FEATURE SERIES: PRACTICAL PROCESS CONTROL

16: Feedforward Control – Part 2

*In the second of a two-parter, **Myke King** shows how to apply feedforward control*

FIGURE 1 shows our example fired heater. The intent is to add feedforward control to the existing feedback scheme. This comprises a fuel-to-feed ratio algorithm; as the feed rate changes, the fuel is changed in proportion.

However, we need to take account of the process dynamics. It is unlikely that we should change the fuel at exactly the same time as the feed. So, we include dynamic compensation. This comprises two algorithms, connected in series – deadtime and *lead-lag*. Both are standard features of the distributed control system (DCS). Between them they include four tunable parameters – deadtime (θ), gain (K), lead ($T1$), and lag ($T2$).

DEADTIME AND LEAD-LAG

Figure 2 shows the effect of this compensation. It shows the disturbance variable (in our example, the feed flow) changing as a step. The output of the deadtime algorithm is the same as the input, just delayed by θ. The lead-lag algorithm initially generates a spike – the height of which is determined by the ratio $T1/T2$. This is followed by a lagged approach to steady state, governed by $T2$. The steady state change in the output is the change in the DV, multiplied by K.

Figure 1: Feedforward on feed rate

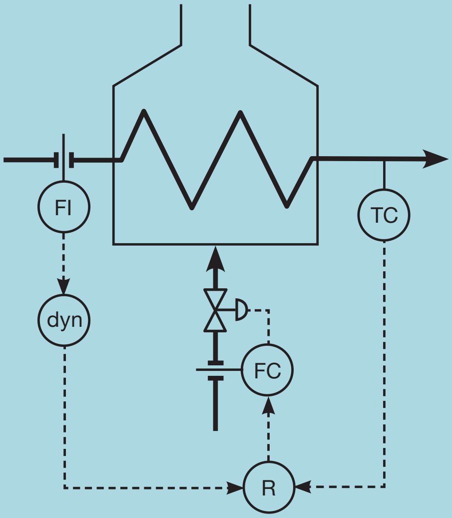
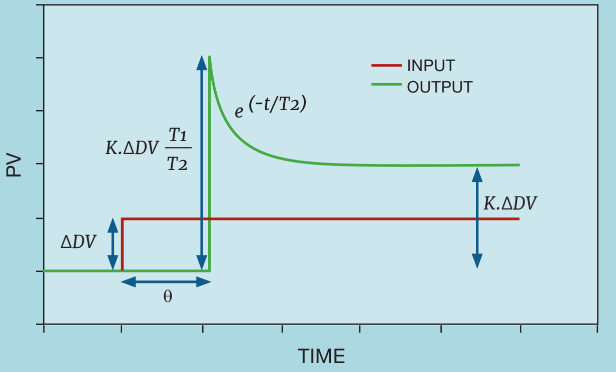


Figure 2: Effect of deadtime and lead-lag algorithms



In addition to adding four tuning constants, if feedforward is added to an existing feedback scheme, we are likely to have to retune the PID controller. As a potential seven-dimensional search, tuning by trial-and-error would be highly impractical. As always, the systematic approach is to first perform step tests. We need the dynamics between the PV (temperature) and MV (fuel flow setpoint). These are $(K_p)_m$, θ_m and τ_m. Ideally, these were used to tune the existing PID controller and should be on record. We also need $(K_p)_d$, θ_d and τ_d – the dynamics of the PV with respect to the DV (feed flow). They are obtained by stepping the DV (with the temperature controller in manual mode).

Figure 3: Feedforward-feedback block diagram

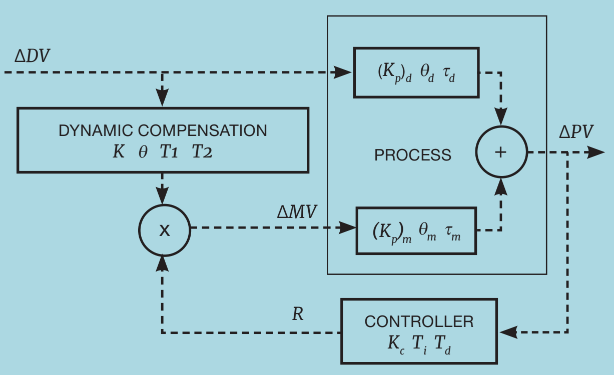


Figure 4: Mismatched process dynamics

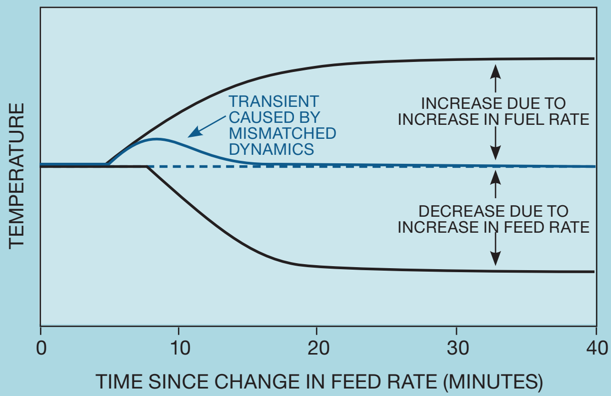


Figure 3 shows the detail of the intended control scheme. Its aim is to ensure there is no change in temperature when the feed flow changes. So following ΔDV, we want ΔPV to be zero. The PV is subject to two disturbances – the change in DV and the corrective change to the MV. These disturbances need to cancel each other out; so the first requirement is that they are opposite in direction. This has already been achieved; $(K_p)_m$ is positive, while $(K_p)_d$ is negative. For them to be the same size:

$$\Delta DV.\left(K_p\right)_d = \Delta DV.K.R\left(K_p\right)_m$$

By definition:

$$\left(K_p\right)_m = \frac{\Delta PV}{\Delta MV} \qquad \left(K_p\right)_d = \frac{\Delta DV}{\Delta MV} \qquad R = \frac{\Delta MV}{\Delta DV}$$

Substituting gives:

$$K = 1$$

If we have chosen ratio, rather than bias, feedforward, this will always be the result. The calculations for feedforward control do not include $(K_p)_m$ or $(K_p)_d$. To tune the feedback controller, we require $(K_p)_m$ but $(K_p)_d$ can have any value. So, if the relationship between the PV and the DV is highly non-linear – even if the gain changes sign, the tuning of the feedforward scheme will be robust.

Bias feedforward is less forgiving:

$$K = -\frac{\left(K_p\right)_d}{\left(K_p\right)_m}$$

So far, we have not taken account of the process dynamics. The steady state change in PV will be zero, but our design will only work well if θ_d has the same value as θ_m and τ_d is the same as τ_m. Figure 4 shows the transient effect if this is not the case. We must tune the controller so that, not only are the two changes equal and opposite in direction, but they arrive at the same time. For the deadtimes to be the same:

$$\theta_d = \theta + \theta_m \qquad \text{or} \qquad \theta = \theta_d - \theta_m$$

For the lags to be the same, we first must neutralise τ_m and then replace it with τ_d, so:

$$T1 = \tau_m \qquad \text{and} \qquad T2 = \tau_d$$

There is no guarantee that the result for θ will be positive. In the absence of a clairvoyant controller, we set θ to zero and increase $T1$ by $(\theta_m - \theta_d)$. As an approximation, we make up for the correction being late by increasing the spike.

FILTER

We saw in *TCE 994* that we must ensure noise in the PV isn't transmitted through the PID controller to the control valve. The addition of feedforward control brings the possibility of noise in the DV doing the same. As usual, we can filter the measurement. Provided this is in place when we perform the step-testing, then its impact on the dynamics will be taken into account.

RETUNING THE PID

Figure 5 shows the before and after configuration, when ratio feedforward is added to an existing feedback controller. The PID controller is dimensionless; for its output to become the setpoint of the fuel flow controller it is converted to engineering units by multiplying by the range of the flow controller. When the ratio is included, the output of the PID controller is now multiplied by the range of the ratio. It is then multiplied by the DV. So, the effective controller gain has been multiplied by:

$$\frac{R_{range}DV}{MV_{range}}$$

To correct for this, we change the controller gain:

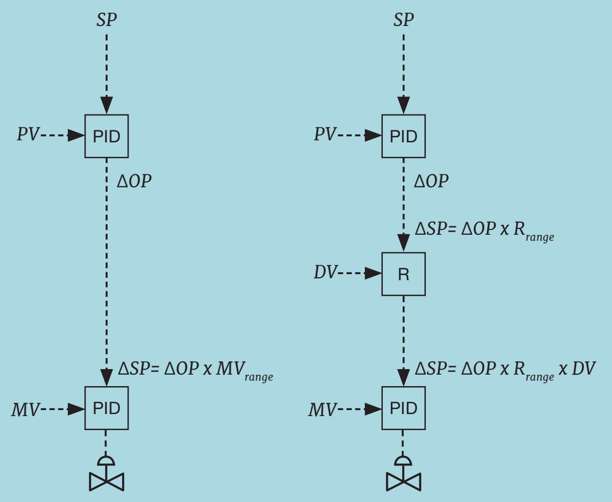
$$(K_c)_{new} = K_c \frac{MV_{range}}{R_{range}DV^*}$$

DV is not a constant. The value DV^* is the value of the DV when the MV was stepped to obtain the dynamics of the PV.

Alternatively, step tests can be performed on the fuel-to-feed ratio target to obtain the dynamics of the temperature. These would be used to derive the new PID tuning parameters.

If we permit the process operator to have the feedback controller in service without feedforward, we have to automate the change of K_c. Ideally, we remove the need by choosing the range of the ratio so that the correction factor is 1.

Figure 5: Addition of feedforward controller



$$R_{range} = \frac{MV_{range}}{DV^*}$$

However, this is only possible if the chosen range covers all possible operating conditions.

