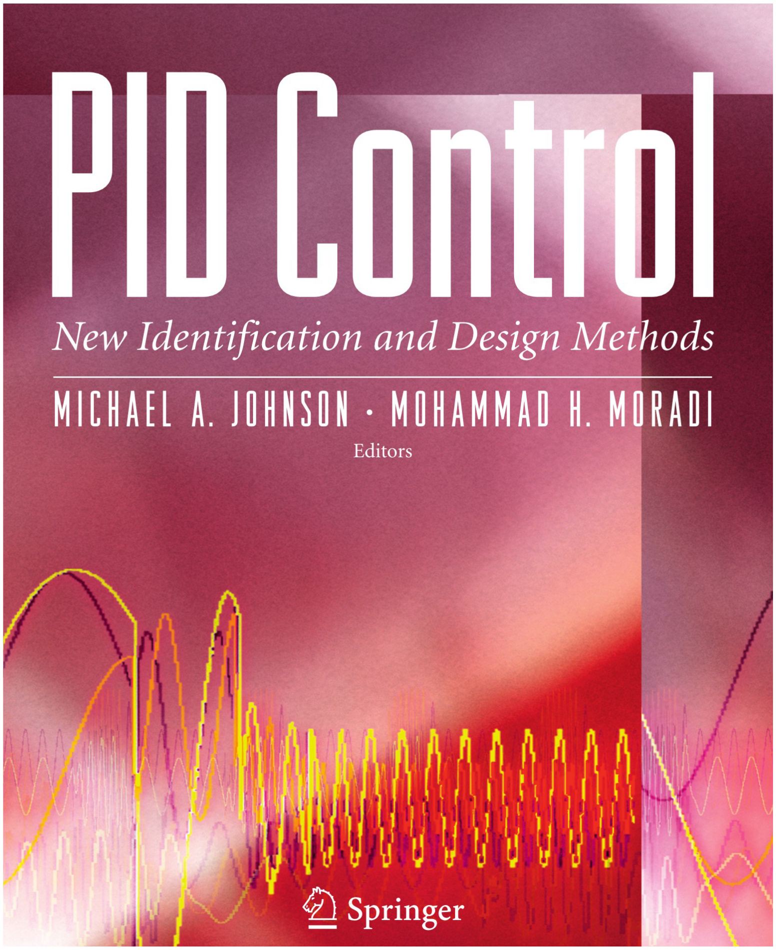



### 2.5.2 Cascade Control Systems

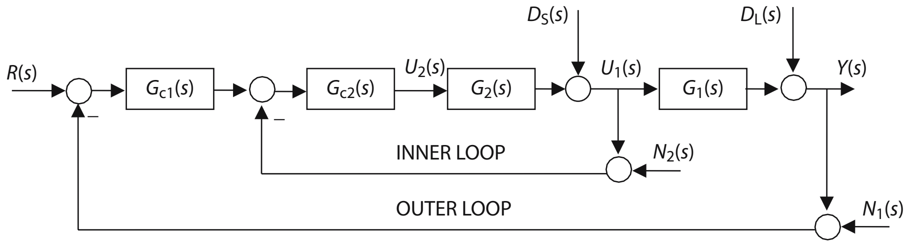
Many industrial processes are sequential in operation; one process output becomes a process input to the next stage in the process line. Sometimes the processes are connected continuously by a linking material input such as steam or a fluid feedstock. An important source of upset in sequential processes is a variation in the quality of the incoming material supply and a mismatch with the setup of the receiving unit. If an internal process measurement or a measurement between processes is available then a simple multi-loop control system often used in this situation is the cascade control system. Earlier in Chapter 1 there was a very good example of a cascade control system. The discussion of the industrial operator interfaces for a DCS provided by Siemens revealed a cascade control loop where an internal temperature measurement was being used to correct for any disturbances in a drying process. An important observation was that the DCS system had standard tools to facilitate the easy setup of a cascade control loop which is a highly structured form of multi-loop control.

To recap, cascade control arises from the control of two sequential processes where the output of the first or inner process supplies the second or outer process in the sequence. It is assumed that a measurement is available of the output of the inner process and that there is a measurement of the outer process variable. Thus there are two main objectives for cascade control:

1. Use the inner measure to attenuate the effect of supply disturbances or any internal process disturbance on the outer process in the sequence.

