Control Principles 1

Learning Outcomes

This chapter introduces the basic principles and concepts of control systems. On completion, you should be able to:

1. Compare and differentiate between simple open-loop and closed-loop control systems.
2. Compare the relative advantages and disadvantages of these systems.
3. Describe examples of such systems, in both engineering and non-engineering situations.
4. Derive the transfer function for simple control systems.
5. Appreciate the causes of instability in closed-loop control systems.
6. Describe the response of a control system, when subjected to a step input.

1 Introduction

The subject of automatic control is a fairly complex one. This chapter, therefore, is designed to give you an insight and 'feel' for the underlying principles involved. It is therefore mainly descriptive, and the mathematical content is minimal.

When the term 'automatic control' is used, most people would take this as applying to some form of engineering system. However, the control principles used in engineering systems apply equally to many other situations. Despite the very wide range of control systems, they may all be analysed by using the same techniques. In this regard, the use of analogies is very useful.

2 Non-engineering Applications

A few examples of non-engineering applications of control systems are as follows:

Budgetary control	Management	Educational systems
Economic systems	Marketing	Medical systems
Public transport	Commerce	Human behaviour

It should be apparent that, in all of the above areas, a formalised control is essential. Ideally, the control would be perfect. Unfortunately, in the real world most systems are far from perfect. The main problem with the above examples is that, in each case, there are many variables to take into account. Hence, the system of control needs to be very complex. Thus, if only one of the variables goes out of control, this tends to have a 'knock-on' effect—often with drastic results. Most engineering control systems deal with only one or two variables at a time. They are therefore capable of performing with much greater precision.

3 Engineering Applications

Some common examples of engineering control systems are:

Machine tool operation
Temperature control
Generator output control
Liquid and bulk level control
Automatic pilots for aircraft and ships
Radio telescope positioning
Video recorder drives
Motor vehicle power steering and antilock braking
Assembly of electronic components

The variables most commonly requiring control are: Linear and angular position; velocity; pressure; voltage and current; flow rate.

4 Classification of Control Systems

Any control system consists of separate components or elements, which are interconnected in order to regulate or control a variable quantity or process. The behaviour of each individual element will affect the behaviour of the whole system. All systems will have a demand or reference (input) **signal**, and a corresponding output **signal**.

> In this context the term **signal** is used in its widest sense. It refers to the quantity involved; thus it may be a mechanical position, a pressure, a voltage, or some other physical quantity

Control systems may be classified into one of two main groups. These are open-loop and closed-loop systems. The essential difference is that, in closed-loop control some form of feedback of information is provided, between output and input. This use of feedback enables *automatic* corrective action, if the output deviates from the demanded value. Open-loop systems do not have any provision for such feedback. Thus, once an input demand has been made the system is left to respond, in the hope that it will respond correctly. A simple example of an open-loop system is that of a golfer making a tee shot. Let us assume that the club strikes the ball at exactly the correct angle, and with exactly the right force. Once the ball leaves the club face, the golfer has no further control over it. Thus, if there is a sudden gust of wind, or the ball hits a small bump on the fairway, it will not come to rest at the intended spot.

5 Open-loop Systems

These are the simplest form of control system. They are not necessarily the best solution, but for some applications, may be sufficient. Consider the following examples:

1 A simple electric fire is used to heat a room. When the supply is turned on, the room temperature increases. However, without any further intervention the room will probably become too warm. The only way to correct this would be to turn off the supply. This system is illustrated in the **block diagram** (Fig. 1), which also shows the various signals involved.

