19 AUTOMATIC CONTROL

Introduction

Physical systems or mechanisms are required to be adjusted or controlled so that they perform their specific duties. This is done either manually or automatically. Automatic control is desired in order to save the human operator from drudgery. It is also more efficient.

Self-actuated or automatic control of mechanisms is not a new thing. A centrifugally actuated ball governor which controls the throttle valve to maintain a constant speed of an engine is an example of an automatically controlled mechanism. In process industries where production is the outcome of continuous flow through consecutive treatments, automatic control ensures the uniformity and quality of products and reduces the time of machine watching, and thus the wage bills. Examples are paper, chemical or foodstuff industries.

In control systems, the result of the act of adjustment, i.e., closing a valve, moving a lever, pressing a button, etc., is known as *command* and the subsequent result or behaviour of the system as *response*. Automatic control of variables such as length, temperature, radius etc., that occur in industrial flow production is known as *process control*.

19.1 OPEN AND CLOSED-LOOP CONTROL (UNMONITORED AND MONITORED CONTROL)

Control in which the input command is not influenced by the behaviour of the system response (output) is called an *open-loop* or *unmonitored control*. Examples are

(i) Traffic control on the roads by lights where the timing mechanism is preset irrespective of traffic
(ii) Switching off the street lights of a town at a predetermined time by a time-switch irrespective of the fact that the sun rises at a different time each day
(iii) Switching off an electric heater by a time-switch irrespective of whether the dish has been prepared or not

A *closed-loop control system* is one in which the actual value of a controlled quantity is measured and compared continuously with the desired value. The quantity measured may be load or input. In the traffic control system mentioned above, if the flow of traffic is measured either by direct human observation or by counting impulses due to the vehicles passing over a pressure pad, and then changing the time setting accordingly, it becomes a closed-loop control.

Another example of closed-loop control can be that of a water heater. The desired temperature may be maintained by an operator with the help of a thermometer and an electric rod fitted with an on/off switch. He will observe the thermometer continuously and will switch on the heater whenever the temperature of water rises above the desired temperature and switch it off when it falls below the same. Instead of the operator, a thermostat can also serve the purpose of switching on/off the heater thus making the system fully automatic.

A differential device used to measure the actual controlled quantity and to compare it continuously with the desired value is known as an *error detector* or *deviation sensor.*

Measuring the output for comparison with the input is known as *feedback*.

19.2 AMPLIFICATION

Usually, an error detector itself does not have sufficient power output to actuate the correcting mechanism directly. The error signal has to be amplified by using a gear-box, lever system or a hydraulic/pneumatic relay.

19.3 ACTUATOR (SERVOMOTOR)

An *actuator* is an external source of power connected to the input of the controlled machine and serves to reduce the error. Thus it is a device which produces a limited angular or linear motion and may be mechanical, hydraulic or electric. A *servomotor* is usually hydraulic or electric and has a continuous output.

19.4 TRANSDUCER

A *transducer* is a converting device that converts the measurement of the quantity to be controlled into different units, e.g., angular velocity into potential difference, pressure change into angular rotation as in a bourdon tube, temperature change into *emf* as in a thermocouple, linear strain into resistance change as in strain gauge, and so on. It is also usual to convert the error signal into an electric quantity due to the relative ease with which minute electric signals can be detected, transmitted, amplified and manipulated by using solid state electronic means. However, when reliability under adverse operating conditions (high temperature, radiation, dusty atmosphere, corrosiveness, etc.) is desired, pneumatic means should be preferred.

19.5 BLOCK DIAGRAMS

A *block diagram* is a symbolic outline of a system in which various components or operations are represented by rectangles in an ordered sequence. The rectangles are connected by arrows showing the flow of the working medium or of information.

Figure 19.1 shows the block diagram of an ordinary carburettor, and Fig. 19.2 a rocket launching system and its block diagram. Figure 19.3 shows the controlling system of a turbine and its block diagram.

