XMUT315 Control Systems Engineering

Note 5: Feedback Control Systems

Topic

- Introduction to feedback control systems.
- Mechanisms in feedback control systems.
- Effects of feedback on gain, stability, noise, and sensitivity.
- Feedforward control systems.
- Input functions for evaluation and testing.
- Controller or compensator in feedback control systems.
- Examples of controller or compensator.

1. Introduction to Feedback Control Systems

A block diagram of a basic feedback loop is shown in the figure below. The system loop is composed of two components, the process P and the controller. The controller has two blocks the feedback block C and the feedforward block F.

There are two disturbances acting on the process, the load disturbance d and the measurement noise n. The load disturbance represents disturbances that drive the process away from its desired behaviour.

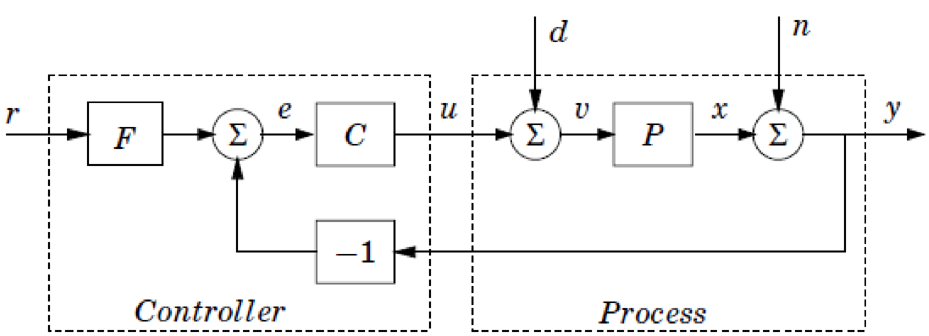


Figure 1: Typical components in the feedback control system.

The process variable x is the real physical variable that we want to control. Control is based on the measured signal y, where the measurements are corrupted by measurement noise n. Information about the process variable x is thus distorted by the measurement noise. The process is influenced by the controller via the control variable u. The process is thus a system with three inputs and one output.

The inputs are the control variable u, the load disturbance d and the measurement noise n. The output is the measured signal.

The controller is a system with two inputs and one output. The inputs are the measured signal y and the reference signal r and the output is the control signal u.

Note that the control signal u is an input to the process and the output of the controller and that the measured signal is the output of the process and an input to the controller. In the figure above, the load disturbance was assumed to act on the process input. This is a simplification the disturbance can enter the process in many ways.

1.1. Issues in Feedback Control Systems

Many issues must be considered in analysis and design of control systems. Some of the basic requirements are:

- Stability of the systems - The possibility of instabilities is the primary drawback of feedback control systems. Avoiding instability is thus a primary goal.
- Ability to follow reference signals - It is also desirable that the process variable follows the reference signal faithfully.
- Reduction of effects of load disturbances - The system should also be able to reduce the effect of load disturbances.
- Reduction of effects of measurement noise - Measurement noise is injected into the system by the feedback. This is unavoidable, but it is essential that not too much noise is injected.
- Reduction of effects of model uncertainties - It must also be considered that the models used to design the control systems are inaccurate. The properties of the process may also change. The control system should be able to cope with moderate changes.

The focus on different abilities varies with the application. In process control, the major emphasis is often on attenuation of load disturbances, while the ability to follow reference signals is the primary concern in motion control systems.

1.2. Equations in Feedback Control Systems

The feedback loop in Figure 1 is influenced by three external signals, the reference r, the load disturbance d and the measurement noise n. There are at least three signals x, y and u that are of great interest for control.

This means that there are nine relations between the input and the output signals. Since the system is linear these relations can be expressed in terms of the transfer functions. Let X , Y, U, D, N and R be the Laplace transforms of x, y, u, d, n and r, respectively. The following relations are obtained from the block diagram in Figure 1.

$$X(s) = \frac{P(s)}{1+P(s)C(s)}D(s) - \frac{P(s)C(s)}{1+P(s)C(s)}N(s) + \frac{P(s)C(s)F(s)}{1+P(s)C(s)}R(s)$$
$$Y(s) = \frac{P(s)}{1+P(s)C(s)}D(s) + \frac{1}{1+P(s)C(s)}N(s) + \frac{P(s)C(s)F(s)}{1+P(s)C(s)}R(s)$$
$$U(s) = -\frac{P(s)C(s)}{1+P(s)C(s)}D(s) - \frac{C(s)}{1+P(s)C(s)}N(s) + \frac{C(s)F(s)}{1+P(s)C(s)}R(s)$$

To simplify notations, we have dropped the arguments of all Laplace transforms. There are several interesting conclusions we can draw from these equations. First, we can observe that several transfer functions are the same and that all relations are given by the following set of six transfer functions.

$$\frac{PCF}{1+PC} \qquad \frac{PC}{1+PC} \qquad \frac{P}{1+PC}$$
$$\frac{CF}{1+PC} \qquad \frac{C}{1+PC} \qquad \frac{1}{1+PC}$$

The transfer functions in the first column give the response of process variable and control signal to the set point. The second column gives the same signals in the case of pure error feedback when F = 1. The transfer function $P/(1 + PC)$ in the third column tells how the process variable reacts to load disturbances the transfer function $C/(1 + PC)$ gives the response of the control signal to measurement noise.

Notice that only four transfer functions are required to describe how the system reacts to load disturbance and the measurement noise and that two additional transfer functions are required to describe how the system responds to set point changes.

The special case when F + 1 is called a system with (pure) error feedback. In this case, all control actions are based on feedback from the error only. In this case, the system is completely characterized by four transfer functions, namely the four rightmost transfer functions in the list.

$\frac{PC}{1+PC}$ the complementary sensitivity function

$\frac{P}{1+PC}$ the load disturbance sensitivity function

$\frac{C}{1+PC}$ the load disturbance sensitivity function

$$\frac{1}{1+PC} \quad \text{the sensitivity function}$$

2. Mechanisms in Feedback Control Systems

Feedback in control systems is important for enabling the system to be aware of its conditions and its performance.

2.1. Feedback Control and Disturbance

We wish for the given system a controlled output i.e. the system gives output (O) that is equal to input (I), despite disturbances (D). This could be achieved by adding feedback system.