> A **block diagram** is a means of showing the interconnections in a system. Each element in the system is represented by a box, which is used to identify its function. It allows the overall function of the system to be readily seen, without showing every single detail of each element. It also enables the signal paths to be clearly seen

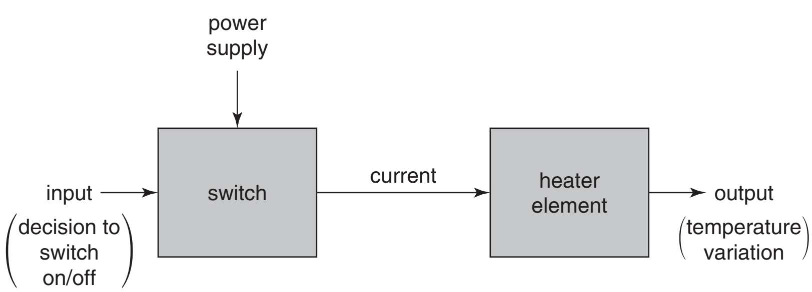

Fig. 1

2 A generator is driven by a steam turbine. The voltage output of the generator depends upon its speed. Its speed depends upon the steam pressure into the turbine. Thus, to achieve a particular output voltage, the steam pressure is adjusted accordingly. If the electrical

load on the generator is suddenly increased, its terminal voltage will fall. This condition is not therefore automatically corrected. The block diagram is shown in Fig. 2.

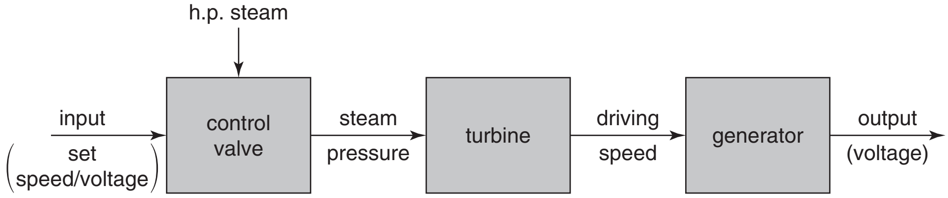

Fig. 2

6 Closed-loop Systems

A closed-loop system must have some means of comparing the value of its output with the desired value. This involves feeding back information about the output, and making the comparison. Thus, a feedback loop is required, which will form one input to a device known as a *comparator*. The other input to the comparator will be the demand or reference signal. If there is any difference between the desired and actual values of the output, the comparator will produce the appropriate output signal. This signal is known as the *error signal*. Hence, all closed-loop systems are said to be *error actuated*.

Consider the two previous open-loop examples. Each of these could be converted to closed-loop, as follows:

1 By installing a room thermostat, the desired temperature may be set. In addition, the actual temperature of the room can be compared with the desired value. The comparison element in the thermostat is a bimetallic strip. The two metals involved have different coefficients of expansion. Thus, as the temperature varies, so the strip bends. One end of the strip is fixed, and the other end moves the position of an electrical contact. The temperature setting dial alters the effective spacing between a second electrical contact and that operated by the bimetallic strip. By this means, the electrical supply to the heater can be switched. The block diagram is shown in Fig. 3.

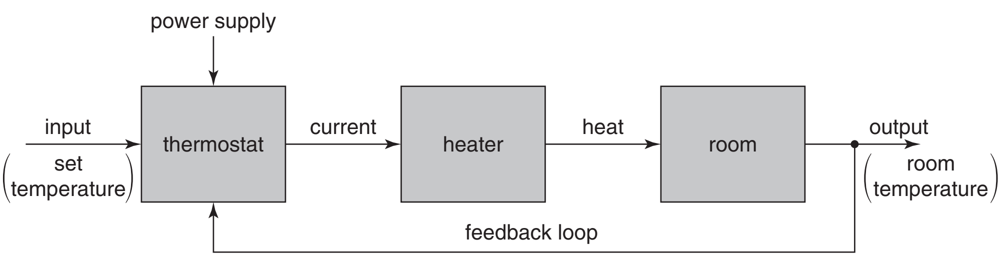

Fig. 3

Dead-band is the range of input change to which the system does not respond

Note: In this example, there is not a direct physical feedback path. However, the temperature of the air in the room completes the feedback loop.

This form of control is known as ON/OFF closed-loop control. The graph of the variations in room temperature are shown in Fig. 4. From this, it may be seen that the temperature varies about the desired value. The resulting **dead-band** is typical of any ON/OFF closed-loop control system. The reason for the dead-band in this example, is the response time of the heater element. When the desired temperature is achieved, the thermostat disconnects the heater. However, the heater element will take a certain amount of time to cool. The room temperature will therefore continue to increase slightly. Similarly, when the room starts to cool, there will be a small time lag in the response of the bimetallic strip. The heater element will also take some time to reach its operating temperature. These two delays together account for the room temperature falling below the desired value.