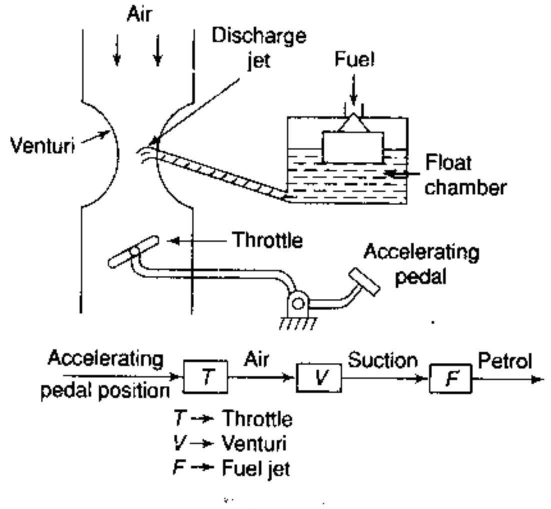


Fig. 19.1

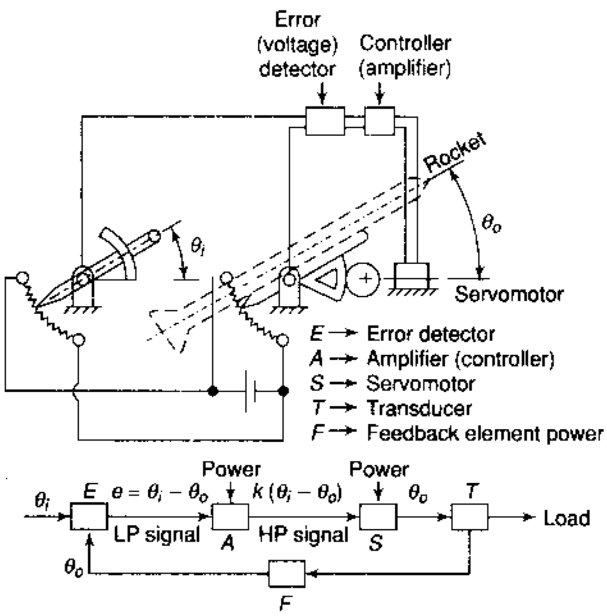


Fig. 19.2

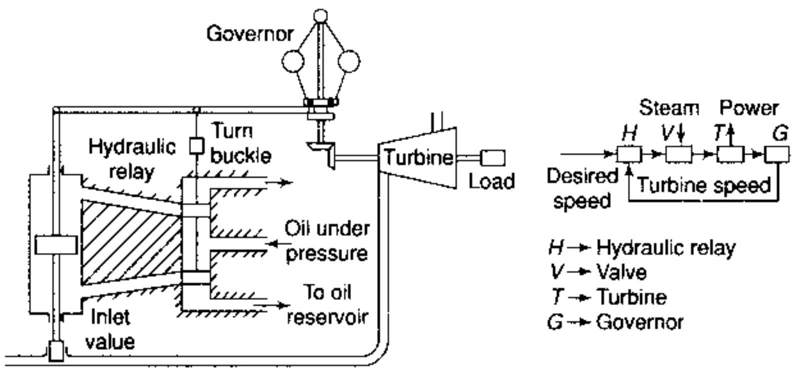


Fig. 19.3

19.6 LAG IN RESPONSE

In any system, usually, there is a *lag* or *delay in response* (output) due to some inherent cause and it becomes difficult to measure the input and output simultaneously. In a shaft transmitting torque, there is an angular lag of one end of the shaft behind the other. Inertia delays a motor attaining its required velocity after the application of a torque. In a steam turbine, if the load is suddenly reduced, there will be some lag in the closing of the steam valve by the hydraulic relay as the first movement of the piston valve will not be sufficient to open the ports. This lag increases the probability of unstable operation.

19.7 DAMPING

When a torque is applied in a system in a direction opposite to its motion, it is known as *damping*. In case of coulomb damping, the opposition is constant and thus there will be a constant difference (error) between the input and the output under steady conditions. In the viscous damping provided by a dashpot, the opposition is proportional to the relative velocity. As the relative velocity is zero in the steady state, the damping is also zero.

19.8 FIRST-ORDER SYSTEM RESPONSE

The first-order system may be linear or torsional.

Linear System

Figure 19.4 shows a system consisting of a massless spring of stiffness s. A constant input is represented by x whereas y represents the output of the system. First, the input signal x is compared with the output signal y. Then the difference $e = x - y$ is passed on to the motor which produces an output torque T proportional to e (or $= se$). The system also has a viscous resistance with damping coefficient c indicating damping force per unit velocity.

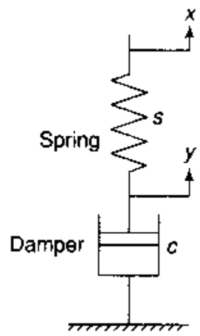


Fig. 19.4

The equation of motion is

$$c\dot{y} = se = s(x - y) = sx - sy$$

or
$$c\dot{y} + sy = sx \tag{19.1}$$

or
$$\dot{y} + \frac{s}{c}y = \frac{s}{c}x$$

This is a first-order differential equation. Its solution is given by complimentary function and particular integral.

Complimentary function is the solution of the equation

$$\dot{y} + \frac{s}{c}y = 0$$

and the solution is $\quad y = C_1 e^{-\frac{s}{c}t}$

where C_1 is a constant.

Particular integral can be found by using D operator, i.e.,

$$PI = \frac{(s/c)x}{D + (s/c)} = \frac{(s/c)x}{0 + (s/c)} = x$$

Therefore, the complete solution is
$$y = x + C_1 e^{-\frac{s}{c}t} \tag{19.2}$$

When $t = 0$, $\quad y = 0$

$$\therefore \qquad 0 = x + C_1 \quad \text{or} \quad C_1 = -x$$

and thus
$$y = x - xe^{-\frac{s}{c}t} = x\left(1 - e^{-\frac{s}{c}t}\right) = x\left(1 - e^{-\frac{t}{T}}\right) \tag{19.3}$$

where $T = c/s$ is known as the *time constant* of the system.

