanger (Figure 2.9d).[2] A liquid flowing at rate W is to be heated from temperature T_1 to controlled temperature T_2 by steam flowing at rate W_s. The energy balance, excluding any losses, is

$$WC_p(T_2 - T_1) = W_s\lambda \qquad \textbf{2.9(8)}$$

Coefficient C_p is the heat capacity of the liquid and λ is the latent heat given up by the steam in condensing. Solving for W_s yields

$$W_s = WK(T_{2\text{set}} - T_1) \qquad \textbf{2.9(9)}$$

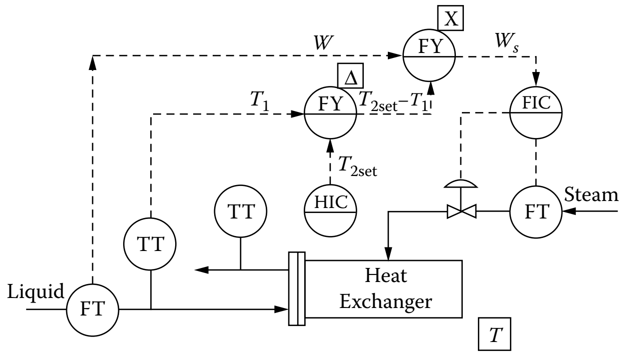

FIG. 2.9d
Steam flow is calculated here to satisfy the steady-state heat balance.

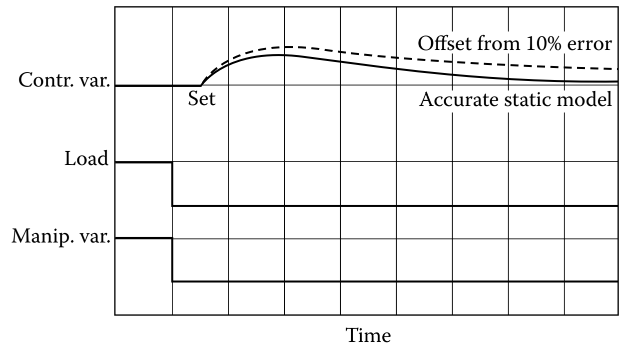

FIG. 2.9e
The dynamic response of the uncompensated feedforward system when the controlled variable responds faster to changes in load than to changes in manipulated flow.

where $K = C_p/\lambda$, set point T_{2set} replaces T_2, and W and T_1 are load components to which the control system must respond.

Note that this energy balance is imperfect, because it disregards minor loads such as the heat losses to the environment and any variations in the enthalpy of the steam. Another factor is that even the two major loads cannot be measured perfectly, as there are no error-free sensors of flow and temperature. The net result is a model that is approximately an energy balance around this process.

An implementation of Equation 2.9(9) is given in Figure 2.9d. A control station introduces T_{2set} into the difference block [Δ] where input T_1 is subtracted. The gain of this block is adjusted to provide the constant K. Its output is then multiplied by the liquid flow signal W to produce the required set point for steam flow.

During startup, if the actual value of the controlled variable does not equal the set point, an adjustment is made to gain K. Then, after making this adjustment, if the controlled variable does not return to the set point following a change in load, the presence of an error in the system is indicated. The error may be in one of the calculations, a sensor, or some other factor affecting the heat balance that was not included in the system. Heat losses and variations in steam pressure are two possible sources of error in the model. Since any error can cause a proportional offset, the designer must weigh the various sources of error and compensate for the largest or most changeable components where practical. For example, if steam pressure variations were a source of error, the steam flowmeter could be pressure compensated. Because of all these errors, feedforward control as shown in Figure 2.9d is seldom used without feedback trim. Later in this section, a feedback controller will be added to automatically correct the loop for the errors in the model.

Dynamic Model

With the feedforward model as implemented in Figure 2.9d, a step decrease in liquid flow results in a simultaneous and proportional step decrease in steam flow. Transient errors following a change in load are to be expected in feedforward control systems. Two typical dynamic responses of the controlled variable are shown in Figure 2.9e; the offset in the dashed curve results from a 10% error in the static calculations.