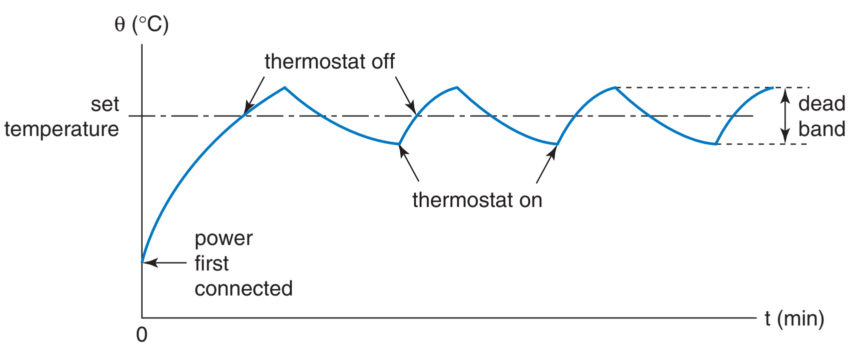

Fig. 4

2 For the generator system, the loop could be closed in a number of ways. Firstly, let us consider the use of a human operator. The voltage output of the generator could be displayed on a voltmeter, and the operator could then observe any variation of output. When such a change occurred, the operator could adjust the control valve accordingly. Although, technically, this would constitute a closed-loop system, it would be a very unsatisfactory one. The operator would at some stage start to daydream, fall asleep, or need to take a break. This would then break the feedback loop. Even if the operator could stay fully alert all the time, his/her response in applying the necessary corrections would be relatively slow. In addition, it is quite likely that over/under corrections would result, particularly if the load variations were quite rapid. In order to make the system truly automatic, with a fast reaction time, and not subject to fatigue etc., the human operator must be replaced.

One method of achieving this would be as follows. A **tachogenerator** would be attached to the generator drive shaft. This would provide a feedback signal (voltage) that *represents* the output of the generator. The steam control valve would be a motorised valve. The comparator would be in the form of either a **differential amplifier** or a **summing amplifier**.The demand signal input to the comparator would be derived from a potentiometer. The corresponding block diagram is shown in Fig. 5.

A **tachogenerator** (or 'tacho') is a small d.c. generator which will produce an output voltage that is directly proportional to its speed.

A **differential amplifier** is one which has two input terminals. The output of the amplifier is equal to the *difference* between its inputs.

A **summing amplifier** is one which also has two (or more) input terminals. Its output is the sum of the inputs. However, if one input is of the opposite polarity to the other, then the output will be equal to the *difference* between its inputs.