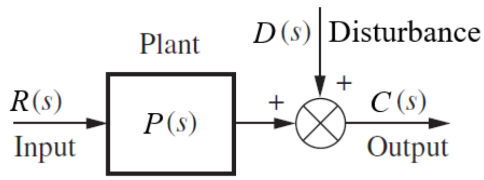
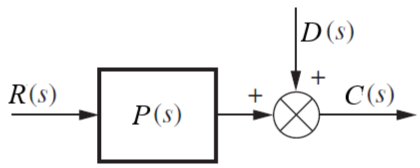


Figure 2: Open loop system with disturbance.

For an open-loop systems (i.e. without feedback) as shown above, the process or plant with a transfer function P, perturbed by a disturbance D. Depending on its magnitude, the disturbance might affect the system significantly.

Example for Tutorial 1: Performance of Open-Loop Feedback System

For an open-loop system as shown below, attempt the following tasks.



a. Suppose that the P is 10 and disturbance D is 0, determine the value of R so, the output of the system (C) becomes 1. [2 marks]

b. When P changes by 10% to 11, determine the value of output (C). Describe what would happen if disturbance were changed by 0.1. [2 marks]

Answer

a. If the output C is to be 1, just make the input R = 0.1.

b. But, if the P changes by 10% to 11, then the C changes by 10% to 1.1. If disturbance D is 0.1, then the C will also change by 0.1.

Now, we have closed-loop system with feedback added. Considering the 'closed loop' system below, the P represents the system or device being controlled and the C is the controller.

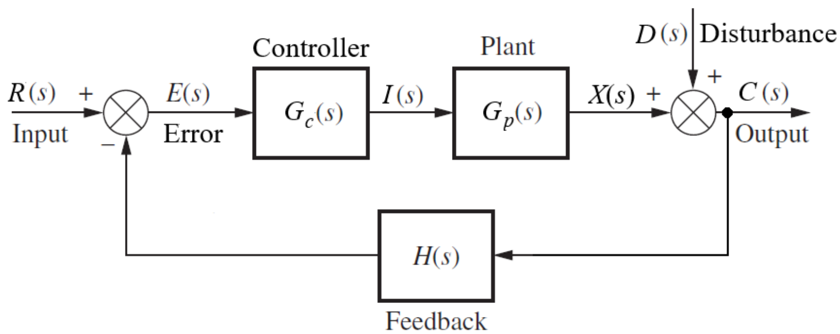


Figure 3: Feedback system and added controller with disturbance.

Considering a unity feedback system i.e. $H(s)$ = 1, the equation that represents the output of the system (C) is:

$$C = \left(\frac{G_C G_P}{1 + G_C G_P}\right) I + \left(\frac{1}{1 + G_C G_P}\right) D$$

For unity feedback, $H(s) = 1$, the error signal (E) is:

$$E = R - C \qquad (Eq.1)$$

The plant output (X) is:

$$X = E(G_C)(G_P) \qquad (Eq.2)$$

The output of feedback system with disturbance (C) is:

$$C = X + D \qquad (Eq.3)$$

From equation (3), knowing $X = C - D$, substitute the X in equation (2):

$$C - D = E(G_C)(G_P) \qquad (Eq.4)$$

Substituting E parameter in equation (4) with equation (1):

$$C - D = (R - C)(G_C)(G_P)$$

Rearranging the equation above, the output of the system is:

$$C = \left(\frac{G_C G_P}{1 + G_C G_P}\right) R + \left(\frac{1}{1 + G_C G_P}\right) D \qquad (\mathrm{Q.E.D})$$

Ignoring disturbances (D = 0), by applying feedback equation:

$$C = \left(\frac{G_C G_P}{1 + G_C G_P}\right) R$$

Example for Tutorial 2: Performance of Feedback System

For a unity feedback system equation as shown below, ignoring disturbances, perform the following tasks:

$$C = \left(\frac{G_C G_P}{1 + G_C G_P}\right) R + \left(\frac{1}{1 + G_C G_P}\right) D$$

a. If G_P is 10 and G_C and R are 1 and 10 respectively, determine the value of output (C). [2 marks]

b. Now change G_P to 11, but G_C and R are the same, determine the value of output (C). [2 marks]

c. Comment on the results obtained in part (a) and (b) [2 marks]

Answer

a. Ignoring disturbances (D = 0), by applying feedback equation, the output of the system is:

$$C = \left(\frac{G_C G_P}{1 + G_C G_P}\right) R$$

Let G_P = 10, as before, and G_C = 10, the output of the system is:

$$C = \left[\frac{(10)(10)}{1 + (10)(10)}\right] R = \left(\frac{100}{101}\right) R = (0.99)R$$

If R is 1, then C is 0.99 (i.e. it is within 1% of being 1).

b. But, if G_P changes to 11, then C = R (110/111) = 0.99. Thus, unlike the open-loop system, if R is 11, C is still about 0.99.

c. From the given example, we can conclude that negative feedback reduces effects on the output when the parameter of the system changes and it makes output almost the same as input.

2.2. Disturbances Control

For a unity feedback system (i.e. $H(s)$ = 1) with disturbance, the components of the system are as shown in the figure below.

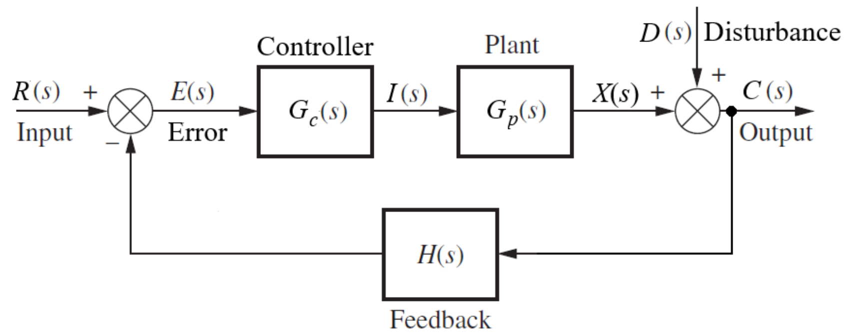


Figure 4: Feedback system and added controller with disturbance.