2. Use the outer process measurement to control the process final output quality.

Figure 2.29 shows the cascade control system structure.




**Key**

$G_1(s)$, Outer process model
$D_L(s)$, System load disturbance
$G_{c1}(s)$, Outer process controller

$G_2(s)$, Inner process model
$D_S(s)$, System supply disturbance
$G_{c2}(s)$, Inner process controller

$Y(s)$, System output
$N_1(s)$, Outer process measurement noise
$U_1(s) = Y_2(s)$, Outer process input

$Y_2(s) = U_1(s)$, Inner system output
$N_2(s)$, Inner process measurement noise
$U_2(s)$, Inner process input

$R(s)$, Reference signal

**Figure 2.29** Cascade control loop.

### The Outer Loop

The outer loop is sometimes referred to as the Master or Primary loop. It contains the process output $Y(s)$, which is under primary control. The outer process is denoted $G_1(s)$ and the whole process is subject to load disturbances denoted $D_L(s)$. The outer loop equation is

$$Y(s) = G_1(s)U_1(s) + D_L(s)$$

where the important connecting relation is $U_1(s) = Y_2(s)$, so that the output from the inner process $Y_2(s)$ becomes the input $U_1(s)$ to the outer process. The outer process output is to be controlled to attain a given reference signal $R(s)$ and the measured output used in the comparator is corrupted by outer process measurement noise $N_1(s)$. Thus, the overall control objective is to make the outer process output, $Y(s)$ track the reference $R(s)$ in the presence of process load disturbance $D_L(s)$ and outer process measurement noise, $N_1(s)$. In the case of three-term control being used in the cascade loop, good reference tracking and load disturbance rejection will require integral action in the outer controller.

### The Inner Loop

The inner loop is sometimes referred to as the Slave or Secondary loop. The loop contains the inner or supply process denoted $G_2(s)$. This inner process is subject to supply disturbances, denoted $D_S(s)$, and the inner process equation is

$$Y_2(s) = G_2(s)U_2(s) + D_S(s)$$

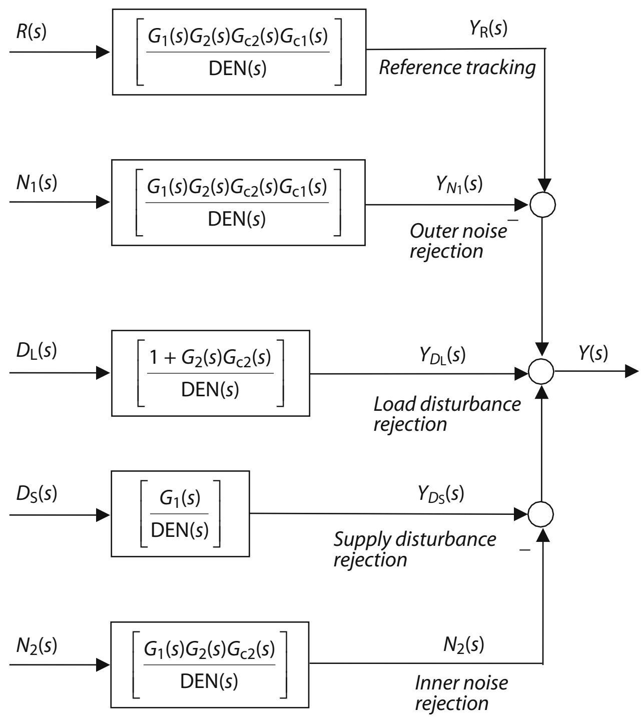
The output from the inner process becomes the input to the outer process, namely $U_1(s) = Y_2(s)$. The control of the inner process uses the inner loop and this comprises an inner comparator and an inner loop measurement of output $Y_2(s)$, which is corrupted by inner process measurement noise $N_2(s)$. The main inner loop control objective is to attenuate the effect of the supply disturbances $D_S(s)$. These usually represent variations in quality of the material supply (flow rate fluctuations, temperature variations, for example) to the outer process. A second objective for the inner loop is to limit the effect of actuator or inner process gain variations on the control system performance. Such gain variations might arise from changes in operating point due to set point changes or sustained disturbances. When three-term control is used in the cascade loop, fast supply load disturbance rejection will require a fast inner loop design, and this possibly means a high-gain proportional inner controller.

