Feedforward and Ratio Control

In Chapter 8 it was emphasized that feedback control is an important technique that is widely used in the process industries. Its main advantages are as follows.

1. Corrective action occurs as soon as the controlled variable deviates from the set point, regardless of the source and type of disturbance.

2. Feedback control requires minimal knowledge about the process to be controlled; in particular, a mathematical model of the process is *not* required, although it can be very useful for control system design.

3. The ubiquitous PID controller is both versatile and robust. If process conditions change, retuning the controller usually produces satisfactory control.
However, feedback control also has certain inherent disadvantages:

1. No corrective action is taken until after a deviation in the controlled variable occurs. Thus, *perfect control*, where the controlled variable does not deviate from the set point during disturbance or set-point changes, is theoretically impossible.

2. Feedback control does not provide predictive control action to compensate for the effects of known or measurable disturbances.

3. It may not be satisfactory for processes with large time constants and/or long time delays. If large and frequent disturbances occur, the process may operate continuously in a transient state and never attain the desired steady state.

4. In some situations, the controlled variable cannot be measured on-line, and, consequently, feedback control is not feasible.
Introduction to Feedforward Control

The basic concept of feedforward control is to measure important disturbance variables and take corrective action before they upset the process. Feedforward control has several disadvantages:

1. The disturbance variables must be measured on-line. In many applications, this is not feasible.

2. To make effective use of feedforward control, at least a crude process model should be available. In particular, we need to know how the controlled variable responds to changes in both the disturbance and manipulated variables. The quality of feedforward control depends on the accuracy of the process model.

3. Ideal feedforward controllers that are theoretically capable of achieving perfect control may not be physically realizable. Fortunately, practical approximations of these ideal controllers often provide very effective control.
Figure 15.2 The feedback control of the liquid level in a boiler drum.
A boiler drum with a conventional feedback control system is shown in Fig. 15.2. The level of the boiling liquid is measured and used to adjust the feedwater flow rate.

This control system tends to be quite sensitive to rapid changes in the disturbance variable, steam flow rate, as a result of the small liquid capacity of the boiler drum.

Rapid disturbance changes can occur as a result of steam demands made by downstream processing units.

The feedforward control scheme in Fig. 15.3 can provide better control of the liquid level. Here the steam flow rate is measured, and the feedforward controller adjusts the feedwater flow rate.
Figure 15.3 The feedforward control of the liquid level in a boiler drum.
Fig. 15.4 The feedforward-feedback control of the boiler drum level.

- In practice, feedforward control is normally used in combination with feedback control.

- Feedforward control is used to reduce the effects of measurable disturbances, while *feedback trim* compensates for inaccuracies in the process model, measurement error, and unmeasured disturbances.
Feedforward Controller Design Based on Dynamic Models

In this section, we consider the design of feedforward control systems based on dynamic, rather than steady-state, process models.

• As a starting point for our discussion, consider the block diagram shown in Fig. 15.11.

• This diagram is similar to Fig. 11.8 for feedback control but an additional signal path through $G_t$ and $G_f$ has been added.
Figure 15.11 A block diagram of a feedforward-feedback control system.
The closed-loop transfer function for disturbance changes is:

\[
\frac{Y(s)}{D(s)} = \frac{G_d + G_t G_f G_v G_p}{1 + G_c G_v G_p G_m}
\]  

(15-20)

Ideally, we would like the control system to produce \textit{perfect control} where the controlled variable remains exactly at the set point despite arbitrary changes in the disturbance variable, \(D\). Thus, if the set point is constant \((Y_{sp}(s) = 0)\), we want \(Y(s) = 0\), even though \(D(s)\)

\[
G_f = -\frac{G_d}{G_t G_v G_p}
\]  

(15-21)

• Figure 15.11 and Eq. 15-21 provide a useful interpretation of the ideal feedforward controller. Figure 15.11 indicates that a disturbance has two effects.

• It upsets the process via the disturbance transfer function, \(G_d\); however, a corrective action is generated via the path through \(G_t G_f G_v G_p\).
• Ideally, the corrective action compensates exactly for the upset so that signals $Y_d$ and $Y_u$ cancel each other and $Y(s) = 0$.