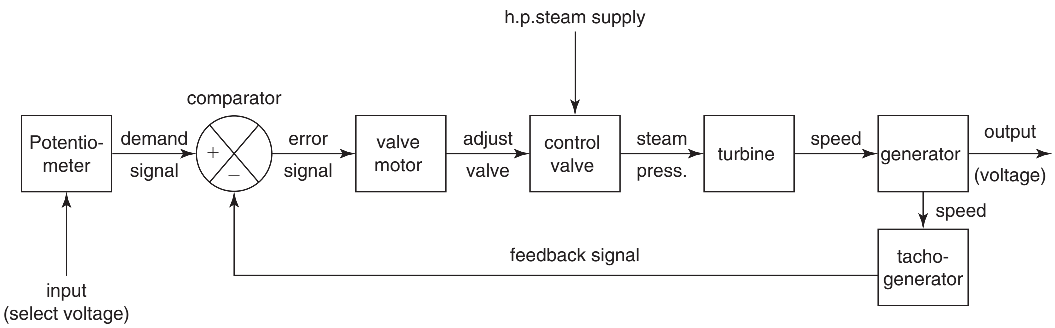

Fig. 5

The system operates as follows. The desired output voltage is dialled up on the rotary potentiometer at the input. The movable contact on this potentiometer therefore provides the demand signal to the comparator. Assuming that the generator is stationary at this time, a large error signal is then fed to the steam valve motor. This, in turn, will open the valve. The generator now starts to build up speed, and consequently starts to generate an output voltage. The tachogenerator now provides a feedback signal to the comparator. The resulting error voltage therefore decreases. The valve motor continues to open the valve, but at a slower rate. When the generator achieves the correct speed to produce the demanded output voltage, the tachogenerator feedback voltage will be equal to the demand signal voltage from the potentiometer. The error signal to the valve motor will now be zero. This motor stops, and the generator continues to run at the set speed. If, at some later stage, the generator load varies, the slight change in its speed will cause a change in the feedback signal from the tachogenerator. This will produce an error signal from the comparator. The steam valve motor will then automatically adjust the speed, and rapidly return the output voltage to the demanded value.

Note: The circular symbol, with a 'cross' inside, is the general symbol for a comparator. It should also be noted that the demand input to this element is marked with a plus sign, and the feedback signal with a minus sign. This is to indicate that the two signals are in opposition to each other. It also indicates that *negative* feedback is employed.

This form of closed-loop control is known as continuous control. The system is, of course, error actuated, as is the ON/OFF temperature control system described. In the latter case, this resulted in a comparatively large dead-band, and a continuous variation of the temperature, about the demanded value. In the continuous control system these large fluctuations of output do not usually occur. This is because, when the output starts to vary from the desired value, the corrective action is almost instantaneous. Thus, any deviation from demanded value is very brief, and consequently very small. In addition, if the load on the generator remains constant, there will be no deviation from the desired output.

7 Transfer Functions and Block Diagrams

The transfer function of an element is the ratio of its output quantity to its input quantity. This ratio should not be confused with efficiency. The efficiency of a device is the ratio of the output *power* to the input *power.* It is usual for the output of an element to be a different physical quantity to the input. For example, consider a rotary potentiometer. The input is in the form of a mechanical displacement of the movable contact. The output is the voltage tapped off from the potentiometer track. Figure 6 shows the electrical arrangement, and Fig. 7 the system

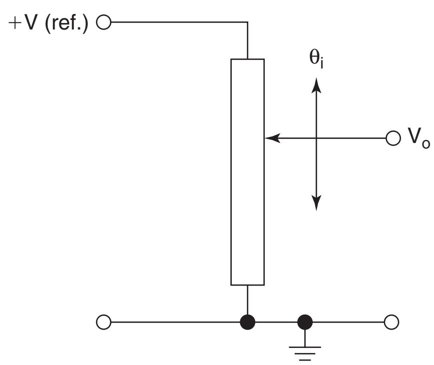

Fig. 6

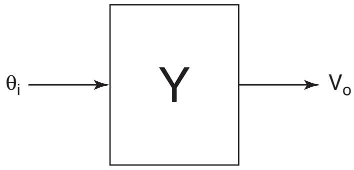

Fig. 7

block diagram. When a control system is shown in block diagram form, it is normal practice to write the appropriate transfer function in each block.

Considering Fig. 7, the transfer function, Y for the potentiometer is:

$$Y = \frac{V_o}{\theta_i} \text{ volt/rad} \tag{1}$$

or, in terms of the output of the block:

$$V_o = Y\theta_i \text{ volt} \tag{2}$$

When dealing with a complete control system, the overall transfer function for the system is a combination of the individual transfer functions. For an open-loop system, the overall transfer function is simply the product of the individual transfer functions. Consider the generalised open-loop system shown in Fig. 8.