Also,

$$\frac{y}{x} = 1 - e^{-\frac{t}{T}} \tag{19.4}$$

Figure 19.5 shows the graphical representation of y/x vs. t/T. As t increases y tends to reach x. When $t/T = 1$, $y/x = 1 - 0.368 = 0.632$.

$e^{-t/T}$ is known as the dynamic error which reduces with increase in t and vanishes when t is infinity. However, for practical purposes, one need not wait till t reaches infinity. Instead, an accepted value of error is specified and the *settling time* is obtained when the steady state response enters in a band around the final steady state value. The usual value of band is taken between 2 to 5 per cent.

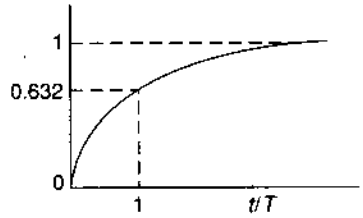


Fig. 19.5

Torsional System

Figure 19.6 shows a system consisting of a massless torsional spring of stiffness q. First the input signal θ_i is compared with the output signal θ_o. Then the difference $e = \theta_i - \theta_o$ is passed on to the motor which produces an output torque T proportional to e (or $= qe$). The system has a viscous resistance with damping coefficient c.

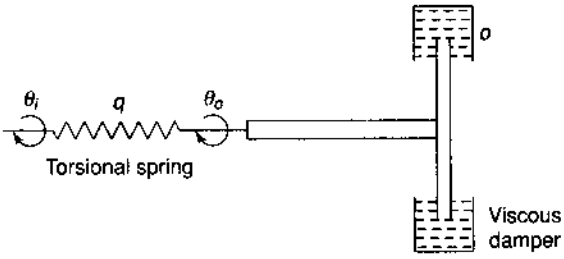


Fig. 19.6

The equation of motion is

$$c\dot{\theta}_o = qe = q\theta_i - q\theta_o \tag{19.5}$$

or

$$c\dot{\theta}_o + q\theta_o = q\theta_i \tag{19.6}$$

or

$$\dot{\theta}_o + \frac{q}{c}\theta_i = \frac{q}{c}\theta_i$$

It is a first-order differential equation. Its solution is given by complimentary function and particular integral.

The complimentary function is the solution of the equation

$$\dot{\theta}_o + \frac{q}{c}\theta_i = 0 \text{ and is } \theta_o = C_1 e^{-\frac{q}{c}t}$$

Particular integral can be found using the D operator and is given as

$$PI = \theta_i$$

Therefore, the complete solution is $\theta_o = \theta_i + C_1 e^{-\frac{q}{c}t}$

When $t = 0$, $\theta_o = 0$

$$\therefore \qquad 0 = \theta_i + C_1 \quad \text{or} \quad C_1 = -\theta_i$$

and

$$\theta_o = \theta_i - \theta_i e^{-\frac{q}{c}} = \theta_i\left(1 - e^{-\frac{t}{T}}\right) \tag{19.7}$$

where $T = c/q$ is the *time constant* of the system.

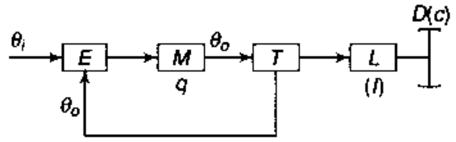
Example 19.1 *The time constant of a thermometer is 8 s. Suddenly it is inserted in a bath of temperature 72°C. Determine the temperature recorded by the thermometer after 5 s.*

Solution

$$y = x\left(1 - e^{-\frac{t}{T}}\right) = 72\left(1 - e^{-\frac{5}{8}}\right) = \underline{33.46°}$$

19.9 SECOND-ORDER SYSTEM RESPONSE

In the system considered in the previous section (Fig. 19.6), if the mass of the spring is also taken into account, it becomes a second-order system. Figure 19.7 shows the block diagram of such a system. First, the input signal θ_i is compared with the output signal θ_0. Then the difference $e = \theta_i - \theta_0$ is passed on to the motor which produces an output torque T proportional to e (or $= qe$). The system has a viscous resistance with damping coefficient c.



$E \rightarrow$ Error detector
$M \rightarrow$ Motor
$T \rightarrow$ Transducer
$L \rightarrow$ Load
$D \rightarrow$ Damper

Fig. 19.7

Let the combined moment of inertia of the motor and load be I.