The equation that represents the output of the system for given input and disturbance is:

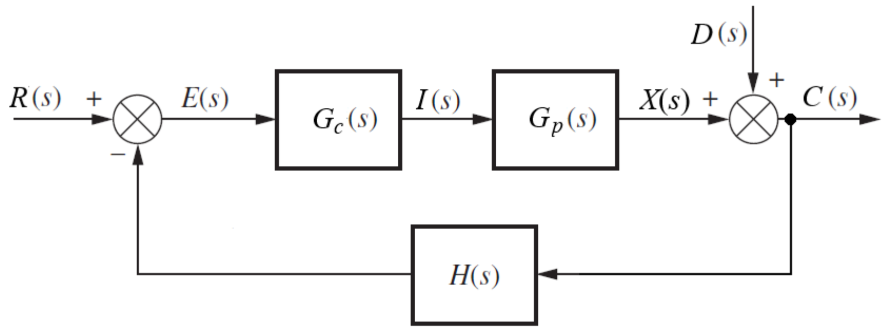
$$C = \left(\frac{G_C G_P}{1 + G_C G_P}\right) R + \left(\frac{1}{1 + G_C G_P}\right) D$$

To see the effect of disturbances, assume that the input, R is 0, then:

$$\frac{C}{D} = \frac{\text{Forward}}{1 - \text{Loop}} = \frac{1}{1 + G_C G_P}$$

Example for Tutorial 3: Disturbance in Feedback System

For a unity feedback system with disturbance, determine the output of the system (C) if G_C = 10, G_P = 10, and D = 0.1. Does feedback have any impact on the disturbance in the system? [2 marks]



Answer

For unity feedback (i.e. $H(s)$ = 1), G_C = 10, G_P = 10, and D = 0.1, the output due to disturbance only is:

$$\frac{C}{D} = \frac{\text{Forward}}{1 - \text{Loop}} = \frac{1}{1 + G_C G_P}$$

Thus

$$C = \left[\frac{1}{1 + (10)(10)}\right] 0.1 = \frac{0.1}{101} = 0.00099$$

Based on the result given above, it seems that feedback contributes to significant reduction of the disturbance in the system.

2.3. Principle of Superposition

For a unity feedback system i.e. $H(s)$ = 1, if $G_C G_P$ large, then the output, the output is approximately very close to input, C ~ R + 0 = R.

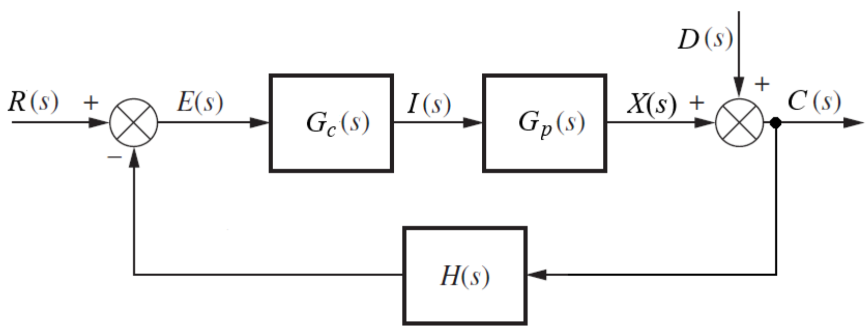


Figure 5: Feedback system and added controller with disturbance.

So, feedback makes output almost the same as input. It reduces effect of change in device and minimises effects of disturbances. This relationship is true if the 'loop gain', $G_C G_P$, is high.

$$C = \left(\frac{G_C G_P}{1 + G_C G_P}\right) R + \left(\frac{1}{1 + G_C G_P}\right) D$$

Note: We can't just keep increasing the 'gain' of C. We need to consider the dynamics of the blocks e.g. there could be a block in the feedback path which would be affected.

3. Effects of Feedback on Control System

By applying feedback in the control systems, it can influence and effect the characteristics and behaviours of the control systems.

3.1. Effects of Feedback on Gain

Negative feedback reduces the error between the reference input, $R(s)$ and system output.

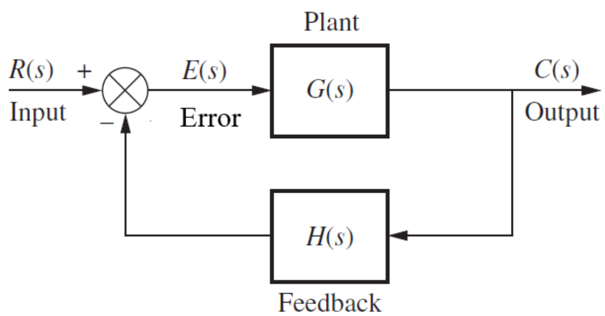


Figure 6: Gain in the feedback control system.

From the equation below, we can say that the overall gain of negative feedback closed loop control system is the ratio of 'G' and $(1 + GH)$. Thus:

$$\text{Gain} = \left|\frac{G}{1 + GH}\right|$$

And

$$T = \frac{G}{1 + GH}$$

So, the overall gain may increase or decrease depending on the value of $(1 + GH)$.

- If the value of $(1 + GH)$ is less than 1, then the overall gain increases. In this case, 'GH' value is negative because the gain of the feedback path is negative.
- If the value of $(1 + GH)$ is greater than 1, then the overall gain decreases. In this case, 'GH' value is positive because the gain of the feedback path is positive.

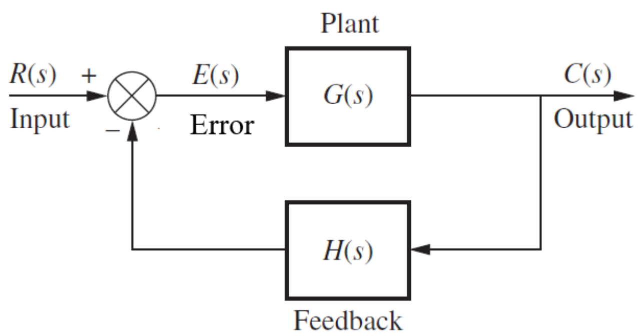
In general, 'G' and 'H' are functions of frequency. So, the feedback will increase the overall gain of the system in one frequency range and decrease in the other frequency range.