**Example 15.2** \[ G_f = -\frac{G_d}{G_t G_v G_p} \] (15-21)

Suppose that

\[ G_d = \frac{K_d}{\tau_d s + 1}, \quad G_p = \frac{K_p}{\tau_p s + 1} \] (15-22)

Then from (15-22), the ideal feedforward controller is

\[ G_f = -\left( \frac{K_d}{K_t K_v K_p} \right) \left( \frac{\tau_p s + 1}{\tau_d s + 1} \right) \] (15-23)

This controller is a lead-lag unit with a gain given by $K_f = -K_d/K_tK_vK_p$. The dynamic response characteristics of lead-lag units were considered in Example 6.1 of Chapter 6.
Example 15.3 \( G_f = -\frac{G_d}{G_t G_v G_p} \) (15-21)

Now consider

\[
G_d = \frac{K_d}{\tau_d s + 1}, \quad G_p = \frac{K_p e^{-\theta s}}{\tau_p s + 1}
\] (15-24)

From (15-21),

\[
G_f = \left( \frac{K_d}{K_t K_v K_p} \right) \left( \frac{\tau_p s + 1}{\tau_d s + 1} \right) e^{s \theta} \] (15-25)

Because the term \( e^{s \theta} \) is a negative time delay, implying a predictive element, the ideal feedforward controller in (15-25) is physically unrealizable. However, we can approximate it by omitting the \( e^{s \theta} \) term and increasing the value of the lead time constant from \( \tau_p \) to \( \tau_p + \theta \).
Example 15.4

Finally, if

$$G_d = \frac{K_d}{\tau_d s + 1}$$

$$G_p = \frac{K_p}{(\tau_{p1}s + 1)(\tau_{p2}s + 1)}$$

(15-26)

then the ideal feedforward controller,

$$G_f = -\left(\frac{K_d}{K_t K_v K_p}\right)\left(\frac{\tau_{p1}s + 1)(\tau_{p2}s + 1)}{(\tau_d s + 1)}\right)$$

(15-27)

is physically unrealizable because the numerator is a higher order polynomial in $s$ than the denominator. Again, we could approximate this controller by a physically realizable one such as a lead-lag unit, where the lead time constant is the sum of the two time constants, $\tau_{p1} + \tau_{p2}$. 
Ratio Control

Ratio control is a special type of feedforward control that has had widespread application in the process industries. The objective is to maintain the ratio of two process variables as a specified value. The two variables are usually flow rates, a manipulated variable $u$, and a disturbance variable $d$. Thus, the ratio

$$R = \frac{u}{d}$$

is controlled rather than the individual variables. In Eq. 15-1, $u$ and $d$ are physical variables, not deviation variables.
Typical applications of ratio control include:

1. Setting the relative amounts of components in blending operations
2. Maintaining a stoichiometric ratio of reactants to a reactor
3. Keeping a specified reflux ratio for a distillation column
4. Holding the fuel-air ratio to a furnace at the optimum value.
Figure 15.5 Ratio control, Method I.
• The main advantage of Method I is that the actual ratio $R$ is calculated.

• A key disadvantage is that a divider element must be included in the loop, and this element makes the process gain vary in a nonlinear fashion. From Eq. 15-1, the process gain

$$K_p = \left( \frac{\partial R}{\partial u} \right)_d = \frac{1}{d}$$

(15-2)

is inversely related to the disturbance flow rate $d'$. Because of this significant disadvantage, the preferred scheme for implementing ratio control is Method II, which is shown in Fig. 15.6.
Figure 15.6 Ratio control, Method II
Regardless of how ratio control is implemented, the process variables must be scaled appropriately.

For example, in Method II the gain setting for the ratio station $K_d$ must take into account the spans of the two flow transmitters.

Thus, the correct gain for the ratio station is

$$K_R = R_d \frac{S_d}{S_u}$$

(15-3)

where $R_d$ is the desired ratio, $S_u$ and $S_d$ are the spans of the flow transmitters for the manipulated and disturbance streams, respectively.
Example 15.1

A ratio control scheme is to be used to maintain a stoichiometric ratio of H\(_2\) and N\(_2\) as the feed to an ammonia synthesis reactor. Individual flow controllers will be used for both the H\(_2\) and N\(_2\) streams. Using the information given below, do the following:

a) Draw a schematic diagram for the ratio control scheme.

b) Specify the appropriate gain for the ratio station, \(K_R\).

**Available Information**

i. The electronic flow transmitters have built-in square root extractors. The spans of the flow transmitters are 30 L/min for H\(_2\) and 15 L/min for N\(_2\).

ii. The control valves have pneumatic actuators.

iii. Each required current-to-pressure (\(I/P\)) transducer has a gain of 0.75 psi/mA.

iv. The ratio station is an electronic instrument with 4-20 mA input and output signals.
Solution: The stoichiometric equation for the ammonia synthesis reaction is

\[ 3H_2 + N_2 = 2NH_3 \]

In order to introduce the feed mixture in stoichiometric proportions, the ratio of the molar flow rates \( \left( \frac{H_2}{N_2} \right) \) should be 3:1. For the sake of simplicity, we assume that the ratio of the molar flow rates is equal to the ratio of the volumetric flow rates. But in general, the volumetric flow rates also depend on the temperature and pressure of each stream (cf., the ideal gas law).