If there is no static error, the temperature returns to set point eventually. However, the dynamic balance is missing. The decreased steam flow does not result in an instantaneous decrease in heat-transfer rate, because the temperature difference across the heat-transfer surface must first be decreased, and this requires a decrease in shell pressure. The lower shell pressure at lower loads means that the shell contains less steam as the load decreases. Since the static feedforward system does not overtly lower the steam inventory in the shell, it is lowered through a lagging heat-transfer rate, resulting in a transient rise in exit temperature on a falling load; conversely, a transient temperature drop follows a rising load. This transient error reveals a dynamic imbalance in the system—on a drop in load, the exchanger temporarily needs less heat than the steam flow controller is allowing. In order to correct the transient temperature error, a further cutback in the flow of energy must be applied to the exchanger beyond what is required for the steady-state balance.

A more general explanation is provided through the use of Figure 2.9f. This figure shows the load and the manipulated

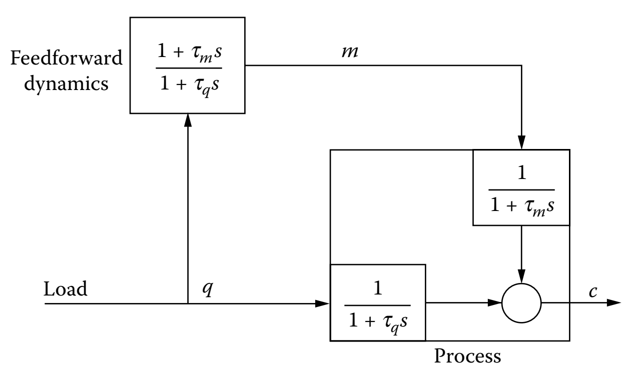

FIG. 2.9f
A feedforward dynamic model for a general process.

variable as entering the process at different points, where they encounter different dynamic elements. In the heat-exchanger example, the liquid enters the tubes while the steam enters the shell. The heat capacities of the two locations are different. As a result, the controlled variable (the liquid temperature) responds more rapidly to a change in liquid flow than to a change in steam flow. Thus, the lag time of the load input is less than that of the manipulated variable.

The objective of the feedforward system is to balance the manipulated variable against the load, providing the forward loop with compensating dynamic elements. Neglecting steady-state considerations, Figure 2.9f shows what the dynamic model must contain to balance a process having parallel first-order lags. The lag time τ_q of the load input must be duplicated in the forward loop, and the lag time τ_m in the manipulated input of the process must be cancelled. Thus the forward loop should contain a lag divided by a lag. Since the inverse of a lag is a lead, the dynamic compensating function is a *lead-lag*. The lead time constant should be equal to τ_m, and the lag time constant should equal τ_q. In the case of the heat exchanger, the fact that τ_m is longer than τ_q causes the temperature rise on a load decrease. This is the direction in which the load change would drive the process in the absence of control.

In transfer function form, the response of a lead-lag unit is

$$G(s) = \frac{1+\tau_1 s}{1+\tau_2 s} \qquad \textbf{2.9(10)}$$

where τ_1 is the lead time constant, τ_2 is the lag time constant, and s is the Laplace operator.

The frequency response of a feedforward loop is usually not significant, since forward loops cannot oscillate. The most severe test for a forward loop is a step change in load. The response of the lead-lag unit output y to a step in its input x is

$$y(t) = x(t)\left(1+\frac{\tau_1-\tau_2}{\tau_2}\varepsilon^{-t/\tau_2}\right) \qquad \textbf{2.9(11)}$$

Its maximum dynamic gain (at $t = 0$) is the lead/lag ratio τ_1/τ_2. The response curve then decays exponentially from this maximum at the rate of the lag time constant τ_2, with 63.2% recovery reached at $t = \tau_2$ as shown in Figure 2.9g. The figure shows some deadtime compensation added to the lead-lag function—however, it is not required for the heat exchanger.

When properly adjusted, the dynamic compensation afforded by the lead-lag unit can produce the controlled variable response having the form shown in Figure 2.9h. This is a signature curve of a feedforward-controlled process — since most processes do not consist of simple first-order lags, a first-order lead-lag unit cannot produce a perfect dynamic balance. Yet a major reduction in peak deviation is achieved over the uncompensated response, and the area can be equally distributed on both sides of the set point.