3.2. Effects of Feedback on Stability

A system is said to be stable if its output is under control. Otherwise, it is said to be unstable.

$$T = \frac{G}{1 + GH} \quad (\text{e.g.}\, 1 + GH = \text{characteristic equation})$$

In the equation above, if the denominator value is zero (i.e. $GH = -1$), then the output of the control system will be infinite. So, the control system becomes unstable.



Note: $1 + GH =$ characteristic equation

Figure 7: Stability in feedback control system.

Therefore, we must properly choose the feedback to make the control system stable. We will look more closely the stability of control system in the subsequent topic in this course.

3.3. Effects of Feedback on Noise

To know the effect of feedback on noise, let us compare the transfer function relations with and without feedback due to noise signal alone. Consider an open-loop control system with noise signal as shown below.

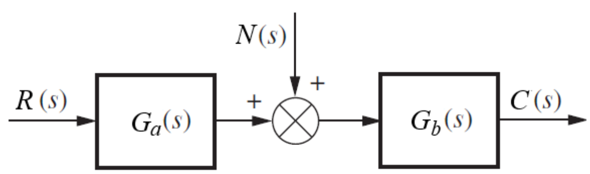


Figure 8: Open-loop control system with noise signal.

By making the other input $R(s)$ equal to zero, the open-loop transfer function due to noise signal alone is:

$$\frac{C(s)}{N(s)} = G_b$$

Consider a closed-loop control system with noise signal as shown below.

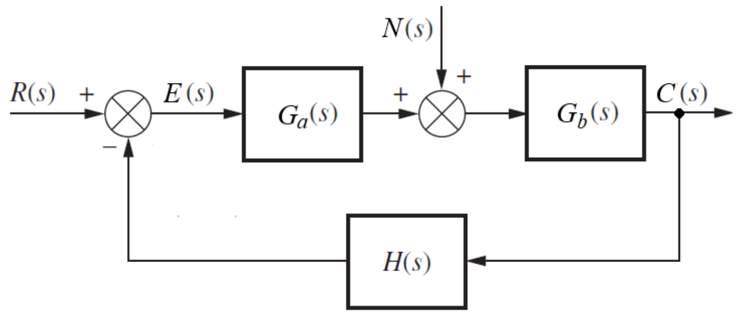


Figure 9: Closed-loop control system with noise signal.

By making the other input $R(s)$ equal to zero, the closed-loop transfer function due to noise signal alone is:

$$\frac{C(s)}{N(s)} = \frac{G_b}{(1 + G_a G_b H)}$$

When we compare the open-loop transfer function equation due to noise with the closed-loop transfer function equation due to noise, in the closed-loop control system, the gain due to noise signal is decreased by a factor of $(1 + G_a G_b H)$ provided that the term $(1 + G_a G_b H)$ is greater than one.

As a result, feedback reduces impact of the noise on the system.

3.4. Sensitivity of System Parameters

The changes in system parameters affect the behaviour of a system. Ideally, parameter changes due to heat, or other causes should not appreciably affect a system's performance.

The degree to which changes in system parameters affect system transfer functions, and hence performance, is called sensitivity.

A system with zero sensitivity (that is, changes in the system parameters have no effect on the transfer function) is ideal. The greater the sensitivity, the less desirable the effect of a parameter change.

Based upon the previous discussion, let us formalise a definition of sensitivity:

Sensitivity is the ratio of the fractional change in the function to the fractional change in the parameter as the fractional change of the parameter approaches zero. That is,

$$S_{F:P} = \lim_{\Delta P \to 0} \frac{\text{Fractional change in the function}, F}{\text{Fractional change in the parameters}, \ P}$$

$$= \lim_{\Delta P \to 0} \frac{\Delta F / F}{\Delta P / P} = \lim_{\Delta P \to 0} \frac{P \Delta F}{F \Delta P}$$

which reduces to:

$$S_{F:P} = \lim_{\Delta P \to 0} \frac{P\delta F}{F\delta P}$$

3.5. Effects of Feedback on Sensitivity (of the Components)

Sensitivity of the overall gain of negative feedback closed-loop control system (T) to the variation in open-loop gain (G) is defined as:

$$S_G^T = \frac{\frac{\partial T}{T}}{\frac{\partial G}{G}} = \frac{\text{Percentage change in } T}{\text{Percentage change in } G}$$

Where: ∂T is the incremental change in T due to incremental change in G.

We can rewrite the equation above as:

$$S_G^T = \frac{\partial T}{\partial G}\left(\frac{G}{T}\right)$$

Do partial differentiation with respect to G on both sides of basic equation for feedback system.

$$\frac{\partial T}{\partial G} = \frac{\partial\left(\frac{G}{1+GH}\right)}{\partial G}$$

Since this partial differentiation is in a form of u'/v', then:

$$\frac{u'}{v'} = \frac{u'v - uv'}{v^2}$$

As a result, the partial differentiation becomes:

$$\frac{\partial T}{\partial G} = \frac{(1)(1+GH) - (GH)}{(1+GH)^2} = \frac{1}{(1+GH)^2}$$

From basic equation for feedback system, you will get:

$$T = \frac{G}{1+GH}$$

Thus

$$\frac{G}{T} = 1 + GH$$

Substitute the above given equations as below.

$$S_G^T = \frac{\partial T}{\partial G}\left(\frac{G}{T}\right) = \left[\frac{1}{(1+GH)^2}\right](1+GH) = \frac{1}{(1+GH)}$$

Thus, we got the sensitivity of the overall gain of closed loop control system as the reciprocal of $(1 + GH)$. So, sensitivity may increase or decrease depending on the value of $(1 + GH)$.

- If the value of $(1 + GH)$ is less than 1, then sensitivity increases. In this case, 'GH' value is negative because the gain of feedback path is negative.

- If the value of $(1 + GH)$ is greater than 1, then sensitivity decreases. In this case, 'GH' value is positive because the gain of feedback path is positive.

In general, 'G' and 'H' are functions of frequency. As a result, feedback will increase the sensitivity of the system gain in one frequency range and decrease in the other frequency range. Therefore, we have to choose the values of 'GH' in such a way that the system is insensitive or less sensitive to parameter variations.

