on the process, and the manipulated variables must therefore be accurately regulated flow rates. An example is the balancing of firing rate vs. thermal power that is being withdrawn as steam from a boiler. Some material and energy are inevitably stored within the process, the content of which will change in passing from one state to another. This change in storage means a momentary release or absorption of energy or material, which can produce a transient in the controlled variable unless it is accounted for in the calculations.

To be complete, then, the control computer should be programmed to maintain the process balance in the steady state and also in transient intervals between steady states. It must consist of both steady-state and dynamic components, like the process: it is, in effect, a model of the process. If the steady-state calculations are correct, the controlled variable will be at the set point as long as the load is steady, whatever its current value. If the calculations are in error, an offset will result, which may change with load. If no dynamic calculations are made, or if they are incorrect, the measurement will deviate from the set point while the load is changing, and for some time thereafter, while new energy levels are being established in the process. If both the steady-state and dynamic calculations are perfect, the process will be continually in balance and no deviation will be measurable at any time. This is the ultimate goal.

In the procedure followed in the design of a feedforward system, the process model is reversed. The manipulated variables are solved for in terms of load components and controlled variables, but where the controlled variables appear in the equations set points are used instead. It is the intent of a feedforward system to force the process to respond as it was designed, to follow the set points as directed without regard to load upsets.

Systems for Liquid Level and Pressure

In Chap. 3, a distinction was made between variables which are integrals of flow and those which are properties of a flowing stream. This distinction takes on added significance now, being reflected in the configuration of the feedforward system. Load is a flow term, of which liquid level and pressure are integrals. Therefore feedforward calculations for liquid level and pressure are generally linear. But where a property of the flowing stream, such as temperature or composition, is to be controlled, the system will be found nonlinear in appearance.

In general, liquid-level and pressure processes appear mathematically as

$$\tau \frac{dc}{dt} = mK_m\mathbf{g}_m - qK_q\mathbf{g}_q \tag{7.1}$$

The terms K_m, $\mathbf{g}_m$, K_q, and $\mathbf{g}_q$ represent the steady-state and dynamic-gain terms for manipulated variable and load. The feedforward control system is to be designed to solve for m, substituting r for c

$$m = \frac{\tau\, dr/dt + qK_q\mathbf{g}_q}{K_m\mathbf{g}_m}$$

Since dr/dt is normally zero,

$$m = q \frac{K_q \mathbf{g}_q}{K_m \mathbf{g}_m} \tag{7.2}$$

Feedforward is commonly applied to level control in a drum boiler. Because of the low time constant of the drum, level control is sensitive to rapid load changes. In addition, constant turbulence prevents the use of a narrow proportional band because this would cause unacceptable variations in feedwater flow. The feedforward system simply manipulates feedwater flow to equal the rate of steam being withdrawn, since this represents the load on drum level. The system is shown in Fig. 7.2.

If the two flowmeters have identical scales, which is to be expected, the ratio K_q/K_m of Eq. (7.2) is 1.0. Furthermore, the dynamic elements $\mathbf{g}_q$ and $\mathbf{g}_m$ are virtually nonexistent. The control system then simply solves the equation

$$W_F = W_s + m_L - 0.5$$

The terms W_F and W_s are mass flows of feedwater and steam, respectively; m_L is the output of the level controller, whose normal value is 0.5.

It must be remembered that liquid-level processes such as this are non-self-regulating. The controlled variable will consequently drift unless feedback is applied. Since integral feedback may not be used alone, because instability would result, a PI controller is always used. In the steady state, feedwater flow will always equal steam flow, so the output of the level controller will seek the bias applied to the computation. If the controller is to be operated at about 50 percent output, that bias must be 0.5, as indicated in the formula. The controller does not have to integrate its output to the entire extent of the load change with a forward loop in service but need only trim out the change in error of the computation during that interval.

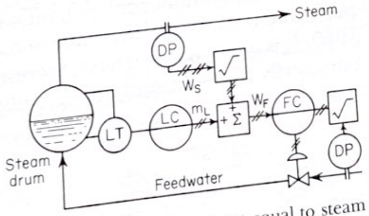

FIG. 7.2 Feedwater flow is set equal to steam flow in a drum boiler.

This feedforward system has two principal advantages: (1) feedwater flow does not change faster or farther than steam flow, and (2) control of liquid level does not hinge upon tight settings of the feedback controller.

Because this feedforward system, like many, is based on a material balance, accurate manipulation of feedwater flow is paramount. In general, the output of a feedforward system is the set point for a cascade flow loop and does not go directly to a valve. Valve position is not a sufficiently accurate representation of flow.

Systems for Temperature and Composition

Temperature and composition are both properties of a flowing stream. Heat and material balances involve multiplication of these variables by flow, producing a characteristic nonlinear process model. Feedforward systems for control of these variables are similarly characterized by multiplication and division. The general form of process model for these applications is

$$c = K_p \frac{m\mathbf{g}_m}{q\mathbf{g}_q} \tag{7.3}$$

A single coefficient K_p is sufficient to identify the steady-state gain.

The feedforward equation to control this general process is simply the solution for m, replacing c with r

$$m = \frac{rq\mathbf{g}_q}{K_p\mathbf{g}_m} \tag{7.4}$$

Notice that the manipulated variable is affected equally by the load and set point, which are multiplied. In level and pressure processes, the set point is added and contributes little to the forward loop.

Because temperature and composition measurements are both subject to dead-time and multiple lags, they are relatively difficult to control. As a result, it is perfectly reasonable to expect that feedforward can be more readily justified in these applications. But along with the need, there likewise exists the problem of defining these processes well enough to use computing control. In addition, nonlinear operations and dynamic characterization are required. Yet multipliers and dividers did not come into common use in control systems until about 1960. It is easy to understand, therefore, why level control was perhaps the first but hardly the most significant application of the feedforward principle.

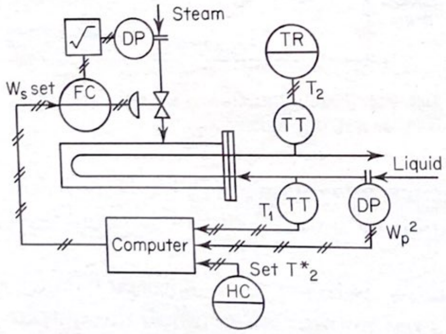

FIG. 7.3 The feedforward control system calculates the correct steam flow to match the heat load.