The global performance of the cascade system can be examined using the full closed-loop transfer function analysis along with a corresponding decomposed performance diagram as shown in Figure 2.30.

The closed-loop transfer function analysis, based on Figure 2.29, yields

$$Y(s)=\left[\frac{G_1(s)G_2(s)G_{c2}(s)G_{c1}(s)}{DEN(s)}\right](R(s)-N_1(s))+\left[\frac{1+G_2(s)G_{c2}(s)}{DEN(s)}\right]D_L(s)$$
$$+\left[\frac{G_1(s)}{DEN(s)}\right]D_S(s)-\left[\frac{G_1(s)G_2(s)G_{c2}(s)}{DEN(s)}\right]N_2(s)$$

where $DEN(s)=1+G_2(s)G_{c2}(s)+G_1(s)G_2(s)G_{c2}(s)G_{c1}(s)$. This is given block diagram form in Figure 2.30.




**Key** DEN(s) = 1 + $G_2(s)G_{c2}(s) + G_1(s)G_2(s)G_{c2}(s)G_{c1}(s)$

**Figure 2.30** Cascade control objectives decomposed.

## PID Cascade Control Performance

There are two controllers to be selected and tuned: the outer controller $G_{c1}(s)$ and the inner controller, $G_{c2}(s)$. The usual approach is that for good tracking of step reference signals then outer controller $G_{c1}(s)$

should be of PI form. The inner controller $G_{c2}(s)$ can be just P for speed of response, or if this is inadequate PI for the rejection of low-frequency supply disturbance signals. Thus common cascade control structures are often termed PI/P and PI/PI. The use of derivative action is usually avoided in the presence of significant measurement noise. It is quite useful to know qualitatively what can be achieved by cascade control for simple models, with simple disturbance types and for different three term control structures. The results of such an investigation are given in Table 2.4.

**Table 2.4** Typical cascade control for simple process models.

| **Outer process** | **Outer controller forms** | **Inner process** | **Inner controller forms** |
|---|---|---|---|
| $G_1(s) = \left[\dfrac{K_1}{\tau_1 s + 1}\right]$ | $G_{c1}(s) = k_{P1} + \dfrac{k_{I1}}{s}$ | $G_2(s) = \left[\dfrac{K_2}{\tau_2 s + 1}\right]$ | $G_{c2}(s) = k_{P2} + \dfrac{k_{I2}}{s}$ |

| **Performance** | **Outer**: $G_{c1}(s)$-P<br>**Inner**: $G_{c2}(s)$-P | **Outer**: $G_{c1}(s)$-P<br>**Inner**: $G_{c2}(s)$-PI | **Outer**: $G_{c1}(s)$-PI<br>**Inner**: $G_{c2}(s)$-P | **Outer**: $G_{c1}(s)$-PI<br>**Inner**: $G_{c2}(s)$-PI |
|---|---|---|---|---|
| Step ref. tracking | Offset exists | Offset exists | Offset eliminated | Offset eliminated |
| Outer noise rejection<br>High frequency | −40 dB per decade | −20 dB per decade | −40 dB per decade | −40 dB per decade |
| Load disturbance rejection<br>Step model | Offset exists | Offset exists | Offset eliminated | Offset eliminated |
| Supply disturbance rejection<br>Step model | Offset exists | Offset eliminated | Offset eliminated | Offset eliminated |
| Inner noise rejection<br>High frequency | −40 dB per decade | −40 dB per decade | −40 dB per decade | −40 dB per decade |

Cascade control:

1. Disturbances arising within the inner loop, $D_s(s)$, are corrected the inner- loop control before they can influence the outer loop output, $Y(s)$.
2. Phase lag existing in the inner loop, $G_2(s)$, is reduced measurable by the inner loop. This improves the speed of response of the outer loop.
3. Gain variations in the inner loop (non-linearity's) are overcome within its own loop
4. The closed loop rise time can be chosen to 3-5 times faster than the rise time of $G_2(s)$.