Example for Tutorial 4: Sensitivity of System

For example, assume a system described as a transfer-function equation as shown below:

$$F = \frac{K}{K + a}$$

a. Determine the value of F when K = 10 and a = 100. [2 marks]

b. If you triple the value of a, determine the value of F now. [2 marks]

c. Comment on the results obtained in parts (a) and (b). [2 marks]

d. Describe the advantage of feedback based on your comment given in part (c). [2 marks]

Answer

a. If K = 10 and a = 100, then F = 0.091.

b. If parameter a triples to 300, then F = 0.032.

c. We see that a fractional change in parameter a of $(300 - 100)/100 = 2$ (a 200% change) yields a change in the function F of $(0.032 - 0.091)/0.091 = 0.65$ (65% change). Thus, the function F has reduced sensitivity to changes in parameter a.

d. As we proceed, we will see that another advantage of feedback is that in general it affords reduced sensitivity to parameter changes.

4. Feedforward Control System

Beside feedback system, there is also a type of control system which is called feedforward control system.

4.1. Feedforward Control System

Feedforward control system has a control element that responds to changes in command or measured disturbance in a pre-defined way. It is based on prediction of plant behavior (requires model). Feedforward control system can react before error occurs:

- Overcome sluggish dynamics and delays.
- Does not jeopardise stability.

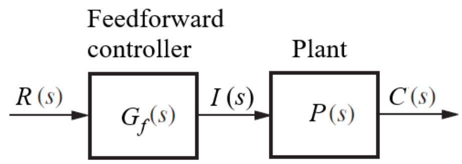


Figure 10: Feedforward system.

4.2. Example of Feedforward System

One of the feedforward control implementations is a model-based prediction of input. Ideally, it consists of exact inverse model of the plant. It can compensate for known plant dynamics and delays (before you get errors). In this example of feedforward system, there are no sensors needed. In the model-based prediction system, the system response must be predictable.

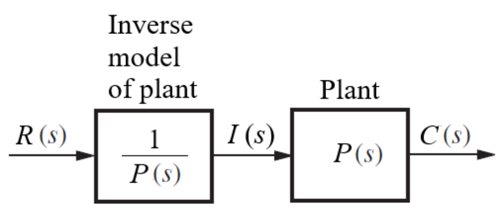


Figure 11: Example of feedforward system.

4.3. Limitation of Feedforward System

There are several limitations of feedforward system:

- The disturbance variables must be measured online. In many applications, this is not feasible.
- To make effective use of feed-forward control, at least an approximate process model should be available. We need to know how the controlled variable responds to changes in both the disturbance and manipulated variables. The quality of feed-forward control depends on the accuracy of the process model.
- Ideal feed-forward controllers that are theoretically capable of achieving perfect control may not be physically realisable. Fortunately, practical approximations of these ideal controllers often provide very effective control.

4.4. Differences between Feedforward and Feedback

There are several differences between feedforward system and feedback system. As illustrated in the figure below, R = set point input, D = Disturbance, I = control signal and C = output.

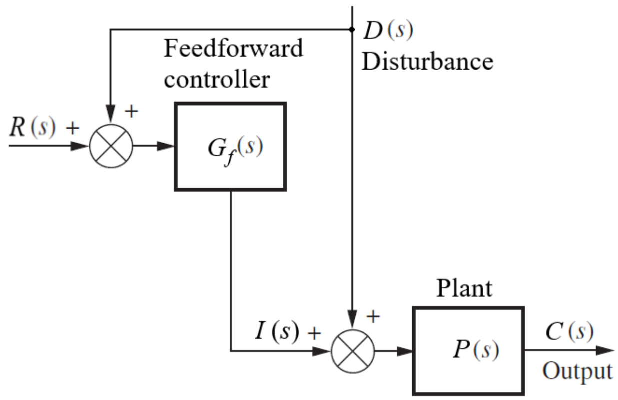


Figure 12: Feedforward control system

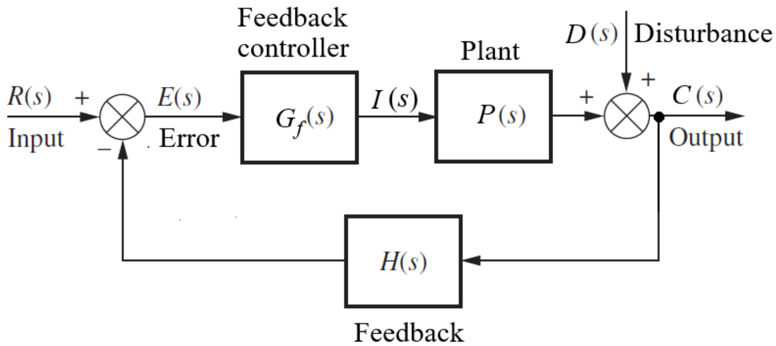


Figure 13: Feedback control system.

For signal output, feedback system depends on the generated feedback signal whereas in the feedforward system the signal is passed to some external load. Difference when we measure of disturbance in the system, it is not needed by feedback, but it is needed by feedback system.

For disturbances, it is detected in feedback system, but it is not detected in feedforward system. The loop in the feedback system is a closed loop and feedforward is open loop.

The focus of feedback system is the output of the system, and the feedforward system puts emphasis on the input of the system. The variable of feedback system is adjusted based on errors whereas it is adjusted based on knowledge in the feedforward system.

Category	**Feedback System**	**Feedforward System**

Signal	Output depends on the generated feedback signal.	The signal is passed to some external load.
Measure of disturbance	Not needed by feedback system	Needed by feedforward system.
Disturbances	Detected in feedback system	Not detected in feedforward system
Loop	Closed loop	Open loop
Focus	Output of the system	Input of the system
Variable	Adjusted based on errors	Adjusted based on knowledge

Table 1: Differences between feedforward system and feedback system.

4.5. Combining Feedback and Feedforward

Feedforward and feedback are often used together:

- Feedforward component provides rapid response.
- Feedback component fills in the rest of the response accurately, compensating for errors in the model.