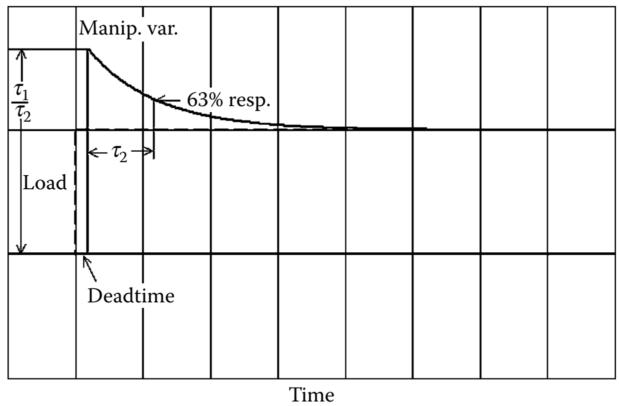

FIG. 2.9g
The step response of a lead-lag unit with deadtime compensation.

The lead-lag unit is applied to the flow signal as $[f(t)]$ in Figure 2.9i. Its settings are particular to that load input, and therefore it must be placed where it can modify that signal and no other. No dynamic compensator is included for T_1, as it is not expected to change quickly.

Tuning the Lead-Lag Unit First, a load change should be introduced without dynamic compensation by setting the lead and lag time constants at equal values or zero to observe the direction of the error. If the resulting response is in the direction that the load would drive it, the lead time should exceed the lag time; if not, the lag time should be greater. Next, measure the time required for the controlled variable to reach its maximum or minimum value. This time should be introduced into the lead-lag unit as the smaller time constant. Thus, if the lead dominates, this would be the lag setting. For example, in Figure 2.9e the temperature responds in the direction the load would drive it, and therefore the lead time setting should exceed the lag time setting. The time required for the temperature in Figure 2.9e to rise to its peak should be set equal to the smaller time constant, in this case equal to the lag time setting. Set the greater time constant at twice

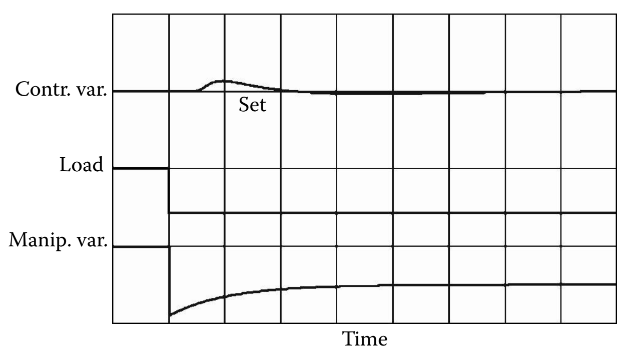

FIG. 2.9h
The typical step response of a dynamically compensated feedforward system.

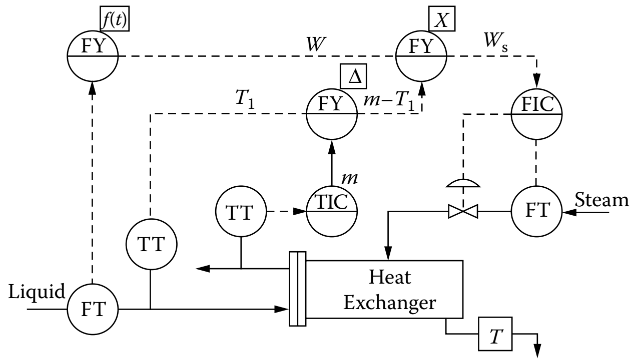

FIG. 2.9i
Feedforward–feedback control of the heat exchanger, with dynamic compensation.

this value and repeat the load change. If the peak deviation is reduced, but the curve is still not equally distributed around the set point, increase the greater time constant and repeat the load change.

The area (integrated error) of the response curve will be equally distributed about the set point if the difference between the lead and lag settings is correct. Once this equalization is obtained, both settings should be increased or decreased with their difference constant until a minimum error amplitude is achieved. When the controller is properly tuned, the steam energy equivalent of the transient (area between temperature and its set point) in Figure 2.9e should match the extra steam introduced (area above input step change) in Figure 2.9g.

If there is a significantly greater deadtime in the load path than in the manipulated-variable path, deadtime compensation may be added, which will reduce the peak deviation. However, if the deadtime in the manipulated-variable path is the longer of the two, exact compensation is impossible, and this is the case in the heat exchanger. Still, careful adjustment of the lead-lag compensator can result in zero integrated error.

Adding a Feedback Loop

Any offset resulting from steady-state errors can be eliminated by adding feedback. This can be done by replacing the feedforward set point with a controller, as shown in Figure 2.9i. The feedback controller adjusts the set point of the feedforward system in cascade, while the feedforward system adjusts the set point of the manipulated flow controller in cascade.