a) The schematic diagram for the ammonia synthesis reaction is shown in Fig. 15.7. The \( H_2 \) flow rate is considered to be the disturbance variable, although this choice is arbitrary because both the \( H_2 \) and \( N_2 \) flow rates are controlled. Note that the ratio station is merely a device with an adjustable gain. The input signal to the ratio station is \( d_m \), the measured \( H_2 \) flow rate. Its output signal \( u_{sp} \) serves as the set point for the \( N_2 \) flow control loop. It is calculated as \( u_{sp} = K_R d_m \).
Figure 15.7 Ratio control scheme for an ammonia synthesis reactor of Example 15.1

b) From the stoichiometric equation, it follows that the desired ratio is \( R_d = u/d = 1/3 \). Substitution into Equation 15-3 gives:

\[
K_R = \left( \frac{1}{3} \right) \left( \frac{30 \text{ L/min}}{15 \text{ L/min}} \right) = \frac{2}{3}
\]
Enhanced Single-Loop Control Strategies

1. Cascade control
2. Inferential control
3. Selective and override control
4. Time Delay Compensation
5. Nonlinear control
6. Adaptive control
Example: Cascade Control

Figure 16.3 Cascade control of an exothermic chemical reactor.
Figure 16.1 A furnace temperature control scheme that uses conventional feedback control.
Figure 16.2 A furnace temperature control scheme using cascade control.
Cascade Control

• Distinguishing features:
  1. Two FB controllers but only a single control valve (or other final control element).
  2. Output signal of the "master" controller is the set-point for “slave" controller.
  3. Two FB control loops are "nested" with the "slave" (or "secondary") control loop inside the "master" (or "primary") control loop.

• Terminology:
  slave vs. master
  secondary vs. primary
  inner vs. outer
Figure 16.4 Block diagram of the cascade control system.
\[
\frac{Y_1}{D_2} = \frac{G_{p1}G_{d2}}{1 + G_{c2}G_v G_{p2}G_{m2} + G_{c1}G_{c2}G_v G_{p2}G_{p1}G_{m1}} 
\] (16 – 5)

\[Y_1 = \text{hot oil temperature}\]

\[Y_2 = \text{fuel gas pressure}\]

\[D_1 = \text{cold oil temperature (or cold oil flow rate)}\]

\[D_2 = \text{supply pressure of gas fuel}\]

\[Y_{m1} = \text{measured value of hot oil temperature}\]

\[Y_{m2} = \text{measured value of fuel gas temperature}\]

\[Y_{sp1} = \text{set point for } Y_1\]

\[\tilde{Y}_{sp2} = \text{set point for } Y_2\]
Example 16.1

Consider the block diagram in Fig. 16.4 with the following transfer functions:

\[ G_v = \frac{5}{s+1} \quad G_{p1} = \frac{4}{(4s+1)(2s+1)} \quad G_{p2} = 1 \]

\[ G_{d2} = 1 \quad G_{m1} = 0.05 \quad G_{m2} = 0.2 \quad G_{d1} = \frac{1}{3s+1} \]

**Figure 16.5** A comparison of \( D_2 \) unit step responses with and without cascade control.
Figure 16.6 A comparison of $D_1$ step responses.
Inferential Control

• **Problem:** Controlled variable cannot be measured or has large sampling period.

• **Possible solutions:**
  1. Control a related variable (e.g., temperature instead of composition).
  2. **Inferential control:** Control is based on an estimate of the controlled variable.
     • The estimate is based on available measurements.
       − Examples: empirical relation, Kalman filter
     • *Modern term:* *soft sensor*
Inferential Control

• Uses easily measure process variables (T, P, F) to infer more difficult to measure quantities such as compositions and molecular weight.
• Can substantially reduce analyzer delay.
• Can be much less expensive in terms of capital and operating costs.
• Can provide measurements that are not available any other way.
Figure 16.12 Soft sensor block diagram used in inferential control.
Selective Control Systems & Overrides

• For every controlled variable, it is very desirable that there be at least one manipulated variable.

• But for some applications,

\[ N_C > N_M \]

where:

\[ N_C = \text{number of controlled variables} \]

\[ N_M = \text{number of manipulated variables} \]

For such cases, it is not possible to eliminate effect of every disturbance from every controlled variable.

• Solution: Use a selective control system or an override. Selective control is also referred as “Auctioneering”.

• Low selector:

\[ Z = \text{Minimum of } X \text{ and } Y \]

• High selector:

\[ Z = \text{Maximum of } X \text{ and } Y \]

• Median selector:

  • The output, \( Z \), is the median of an odd number of inputs
Example: High Selector Control System

Figure 16.13. Control of a reactor hot spot temperature by using a high selector.

- multiple measurements
- one controller
- one final control element