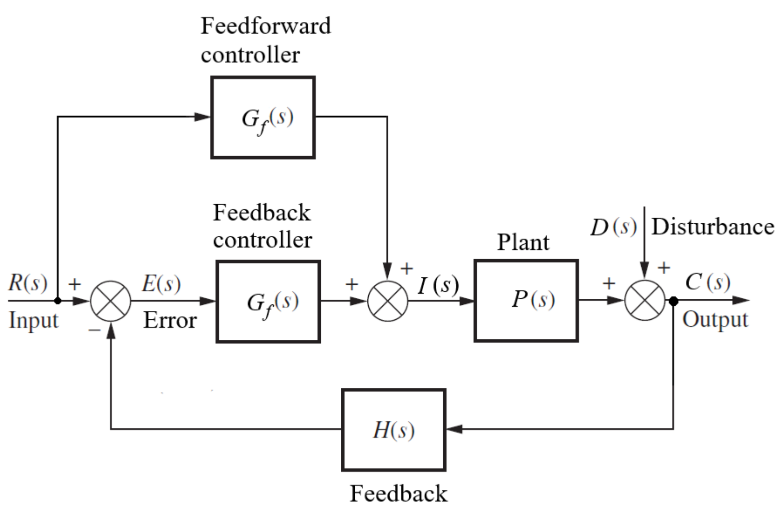
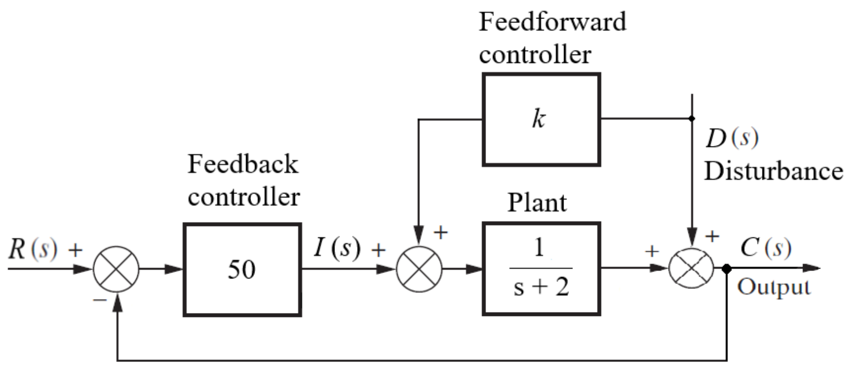


Figure 14: Combining feedback and feedforward.

Example for Tutorial 5: Feedforward System

Consider the control system shown in the figure below with feedforward action for rejection of a measurable disturbance $D(s)$. Determine the value of k, for which the disturbance response at the output $C(s)$ is zero mean.



Answer

Referring to the block diagram given above, the equation for the system is:

$$C(s) = [-50C(s) + kD(s)]\left(\frac{1}{s+2}\right) + D(s)$$

Rearranging the equation given above, it becomes:

$$C(s)\left[1 + \frac{50}{(s+2)}\right] = \left[\frac{k}{(s+2)} + 1\right]D(s)$$

Thus, the transfer function equation of the system is:

$$C(s) = \left(\frac{k+s+2}{s+52}\right)D(s)$$

In the frequency domain, the equation above is now:

$$C(j\omega) = \left(\frac{k+j\omega+2}{j\omega+52}\right)D(j\omega)$$

The disturbance response at the output $C(s)$ is zero mean.

At $\omega = 0$, $C(j0) = 0$, thus:

$$\frac{k+0+2}{0+52} = 0$$

As a result, solving the equation above the value of k is -2.

5. Input Signals

In control systems, there are various types of standardised input that are typically used for evaluating and testing of the systems e.g. impulse, step, ramp, and sinusoid signals. The other types of input in practice are parabolic, square wave, triangle wave, PWM, etc.

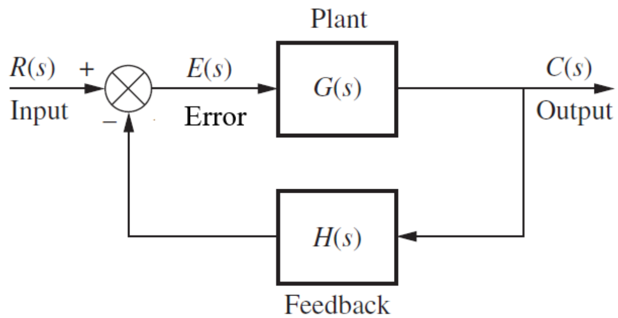


Figure 15: Input and output in control system.

These various inputs are needed to cope with different characteristics and behaviours of practical control systems that exist out there. As shown in the figure above, multiple inputs can be incorporated for testing and evaluation of the systems.

Often that the testing and evaluation involves some disturbances to be introduced into the system. These enable us to look for the characteristics and behaviour of the system beyond ideal system operation.

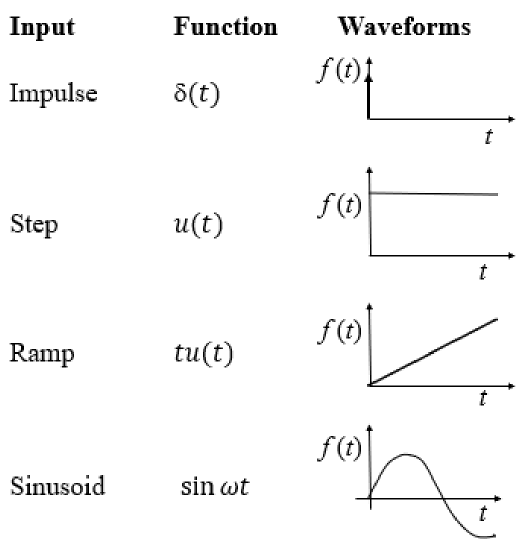


Figure 16: Typical inputs for system testing in control system.

For these standard inputs typically used for evaluating and testing the system in control system:

- An impulse input is a very high-amplitude pulse applied to a system over a very short time (i.e., it is not maintained for a long period of time). That is, the magnitude of the input approaches infinity while the time approaches zero.
- A step input is instantaneously applied at some time (typically taken as zero) and thereafter held at a constant level.

- A ramp input increases linearly with time. However, in practice, there is a physical limit, or the dynamic problem ends before the input gets too large.
- A sinusoid input is typically used for applying a sinusoid signal into the system.