Then, the equation of motion is

$$I\ddot{\theta}_o + c\dot{\theta}_o = qe$$
$$= q\theta_i - q\theta_0$$

or
$$I\ddot{\theta}_o + c\dot{\theta}_o + q\theta_0 = q\theta_i \tag{19.8}$$

The equation is similar to Eq. (18.25) and can also be written as

$$\ddot{\theta}_0 + \frac{c}{I}\dot{\theta}_0 + \frac{q}{I}\theta_0 = \frac{q}{I}\theta_i$$

or
$$\ddot{\theta}_0 + 2\zeta\omega_n\dot{\theta}_o + \omega_n^2\theta_o = \omega_n^2\theta_i \tag{19.9}$$

where $c = 2\zeta I\omega_n$. The response of the system will depend upon the type of the input, i.e., step displacement, step velocity (ramp displacement) or harmonic. The detailed discussion is beyond the scope of this book.

19.10 TRANSFER FUNCTION

In control systems, the relationship between the input and the output (response) is given by a differential equation of motion. If the differential equation is expressed in symbolic form by substituting D for d/dt or by the Laplace transformation, the transfer function is the operational relationship of the output and the input.

Let a system be expressed by the differential equation in symbolic form as

$$(D^2 + 2\,\zeta\,\omega_n D + \omega_n^2)\,\theta_o = \omega_n^2\,\theta_i$$

Then the transfer function is defined as

$$\frac{\theta_0}{\theta_i} = \frac{\omega_n^2}{\omega_n^2 + 2\zeta\omega_n D + D^2}$$

Example 19.2 *Determine the transfer function of a first-order torsional system.*

Solution The equation of motion is

or $c\dot{\theta}_o + q\theta_0 = q\theta_i$ (Eq. 19.6)

or $\frac{c}{q}\dot{\theta}_o + \theta_0 = \theta_i$

Using D operator which indicates the differentiating with respect to time,

$$\left(\frac{c}{q}\right)D\theta_o + \theta_0 = \theta_i$$

or the transfer function is

$$\frac{\theta_0}{\theta_i} = \frac{1}{1+(c/q)D}$$

$$= \frac{1}{1+TD}$$

where $T = c/q$ is the time period.

Example 19.3 *A scale is fixed to the end of a shaft of torsional stiffness 2 N.m/rad. A viscous damping torque of magnitude 1.6 N.m resists the motion of the pointer on a scale at an angular velocity of 2 rad/s. The shaft to which the pointer is attached gets the motion from the input shaft through a reduction gear box which has a gear ratio of 6:1. If the input shaft is suddenly rotated through one complete rotation, determine the*

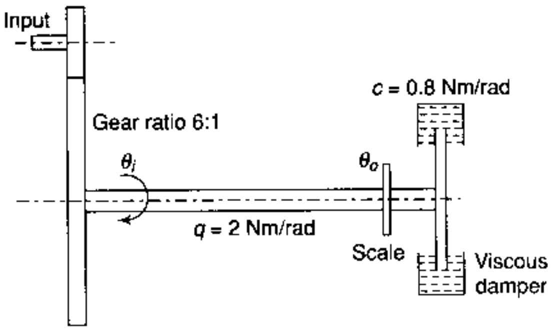


Fig. 19.8

(i) time taken by the pointer to reach the position within 1% of the final value
(ii) transfer function

Solution The system is shown in Fig. 19.8.

(i) Response of the torsional system is given by

$$\theta_o = \theta_i\left(1 - e^{-\frac{t}{T}}\right)$$

As the input shaft is rotated through one complete revolution and the shaft with the pointer receives motion through a gear box with ratio 6:1, the rotation of the shaft with the pointer is $\theta_i = 2\pi/6$ rad $= \pi/3$ rad.

Also, c = Damping torque /unit velocity = 1.6/2 = 0.8 N.m/rad/s

q = Torsional stiffness of the shaft = 2 N.m/rad

Time constant, $T = \frac{c}{q} = \frac{0.8}{2} = 0.4$ s.

$$\therefore\ \theta_o = \frac{\pi}{3}\left(1 - e^{-\frac{t}{0.4}}\right) = \frac{\pi}{3}(1 - e^{-2.5t})$$

The curve for the response of the pointer is shown in Fig. 19.9. It is an exponential time delay curve.

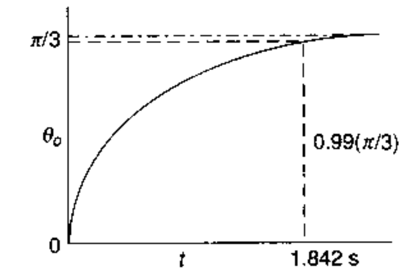


Fig. 19.9

When $\theta_o = (1 - 0.01)\theta_i = 0.99 \times (\pi/3)$

Then, $0.99 \times \frac{\pi}{3} = \frac{\pi}{3}(1 - e^{-2.5t})$

or $e^{-2.5t} = 0.01$

or $e^{2.5t} = 100$

$2.5t = \ln 100 = 4.605$

$t = \underline{1.842\text{ s}}$

(ii) For torsional systems of the first order,

$c\dot{\theta}_o + q\theta_o = q\theta_i$

Writing using D operator,

$\frac{c}{q}D\theta_o + \theta_o = \theta_i$

Time constant, $T = \frac{c}{q} = \frac{0.8}{2} = 0.4$ s

Therefore, $\quad 0.4D\theta_o + \theta_o = \theta_i$

or $\quad (0.4D + 1)\theta_o = \theta_i$

or $\quad \frac{\theta_o}{\theta_i} = \frac{1}{1 + 0.4D}$

As the input to the shaft is through a gear box with a reduction gear ratio of 6:1,