The feedback controller should have the same control modes as it would without feedforward control, but the settings need not be as tight. The feedback controller reacts to a disturbance by creating another disturbance in the opposite direction one-half cycle later. However, the feedforward system positions the manipulated variable so that the error in the controlled variable disappears. If acted upon by a tightly set feedback controller, the correct position calculated by feedforward will be altered, producing another disturbance that prolongs the settling time of the system.

The feedback controller must have the integral mode to eliminate any steady-state offset that might be caused by errors in the sensors, the model, or the calculations. However, the integrated error it sustains following a load change is markedly reduced compared to what it would be following a load change without feedforward. Now its output changes only an amount equal to the change in the *error* in the feedforward calculation. For small load changes, this change in error would approach zero, leading to an integrated error of zero, with or without dynamic compensation. In the presence of feedback, but without dynamic compensation, the transient in Figure 2.9e would be balanced by a following transient on the other side of set point, until the area is equalized. This usually prolongs the response without reducing the peak deviation. The dynamic compensator therefore needs to be tuned with the feedback controller in manual, to approach zero integrated error before adding feedback.

Linear and Bilinear Feedforward Systems

The relationship shown in the energy balance of Equation 2.9(8) is *bilinear*: steam flow is related to both liquid flow and to temperature rise in a linear manner, but as their product rather than their sum or difference. This distinction is crucial to the successful functioning of feedforward control because a bilinear system has variable gains. The feedforward gain—the ratio of steam flow to liquid flow—varies directly with the required temperature rise. This variable gain is accommodated in the system by the multiplier [×].

If inlet temperature were to vary so slowly that it did not require feedforward compensation or if it were not measured, then feedforward from flow alone would be required. Yet the required feedforward gain—the ratio W_s/W—would vary directly with $T_{2set} - T_1$. If either T_{2set} or T_1 were to change, the feedforward gain should change with it. For a bilinear process, then, a linear feedforward system having a constant gain is a misfit—it is accurate at only one combination of secondary load and set point. To be sure, feedback control can trim any errors in the feedforward calculation and return the deviation to zero. But if the error is in the gain term, the feedback controller should adjust the feedforward gain, through a multiplier—otherwise the gain will be incorrect for all subsequent flow changes, resulting in only partial feedforward correction or even overcorrection.

Eliminating inlet temperature as a variable in Figure 2.9i also eliminates the difference block [Δ]. The controller output m then goes directly to the multiplier, and in reducing the temperature deviation to zero, m will assume a value representing $K(T_{2set} - T_1)$. If either T_{2set} or T_1 were then to vary, the feedback controller would respond to the resulting deviation by changing its output until the deviation returns to zero. In so doing, it has changed the gain of the multiplier to the new value of $K(T_{2set} - T_1)$.

Control of composition is also a bilinear process. The required ratio of two flows entering a blender, for example, is a function of their individual compositions and that of the blend. Similarly, the ratio of product flow to feed rate or steam flow to feed rate in a distillation column or evaporator also varies with feed and product compositions. In general, temperature and composition loops are bilinear, and their flow ratios should always be adjusted through a multiplier. By contrast, pressure and level loops are linear, and their feedforward gain can be constant. An example of the latter is three-element drum-level control, where each unit of steam removed from the drum must be replaced by an equal unit of feedwater—the feedforward gain is constant at 1.0.

This distinction is crucial because many "advanced" multivariable control systems are based on a linear matrix with constant coefficients. The plant is tested to develop the coefficients that relate the variables, and the control matrix is built from these results. When the plant operating conditions move away from the original test conditions, the fixed coefficients in the control matrix may no longer represent the process relationships accurately, degrading the performance of the feedforward loops. This may require frequent retesting and recalibration of the matrix. Some multivariable systems contain multiple matrices, each corresponding to its own set of operating conditions and switched into service when those conditions develop.

Self-tuning feedforward control[3] is also available, applied either in a linear (additive) or bilinear (multiplicative) manner, as configured manually. The parameters that are tuned adaptively are the steady-state gain and a lag compensator. The steady-state gain is adjusted to minimize integrated error following a change in measured load, and the lag is adjusted to minimize integral-square error. Load changes must be sharp, clean steps, with settling time allowed between them, for tuning to proceed effectively. But once tuned, random disturbances can be accommodated. However, self-tuning is only recommended where precise modeling and flow control are unavailable.