6. Controller in Feedback System

A controller is one of the most important components of the control system. It is typically designed to be responsible for the management and control of the performance of the system. It is a device or an algorithm that works to maintain the value of the controlled variable at set point.

As shown in the figure below, a control system can control its output(s) to a particular value or perform a sequence of events or perform an event if the specified conditions are satisfied based on the input(s) given.

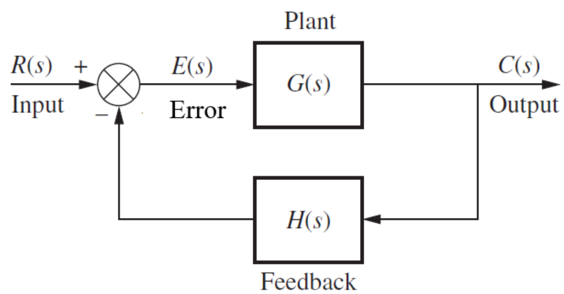


Figure 17: Controller in a process control system.

The controller receives the difference between the reference set point and the measured output (e.g. known as the error) and generates a control action to make the error to zero. The generated control action manipulates the process variable closer to set point.

6.1. Measurements in Controller

The measurement system consists of a sensor and transmitter. As shown in the figure below, the sensor measures the process variable and produces mechanical, electrical, or other related phenomena. The transmitter converts the phenomenon into a signal that is suitable for transmission.

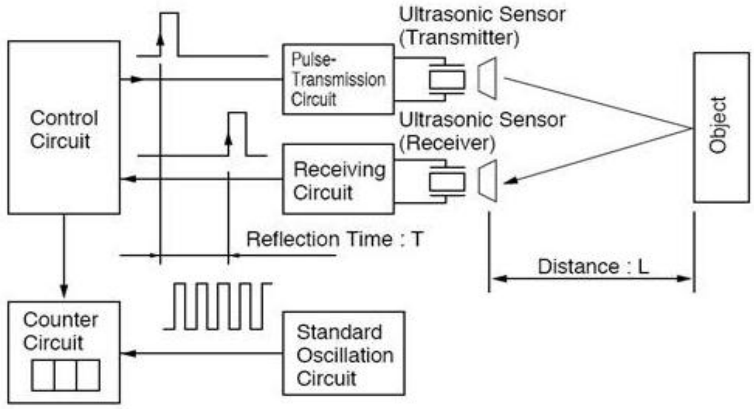


Figure 18: Measurements in controller

6.2. Types of Controllers

Types of controllers in control systems engineering:

- Proportional controller (P)
- Integral controller (I)
- Derivative controller (D)
- Any combination of above e.g. PD, PI, PID, etc.

Other types:

- Fuzzy logic controller.
- Model based controller.
- Neural network controller.

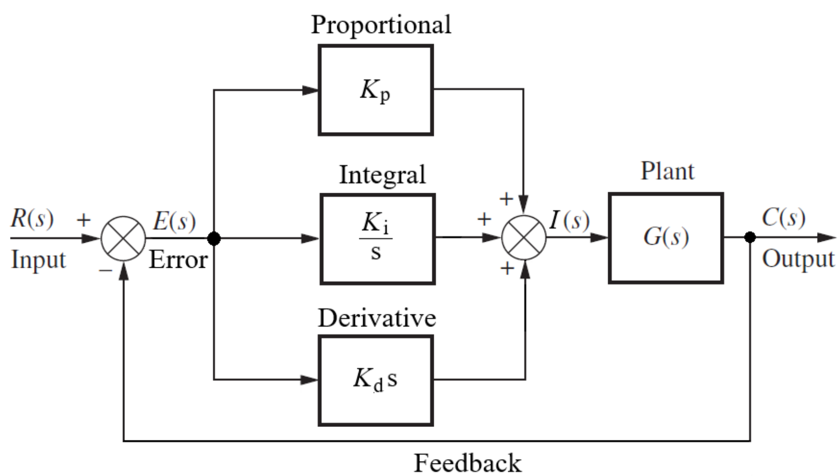


Figure 19: Types of controllers in control systems

7. Compensator

Compensators are used for changing the characteristics and behavior of a system. To obtain the desired performance of the given control system, we use compensators. Compensators are applied to the system in the form of feed forward path gain adjustment.

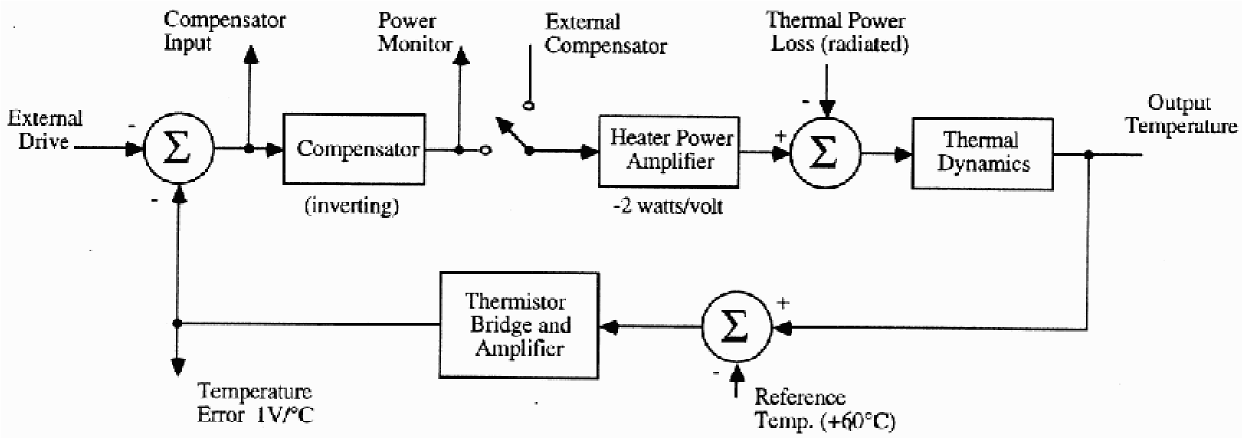


Figure 20: Practical compensator used in a control system.

7.1. Methods of Compensation

Compensator is a type of controller which makes some adjustments to make up for deficiencies in the system.