Therefore, overall transfer function is

$$\frac{\theta_o}{\theta_i} = \frac{1}{6} \times \frac{1}{(1 + 0.4D)}$$

Example 19.4 *Find the transfer function of a Hartnell governor as shown in Fig. 16.12. Assume that the load on the sleeve, the weight of the balls and the friction force are negligible as compared to the inertia forces. The viscous damping coefficient of the sleeve is c.*

In the equilibrium position when the arms holding the balls are vertical, the compression of the spring of stiffness s is x_o, the equilibrium speed is ω_o, and the radial distance of the ball centre from the spindle axis is r_o.

Solution When the balls are in the vertical position,

$$mr_o\omega_0^2 a = \frac{1}{2} s\, x_0 b$$

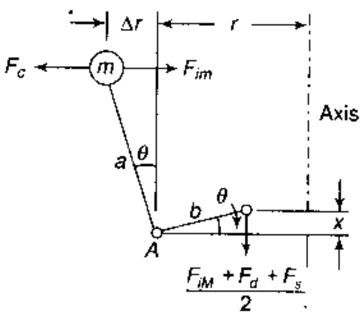


Fig. 19.10

Now, if due to a small change $\Delta\omega$ in speed, the change in radial distance of the ball is Δr and the change in displacement of the sleeve is x, then the forces acting on the bell-crank lever will be (refer Fig. 19.10)

F_c = Centrifugal force due to ball mass

$= m\,(r_o + \Delta r)\,(\omega_o + \Delta\omega)^2$

F_{im} = inertia force of the balls = $m\Delta\ddot{r} = \frac{a}{b}\ddot{x}$

F_{iM} = inertia force of the sleeve mass = $M\ddot{x}$.

F_d = Damping force = $c\dot{x}$

F_s = spring force = $s\,(x_o + x)$

Taking moments about the fulcrum A (taking only one half of the governor into consideration).

$$= m(r_o + \Delta r)(\omega_0 + \Delta\omega)^2 a$$

$$= m\frac{a}{b}\ddot{x}a + \frac{1}{2}M\ddot{x}b + \frac{1}{2}c\dot{x}\,b + \frac{1}{2}s(x_0 + x)b$$

$$= m(r_o + \Delta r)[\omega_0^2 + 2\omega_o\Delta\omega + (\Delta\omega)^2]a$$

$$= m\frac{a}{b}\ddot{x}a + \frac{1}{2}M\ddot{x}b + \frac{1}{2}c\dot{x}\,b + \frac{1}{2}s(x_0 + x)b$$

Neglecting second order small terms,

$$= mr_o\omega_0^2 a + m\Delta r\omega_0^2 a + 2mr_o\omega_0\Delta\omega\, a$$

$$= m\frac{a^2}{b}\ddot{x} + \frac{1}{2}M\ddot{x}b + \frac{1}{2}c\dot{x}\,b + \frac{1}{2}s(x_0 + x)b$$

But when the balls are in vertical position,

$$mr_o\omega_0^2 a = \frac{1}{2}sx_0 b$$

Also, $\quad \theta = \frac{\Delta r}{a} = \frac{x}{b}$

$$\therefore \quad \left(\frac{ma^2}{b} + \frac{Mb}{2}\right)\ddot{x} + \frac{1}{2}cb\dot{x}$$

$$+\left(\frac{1}{2}sb - \frac{ma^2}{b}\omega_0^2\right)x = 2mr_o\,\omega_0\,\Delta\omega\, a$$

Multiplying throughout by $2b$ and using operator D,

$(2ma^2 + Mb^2)\,D^2 x + cb^2Dx + (sb^2 - 2ma^2\omega_0^2)\,x = 4m\,a.b.r_o.\omega_o\,\Delta\omega$

or

$$\left(D^2 + \frac{cb^2}{2ma^2 + Mb^2}D + \frac{sb^2 - 2ma^2\omega_0^2}{2ma^2 + Mb^2}\right)x = \frac{4mabr_o\omega_0\Delta\omega}{2ma^2 + Mb^2}$$

or

$$(D^2 + 2\zeta\omega_n D + \omega_n^2)x = \frac{4mabr_o\omega_0\Delta\omega}{2ma^2 + Mb^2}$$

where

$$2\zeta\omega_n = \frac{cb^2}{2ma^2 + Mb^2} \qquad (\zeta = \text{damping factor})$$

and

$$\omega_n = \sqrt{\frac{sb^2 - 2ma^2\omega_0^2}{2ma^2 + Mb^2}}, \text{ i.e., the natural frequency}$$