Performance

The use of feedback in a feedforward system does not detract from the performance improvement that was gained by feedforward control. Without feedforward, the feedback controller was required to change its output to follow all changes in load. With feedforward, the feedback controller must only change its output by an amount equal to what the feedforward system fails to correct. If a feedforward system applied to a heat exchanger could control the steam flow to within 2% of that required by the load, the feedback controller would only be required to adjust its output to compensate for 2% of a load change, rather than the full amount. This reduction of Δm in Equation 2.9(7) by 50/1 results in the reduction of E by the same ratio. Reductions by 10/1 in errors resulting from load changes are relatively common, and improvements of 100/1 have been achieved in some systems.

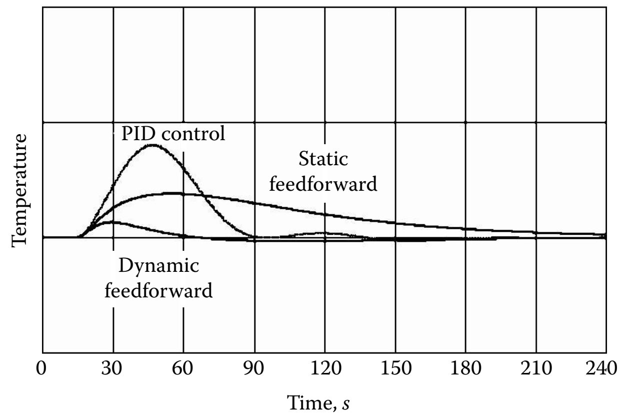

FIG. 2.9j
Comparison of feedforward control of a heat exchanger against optimally tuned PID feedback control.

Figure 2.9j illustrates the control performance of a steam-heated exchanger that has experienced a step decrease in process flow. The static feedforward model reduces the peak deviation substantially but extends settling time and does not improve on the integrated error. Dynamic compensation is seen to be essential in maximizing performance in this example. It is not perfect because the deadtime in the path of the manipulated variable is somewhat longer than that in the load path, and that lost time cannot be made up. Still, the lead-lag compensator has been tuned to eliminate any integrated error.

The feedforward system is more costly and requires more engineering effort than a feedback system does, so prior to design and installation, the control improvement it brings must be determined to be worthwhile. Most feedforward systems have been applied to processes that are very sensitive to disturbances and slow to respond to corrective action and to product streams that are relatively high in value. Distillation columns of 50 trays or more have been the principal systems controlled with this technology. Boilers, multiple-effect evaporators, direct-fired heaters, waste neutralization plants, solids dryers, compressors, and other hard-to-control processes have also benefited from feedforward control.

Variable Parameters

Heat exchangers are characterized by gain and dynamics that vary with flow. The settings of both the PID controller and the feedforward compensator that produced the results shown in Figure 2.9j were optimized for the final flow and would not be optimum for any other flow. Differentiation of the heat-balance equation, Equation 2.9(8), shows the process gain to vary inversely with process flow W:

$$\frac{dT_2}{dW_s} = \frac{\lambda}{WC_p} \qquad \textbf{2.9(12)}$$

If PID control alone is applied, this gain variation can be compensated through the use of an equal-percentage steam valve, whose gain varies directly with steam flow. However, when the PID controller is combined with bilinear feedforward, its output passes through the multiplier shown in Figure 2.9i, where it is multiplied by process flow. This operation keeps the PID loop gain constant, while manipulating steam flow linearly.

Heat-exchanger dynamics—deadtime and lags—also vary inversely with process flow, as is typical of *once-through* processes, i.e., where no recirculation takes place. This problem is less easily solved. The PID controller must have its integral time set relative to the slowest response (lowest expected flow) and its derivative time set relative to its fastest response (highest expected flow), or ideally, programmed as a function of measured flow. Otherwise, instability may result at extreme flow rates. Ideally, lead and lag settings of the feedforward dynamic compensator should also be programmed as a function of measured flow. However, the penalty for not doing so is not severe. The lead-lag ratio is not subject to change because the lags on both sides of the process change in the same proportion with flow. The primary purpose of the dynamic compensator is to minimize the peak deviation following the load change, and this is accomplished by the dynamic gain of the compensator, which is its lead-lag ratio. Any subsequent variation in integrated error is eliminated by the PID controller.

Although parameter variations can also be accommodated by a self-tuning feedforward compensator and feedback controller, these methods are less accurate in arriving at optimum settings and are always late, having tuned for the last flow condition and not for the next one.

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