ADVANTAGES

The most obvious benefit of feedforward control is *disturbance rejection*. By anticipating the impact of measurable disturbances, it will outperform normal feedback control. But there are other advantages. Assuming no change of phase, we can write a simple heat balance for our heater, that relates the change in outlet temperature (ΔT) to the change in fuel flow (ΔF) – where *NHV* is the net heating value of the fuel, η the heater efficiency, and C_p the specific heat of the feed.

$$feed\ rate \times C_p \times \Delta T = NHV \times \eta \times \Delta F$$

$$K_p = \frac{\Delta T}{\Delta F} = \frac{NHV \times \eta}{C_p \times feed\ rate} \propto \frac{1}{feed\ rate}$$

This shows that the process gain varies inversely with feed rate. A little thought would have anticipated this. If we operate at a higher feed rate, for a given increase in fuel (ΔF) the increase in the outlet temperature (ΔT) will be less.

Examination of all tuning methods will show that K_c is inversely proportional to K_p, so:

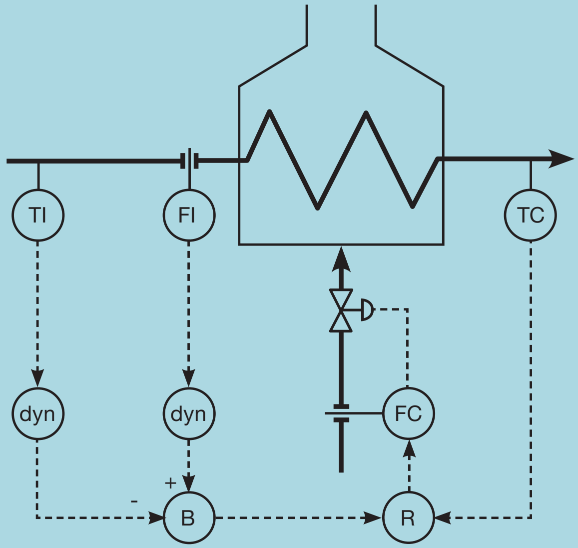
$$K_c \propto feed\ rate$$

While we've developed this relationship for a fired heater, it is true for all processes. The implication is that we would need to retune almost every controller on the process whenever the feed rate changes by more than ±20%. This will occur if the plant turndown ratio exceeds 1.5.

Ratio feedforward control resolves this problem. As Figure 1 shows, the output from the temperature controller is multiplied by the feed rate before becoming the setpoint of the fuel

The most obvious benefit of feedforward control is disturbance rejection. By anticipating the impact of measurable disturbances, it will outperform normal feedback control. But there are other advantages

Figure 6: Inlet temperature feedforward



flow controller. The effective controller gain is thus proportional to feed rate. The temperature controller will perform identically at all feed rates, without retuning.

USE OF MPC

Those familiar with model predictive control (MPC) products will know that they support feedforward control by including disturbance variables. However, control is based on bias, rather than ratio, feedforward. While manipulated variables will be moved in the right direction, in some cases, the size of the correction will be inaccurate. Good design will implement ratio feedforward at the DCS level – with the ratio targets potentially manipulated by the MPC.

While MPC is not yet seen as a replacement for DCS-based regulatory controls, such as heater outlet temperature, it is becoming an option. Increasingly, DCS vendors are including the functionality within the DCS, rather than in the process computer – so providing the necessary reliability. We could retain the ratio feedforward in the DCS and move the temperature control to the MPC. While this might seem strange, it would then readily support the addition of MPC-based bias feedforward to deal with disturbances to the heater inlet temperature. Often overlooked, such disturbances cause the same magnitude changes in the outlet temperature. The addition of this feedforward scheme can be particularly beneficial. Its principal is to bias the fuel-to-feed ratio target (R) to take account of any change in feed enthalpy. Of course, the whole scheme can readily also be based in the DCS, as shown in Figure 6.

The difficulty, however, is obtaining the necessary process dynamics. The inlet temperature is likely to be influenced by

the heat integration. It certainly can't be subjected to a step change – although with the curve-fitting approach to model identification, this is not the main issue. Changing the temperature is likely to require bypassing some upstream heat recovery. While, in principal, we could analyse previous natural disturbances, we would require the temperature controller to have been in manual mode when they occur. Perhaps a more pragmatic approach would be to calculate the feedforward gain (K) from the heat balance. Rearranging the equation above:

$$\Delta R = \frac{\Delta F}{feed\ rate} = \frac{C_p}{NHV.\eta}\Delta T \qquad \text{or} \qquad K = \frac{\Delta R}{\Delta T} = \frac{C_p}{NHV.\eta}$$

Even without the dynamic compensation ($\theta = 0$ and $T1 = T2$) this addition is likely to greatly improve temperature control. Alternatively, we could assume the same dynamics as those for feed flow changes and, as last resort, tune by trial and error. ■

NEXT ISSUE

Our next article will be the first of two developing control schemes for fired heaters. It will focus on schemes which deal well with disturbances to the fuel gas conditions and composition. In particular, it will address commonly implemented design errors that worsen control performance.

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