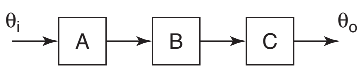

Fig. 8

The output of the first element will be A × its input. Thus the output of the first block is $A\theta_i$. This then forms the input to the next block, the output of which will be $AB\theta_i$. Following this sequence through to the output, we have

$$\theta_o = ABC\theta_i$$

hence, the overall transfer function is:

$$\frac{\theta_o}{\theta_i} = ABC \tag{3}$$

A generalised closed-loop control system is shown in Fig. 9. The overall transfer function for this system can be derived in a similar manner, as follows

$$\begin{aligned}\text{input to first block} &= \theta_i - \theta_o \\ \text{input to second block} &= A(\theta_i - \theta_o)\end{aligned}$$

$$\text{input to third block} = AM(\theta_i - \theta_o)$$
$$\text{therefore, output, } \theta_o = AML(\theta_i - \theta_o)$$
$$\text{so, } \theta_o = AML\theta_i - AML\theta_o$$
$$\text{hence, } \theta_o(1 + AML) = AML\theta_o$$
$$\text{and } \frac{\theta_o}{\theta_1} = \frac{AML}{1 + AML} \quad (4)$$

Note: The symbol (θ) used above may refer to *any* physical property. It does not imply that both the input and output quantities are angles.

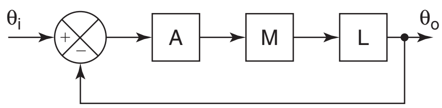

Fig. 9

Worked Example 1

Q **A simple open-loop speed control system consists of an electronic amplifier and a motor. The block diagram is shown in Fig. 10, where V_i is the input demand signal. The transfer function, A, for the amplifier is 10 V/V, and that for the motor, M, is 12 (rad/s)/V. Determine the system transfer function, and hence calculate the demand signal required to produce an output speed of 120 rad/s.**

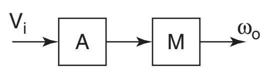

Fig. 10

A

A = 10 volt/volt (i.e. amplifier gain = 10 times)

$B = 12$ (rad/s)/volt; $\omega_0 = 120$ rad/s

$$\text{transfer function} = \frac{\omega_o}{V_i} = AM \text{ (rad/s)/V}$$
$$= 10 \times 12 = 120 \text{ (rad/s)/V } \textbf{Ans}$$
$$\text{hence, } V_i = \frac{\omega_o}{AM} \text{ volt} = \frac{120}{10 \times 12}$$
$$\text{so, } V_i = 1 \text{ V } \textbf{Ans}$$

Worked Example 2

Q **The control system above is converted to a closed-loop system, by the inclusion of a tachogenerator. The transfer function for the tacho, T, is 0.1 V/(rad/s). Sketch the system block diagram. Determine the system transfer function, and calculate the input voltage now required to produce an output speed of 120 rad/s.**

A

A = 10 V/V; M = 12 (rad/s)/V; T = 0.01 V/(rad/s)

The block diagram for the system is shown in Fig. 11.

$$\text{input to amplifier} = V_i - T\omega_o \text{ volt}$$
$$\text{input to motor} = A(V_i - T\omega_o) \text{ volt}$$
$$\text{output of motor, } \omega_o = AM(V_i - T\omega_o) \text{ rad/s}$$
$$\text{therefore, } \omega_o(1 + AMT) = AMV_i \ldots\ldots\ldots\ldots[1]$$
$$\text{and, } \frac{\omega_o}{V_i} = \frac{AM}{1 + AMT} \textbf{ Ans}$$
$$\text{From equation [1], } V_i = \frac{\omega_o(1 + AMT)}{AM}$$
$$= \frac{120 \times (1 + \{10 \times 12 \times 0.01\})}{10 \times 12}$$
$$\text{hence, } V_i = 2.2\text{V } \textbf{Ans}$$

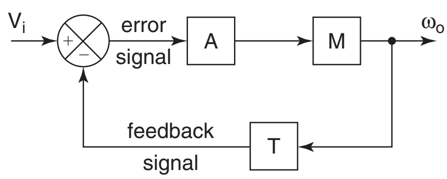

Fig. 11

Note: Let us compare the answers for V_i from these two examples. It is clear that, when negative feedback is employed, a larger input voltage is required in order to produce the same output. Thus, the overall 'gain' of the system is reduced.