Transfer function,

$$\frac{\theta_0}{\theta_i} = \frac{\text{Displacement of the sleeve}(x)}{\text{Change in speed}(\Delta\omega)}$$

$$= \frac{4mabr_o\omega_0\,(2ma^2 + Mb^2)}{D^2 + 2\zeta\omega_n D + \omega_n^2}$$

19.11 TRANSFER FUNCTION RELATIONSHIPS

A control system can have several loops and components, each having its characteristic transfer function.

(i) Open-loop Transfer Function

An open-loop or forward-loop control system has several components having individual transfer functions such as $F_1(D)$, $F_2(D)$, $F_3(D)$, etc., as shown in Fig. 19.11.

$$TF = \frac{\theta_0}{\theta_i} = \frac{\theta_0}{\theta_3}\frac{\theta_3}{\theta_2}\frac{\theta_2}{\theta_1}\frac{\theta_1}{\theta_i} = F_4(D)\,F_3(D)\,F_2(D)\,F_1(D) = KG(D)$$

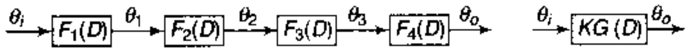


Fig. 19.11

(ii) Closed-loop Transfer Function

A closed-loop or feedback loop is shown in Fig. 19.12.

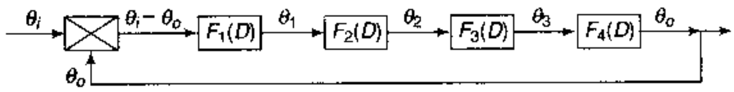


Fig. 19.12

$$\frac{\theta_0}{\theta_i - \theta_0} = KG(D)$$

or

$$\theta_0 = KG(D)\theta_i - KG(D)\,\theta_0$$

or

$$[1 + KG(D)]\,\theta_0 = KG(D)\theta_i$$

$\therefore$

$$TF = \frac{\theta_0}{\theta_i} = \frac{KG(D)}{1 + KG(D)} = \frac{\text{Open loop TF}}{1 + \text{Open loop TF}}$$

Summary

1. Physical systems or mechanisms are required to be adjusted or controlled either manually or automatically so that they perform their specific duties. Automatic control is desired in order to save the human operator from drudgery. It is also more efficient.
2. In control systems, the result of the act of adjustment is known as *command* and the subsequent result or behaviour of the system as *response*.
3. Control in which the input command is not influenced by the behaviour of the system response is called an *open-loop* or *unmonitored control*.
4. A *closed-loop control system* is one in which the actual value of a controlled quantity is measured and compared continuously with the desired value.
5. A differential device used to measure the actual controlled quantity and to compare it continuously with the desired value is known as an *error detector* or *deviation sensor*.
6. An error detector itself has insufficient power output to actuate the correcting mechanism directly. The error signal has to be *amplified* by using a gear-box, lever system or a hydraulic/pneumatic relay.
7. An *actuator* is an external source of power connected to the input of the controlled machine and serves to reduce the error. A *servomotor* is usually hydraulic or electric and has a continuous output.
8. A *transducer* is a converting device that converts the measurement of the quantity to be controlled into different units
9. A *block diagram* is a symbolic outline of a system in which various components or operations are represented by rectangles in an ordered sequence.
10. In any system, usually, there is a *lag* or *delay in response* (output) due to some inherent cause and it becomes difficult to measure the input and output simultaneously.
11. When a torque is applied in a system in a direction opposite to its motion, it is known as *damping*.
12. Transfer function is the operational relationship of the output and the input in control systems, when the relationship between them is expressed in a symbolic form by substituting D for d/dt or by the Laplace transformation in the differential equation of motion of the system.

Exercises

1. What do you mean by automatic control of physical systems or mechanisms? What is its importance?
2. What are the open- and closed-loop control systems? Explain by giving examples.
3. Define the terms related to control systems: command, response, actuator, transducer, lag in response and damping.
4. What is a block diagram in control systems? How is it helpful in the analysis of a system?
5. Derive a relation for the response of a first-order torsional system.
6. What is transfer function? Find the transfer function of a Hartnell governor assuming the load on the sleeve, the weight of the balls and the friction force to be negligible as compared to the inertia forces.
7. Define the open-loop and the closed-loop transfer function relationships.