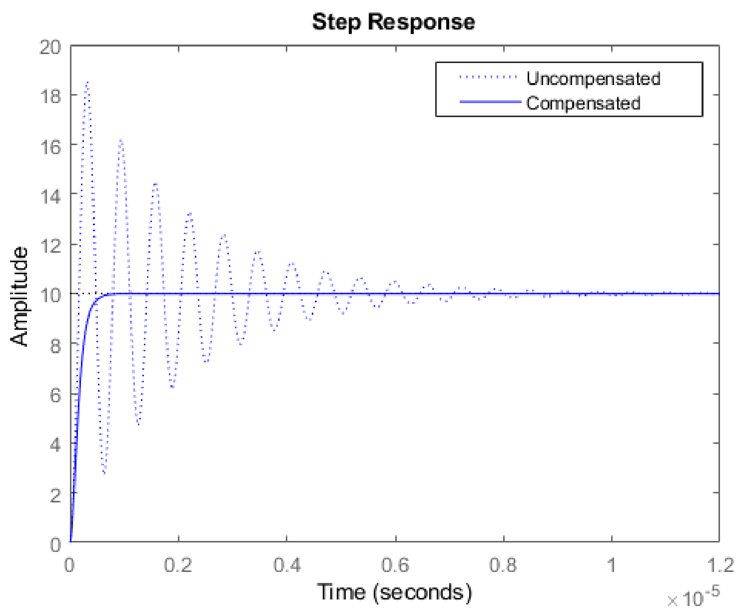


Figure 21: Step response of uncompensated vs. compensated systems

Compensating devices are maybe in the form of electrical, mechanical, hydraulic etc. Most electrical compensator are RC filter.

7.2. Why Do We Need Compensator?

Reasons or rationales on why we need compensator:

- Compensate an unstable system to make it stable.
- A compensating network is used to minimise overshot.
- Compensators could increase the steady state accuracy of the system. An important point to be noted here is that the increase in the steady-state accuracy could bring instability to the system.
- Compensator could also introduce poles and zeros in the system, thereby causes changes in the transfer function of the system. Due to this, performance specifications of the system could potentially change.

7.3. Types of Compensators

Methods of compensation:

- Series compensator.
- Feedback compensator.
- Load compensator.

The simplest compensating network used for compensators in control systems engineering are known as:

- Lead compensators.
- Lag compensators.
- Lead-lag compensators.

7.3.1. Series Compensator

Series compensator: connecting compensating circuit between error detector and plants known as series compensation. Series compensator is implemented if the plant ($G(s)$) is a small-scale system. It is connected in series with the plant means faster response as any change will be immediately processed by the plant.

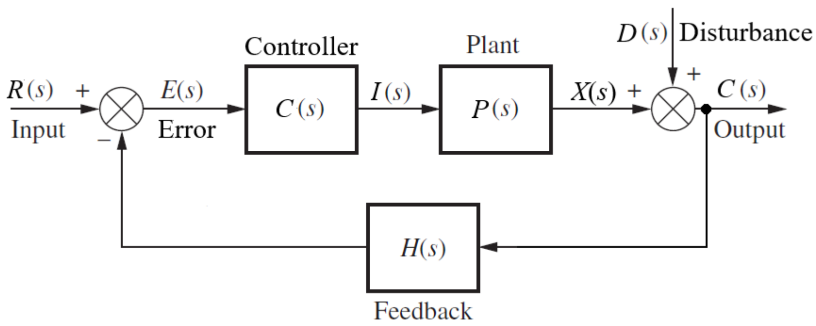


Figure 22: Series compensator

7.3.2. Feedback Compensator

Feedback compensator: when a compensator used in a feedback manner called feedback compensation. This arrangement is considered when plant ($G(s)$) is large in scale or control action is complex. As shown below, the compensator is implemented in the feedback loop.

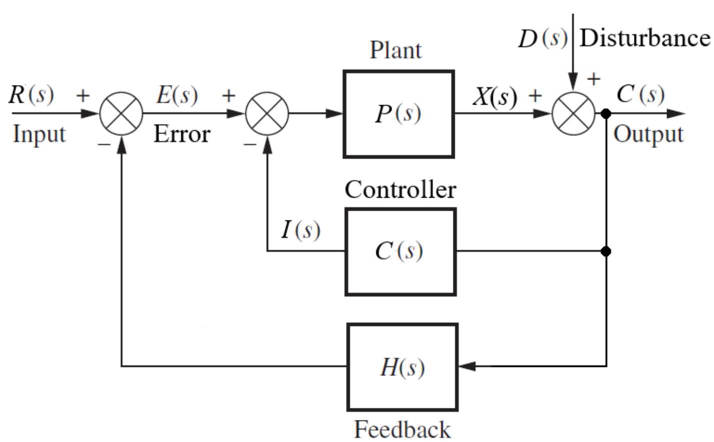


Figure 23: Feedback compensator

7.3.3. Load Compensator

A combination of series and feedback compensator is called load compensation. This is often implemented to accommodate both speed (open loop) and accuracy or complexity (i.e. feedback loop).

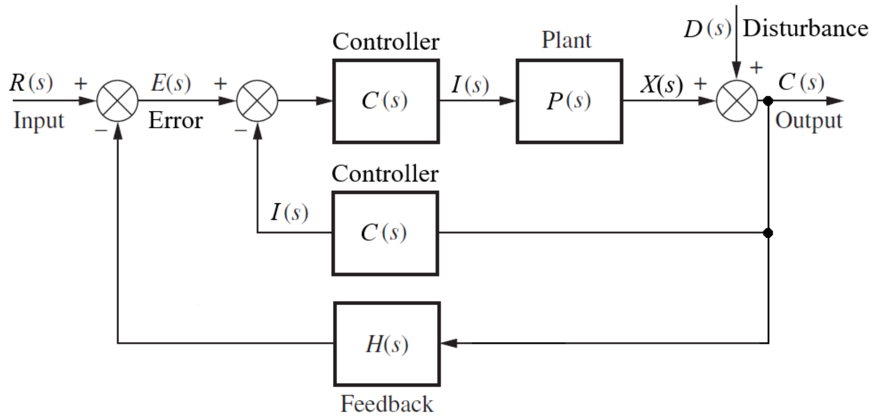


Figure 24: Load compensator