Considering the second example above, it may well occur to you to ask, how the motor can rotate at some constant speed, when the error voltage must then be zero? The answer is that it cannot! This confirms that any closed-loop system must be error actuated. For the system considered, the motor will actually rotate at a speed slightly less than that demanded. There will therefore be a small error signal into the amplifier. After amplification, this will be just sufficient to keep the motor speed constant. This difference, between the desired output and the actual output under constant output conditions, is known as the steady state error. This concept will be dealt with in more detail in Control Principles 2.

8 A Positional Control System

Let us consider the problem of accurately positioning a heavy load, such as the dish antenna of a large radio telescope. Figure 12 shows a simple solution to the problem.

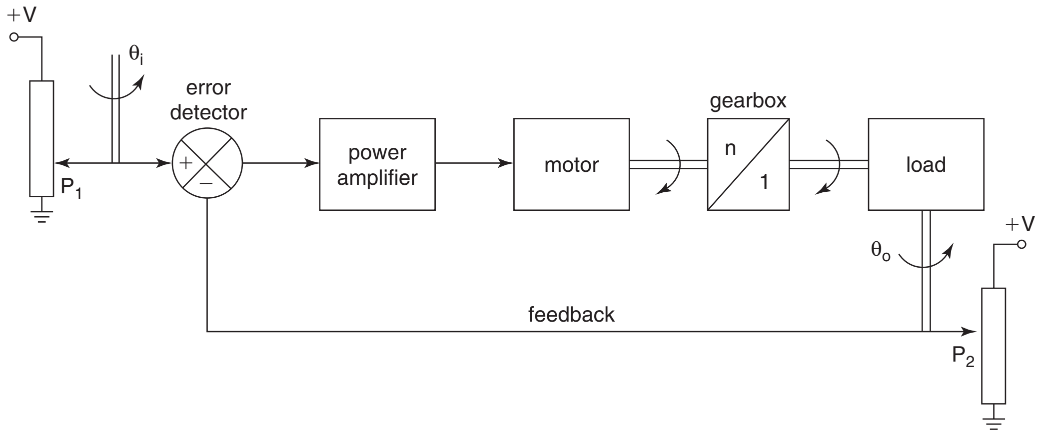

Fig. 12

The desired antenna position is applied to the system by rotating the wiper of potentiometer P_1. The voltage tapped off from P_1 provides the demand signal into the error detector (comparator). The wiper of P_2 is driven by the load, so its voltage output represents the load position. This voltage forms the feedback signal. Both potentiometers are supplied from the same reference supply. If θ_o is different to θ_i, the comparator will produce an error signal. The power amplifier amplifies this error signal in order to drive the motor. The gearbox reduces the amount of torque that the motor has to produce, in order to position the load. When the load arrives at the desired position, θ_o will equal θ_i. The error will then be zero, and the antenna will no longer be driven by the motor.

If the system is disturbed, for example by a strong gust of wind, then the antenna would tend to be moved from its correct position. As soon as this happens, a new error signal is created. This will then cause the motor to correct the antenna position, thus reducing the error once more to zero.

9 System Response and Stability

The solution proposed for the positional control system just described would appear to be ideal. Unfortunately this is not the case. It will tend to suffer from problems of steady state error and instability. Let us first consider the problem of steady state error. Very large masses have to be moved and positioned. As the load approaches the desired position, the error signal becomes progressively smaller. A point will be reached when the amplified error signal is insufficient to keep the motor driving. Thus the load will come to rest at a position other than that desired. Since the system will now be at rest, there will be a steady state error, θ_{ss}.

The obvious solution to this would be to increase the gain of the amplifier(s) in the system. This would have the effect of keeping the motor running longer. Hence, the load will come to rest closer to the desired position. Thus, the steady state error would be reduced.

The increased gain in the system will now aggravate the problem of instability. Since the masses involved are very large, they will possess considerable inertia. In addition, the system would be designed to have as little friction as possible. The effect of friction is to slow down, or damp, the movement. Due to the inertia in the system, the antenna will tend to keep rotating, even when the motor input signal has fallen to zero. Thus, the antenna will tend to overshoot the desired position. This will create an error signal to reverse the motor. The load is then driven back towards the desired position. Once more, the inertia effect will cause the load to overshoot, and the above sequence is repeated.