Appendix I OBJECTIVE-TYPE QUESTIONS

Chapter 1 Mechanisms and Machines

1.1 The lead screw of a lathe with nut is a
(a) rolling pair (b) screw pair (c) turning pair (d) sliding pair

1.2 In a kinematic pair, when the elements have surface contact while in motion, it is a
(a) higher pair (b) closed pair (c) lower pair (d) unclosed pair

1.3 In a kinematic chain, a ternary joint is equivalent to
(a) two binary joints (b) three binary joints (c) one binary joint

1.4 In a four-link mechanism, the sum of the shortest and the longest link is less than the sum of the other two links. It will act as a drag-crank mechanism if
(a) the longest link is fixed
(b) the shortest link is fixed
(c) any link adjacent to the shortest link is fixed

1.5 In a four-link mechanism, the sum of the shortest and the longest link is less than the sum of the other two links. It will act as a crank-rocker mechanism if
(a) the link opposite to the shortest link is fixed
(b) the shortest link is fixed
(c) any link adjacent to the shortest link is fixed

1.6 In a four-link mechanism, the sum of the shortest and the longest link is less than the sum of the other two links. It will act as a rocker-rocker mechanism if
(a) the link opposite to the shortest link is fixed
(b) the shortest link is fixed
(c) any link adjacent to the shortest link is fixed.

1.7 The transmission angle is maximum when the crank angle with the fixed link is
(a) 0° (b) 90° (c) 180° (d) 270°

1.8 The transmission angle is minimum when the crank angle with the fixed link is
(a) 0° (b) 90° (c) 180° (d) 270°

1.9 Which of the following is an inversion of single-slider-crank chain?
(a) Elliptical trammel (b) Hand pump
(c) Scotch yoke (d) Oldham's coupling

1.10 Which of the following is an inversion of double-slider-crank chain?
(a) Whitworth quick return mechanism
(b) Reciprocating compressor
(c) Scotch yoke
(d) Rotary engine

1.11 Oldham's coupling is used to connect two shafts which are
(a) intersecting (b) parallel
(c) perpendicular (d) co-axial

Chapter 2 Velocity Analysis

2.1 The linear velocity of a point B on a link rotating at an angular velocity ω relative to another point A on the same link is
(a) $\omega^2 \cdot AB$ (b) $\omega \cdot AB$ (c) $\omega \cdot (AB)^2$ (d) ω/AB

2.2 The linear velocity of a point on a link relative to another point on the same link is ________ to the line joining the points.
(a) perpendicular (b) parallel (c) at 45°

2.3 The total number of instantaneous centres of a mechanism having n links is
(a) $\frac{n(n-1)}{2}$ (b) $\frac{n-1}{2}$ (c) $\frac{n(n+1)}{2}$ (d) $\frac{n+1}{2}$

2.4 According to Kennedy's theorem, the instantaneous centres of three bodies having relative motion lie on a
(a) curved path (b) straight line (c) point

2.5 The instantaneous centre of a slider moving in a linear guide lies
(a) at pin point (b) at their point of contact (c) at infinity

2.6 The instantaneous centre of a slider moving in a curved surface lies
(a) at infinity (b) at their point of contact
(c) at the centre of curvature (d) at the pin point

2.7 The fixed instantaneous centre of a mechanism
(a) varies with the configuration
(b) remains at the same place for all configurations

2.8 The instantaneous centre of rotation of a circular disc rolling on a straight path is
(a) at the centre of the disc
(b) at their point of contact
(c) at the centre of gravity of the disc
(d) at infinity

2.9 The locus of instantaneous centre of a moving body relative to a fixed body is known as the
(a) space centrode (b) body centrode
(c) moving centrode (d) none of the above

2.10 The space centrode of a circular disc rolling on a straight path is
(a) a circle (b) a parabola
(c) a straight line (d) none of the above

Chapter 3 Acceleration Analysis

3.1 The component of the acceleration directed toward the centre of rotation of a revolving body is known as ________ component.
(a) tangential (b) centripetal (c) Coriolis

3.2 At an instant, the link AB of length r has an angular velocity ω and an angular acceleration α. What is the total acceleration of AB?
(a) $[(\omega^2 \cdot r)^2 + (\alpha \cdot r)^2]^{1/2}$ (b) $[(\omega \cdot r)^2 + (\alpha \cdot r)^2]^{1/2}$
(c) $[(\omega^2 \cdot r)^2 + (\alpha^2 \cdot r)^2]^{1/2}$ (d) $[(\omega \cdot r)^2 + (\alpha^2 \cdot r)^2]^{1/2}$

3.3 At an instant, if the angular velocity of a link is clockwise then the angular acceleration will be
(a) clockwise
(b) counter-clockwise
(c) in any direction (clockwise or counter-clockwise)

3.4 Angular acceleration of a link AB is given by
(a) $\dfrac{\text{Centripetal acc.}}{\text{length } AB}$ (b) $\dfrac{\text{Tangential acc.}}{\text{length } AB}$ (c) $\dfrac{\text{Total acc.}}{\text{length } AB}$