The load will therefore tend to oscillate about the desired position, before finally coming to rest. The greater the gain of the system, the larger the amplitude of these oscillations, but the smaller will be the final steady state error. These effects are illustrated in Fig. 13.

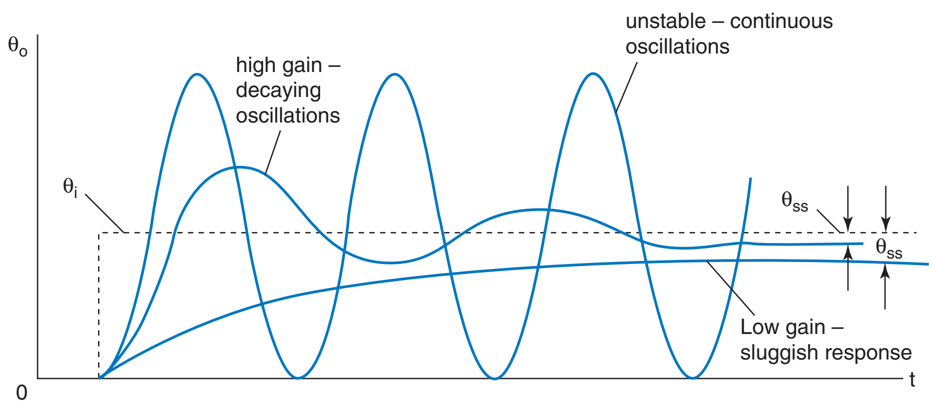

Fig. 13

Violent oscillations of the antenna are obviously undesirable. With the large masses involved, severe structural damage could result. At the same time, the steady state error needs to be as small as possible. Thus we have conflicting requirements. The full solution to these problems is dealt with in Control Principles 2.

High system gain is not the only cause of instability in the system. It has been pointed out that negative feedback is employed in control systems. Negative feedback promotes stability, because the system reacts so as to reduce the error signal to zero. In other words, the feedback signal is in opposition to the demand signal. However, it is possible to have time lags and phase shifts around the closed loop. The effect of these is to make the feedback signal reinforce the demand signal. In this situation we have positive feedback. The result is that the oscillations will be maintained, or in the worst case increased. The system then becomes completely unstable. This situation may be compared to pushing a child's swing. To keep the swing in motion, pushes are applied as the swing starts to move away from you. The natural movement of the swing is thus maintained. This is the application of positive feedback. However, if the pushes are timed to coincide with the backward movement, then it will slow down and stop. This is the application of negative feedback.

In Fig. 13, the input θ_i, is shown as a sudden change from one value to a new one. This sudden change in the demand is known as a step input.

Assignment Questions

1 State the essential difference between open-loop and closed-loop control systems. Illustrate your answer by describing (include block diagrams) two examples of each type (other than those already described in this book).

2 Explain the following control systems terms: (a) demand or reference signal, (b) error signal, (c) error detector, (d) feedback.

3 Explain the difference between continuous control and ON/OFF (discontinuous) control. Give an example of each, together with relevant block diagrams.

4 What is meant by the term transfer function? With the aid of diagrams, show how the overall transfer function can be obtained for (a) an open-loop system, and (b) a closed-loop system.

5 Explain the effect of steady state error. This form of error is reduced by increasing the system gain. What adverse effect can this course of action have?

6 Explain the difference between positive and negative feedback. Why is positive feedback avoided in control systems?

7 For the control system shown in Fig. 14, derive the overall system transfer function.

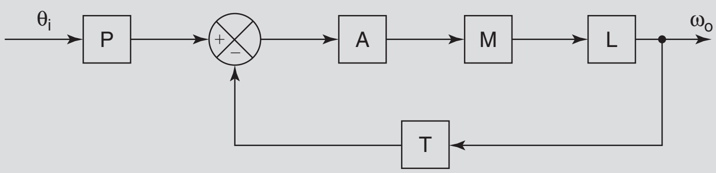

Fig. 14