3.5 A slider moves with uniform velocity v on a revolving link of length r with angular velocity ω. The Coriolis acceleration component of a point on the slider relative to a coincident point on the link is equal to
(a) $2r\,\omega$ parallel to the link (b) $2\,\omega\,v$ perpendicular to the link
(c) $2r\,\omega$ perpendicular to the link (d) $2\,\omega\,v$ parallel to the link

3.6 The Coriolis acceleration component is taken into account for a ________ mechanism.
(a) double-slider crank (b) four-link mechanism
(c) Scotch yoke (d) quick-return mechanism

3.7 The Coriolis acceleration component
(a) lags the sliding velocity by 90°
(b) leads the sliding velocity by 90°
(c) lags the sliding velocity by 180°
(d) leads the sliding velocity by 180°

Chapter 4 Computer-aided Analysis of Mechanisms

4.1 Analytical methods to find velocity and acceleration are the most suitable for
(a) manual calculations
(b) desk-calculator
(c) digital computer

4.2 For analytical solution of mechanisms, ________ links are considered as vectors.
(a) moving links (b) fixed links
(c) all (d) input and output

4.3 Coupler curves are the loci of a point on a ________ link.
(a) coupler (b) output (c) input (d) any

4.4 The number of coupler curves which can be drawn in a mechanism can be
(a) infinite (b) one
(c) equal to number of links (d) depends upon the motion of links

Chapter 5 Graphical and Computer-aided Synthesis of Mechanisms

5.1 The relative pole of a moving link is its centre of rotation relative to a ________ link.
(a) fixed link (b) moving link (c) any link

5.2 Freudenstein's equation is written in the following form:
(a) $k_1 \cos\varphi + k_2 \cos\theta + k_3 - \cos(\theta - \varphi) = 0$
(b) $k_1 \cos\varphi + k_2 \cos\theta + k_3 + \cos(\varphi - \theta) = 1$
(c) $k_1 \cos\varphi + k_2 \cos\theta + k_3 - \cos(\theta - \varphi) = 1$

5.3 Function generation means designing a mechanism in which ________ are related by a function.
(a) output and input links (b) input and coupler links
(c) output and coupler links

Chapter 6 Lower Pairs

6.1 A pantograph consists of
(a) 4 links (b) 6 links (c) 8 links (d) 10 links
6.2 A Hart mechanism uses
(a) 4 links (b) 6 links (c) 8 links (d) 10 links
6.3 A Paucellier mechanism has
(a) 4 links (b) 6 links (c) 8 links (d) 10 links
6.4 Which of these mechanisms gives an approximately straight line?
(a) Hart (b) Watt (c) Paucellier (d) Kempe
6.5 Which of these mechanisms has six links?
(a) Tchebicheff (b) Hart (c) Paucellier (d) Watt
6.6 Which of these mechanisms use two identical mechanisms?
(a) Hart (b) Watt (c) Paucellier (d) Kempe
6.7 The Davis steering gear is not used because
(a) it has turning pairs
(b) it is costly
(c) it has sliding pairs
(d) it does not fulfill the condition of correct gearing
6.8 The Davis steering gear fulfills the condition of correct gearing at
(a) two positions (b) three positions
(c) all positions (d) one position
6.9 The Ackermann steering gear fulfills the condition of correct gearing at
(a) no position (b) one position
(c) three positions (d) all positions
6.10 A Hooke's joint is used to join two shafts which are
(a) aligned (b) intersecting (c) parallel
6.11 The maximum velocity of the driven shaft of a Hooke's joint is
(a) $\omega_1 \cos \alpha$ (b) $\omega_1/\cos \alpha$ (c) $\omega_1 \sin \alpha$ (d) $\omega_1/\sin \alpha$
6.12 The maximum velocity of the driven shaft of a Hooke's joint is at θ equal to
(a) 0° and 180° (b) 90° and 270°
(c) 90° and 180° (d) 180° and 270°

Chapter 7 Cams

7.1 The cam follower used in automobile engines is
(a) roller (b) flat-faced
(c) spherical-faced (d) knife-edged
7.2 In a radial cam, the follower moves in a direction
(a) parallel to the cam axis
(b) perpendicular to the cam axis
(c) along the cam axis
7.3 The cam follower used in air-craft engines is a __________ follower.
(a) roller (b) flat-faced
(c) spherical-faced (d) knife-edged
7.4 The reference point on the follower to lay the cam profile is known as the
(a) cam centre (b) pitch point (c) trace point (d) prime point

7.5 The circle drawn to the cam profile with the minimum radius is called the
(a) prime circle (b) cam circle (c) pitch circle (d) base circle

7.6 The size of the cam depends on
(a) pitch circle (b) prime circle (c) base circle (d) pitch curve

7.7 The angle between the axis of the follower and the normal to the pitch curve is known as the
(a) base angle (b) pressure angle
(c) pitch angle (d) prime angle

7.8 The pressure angle of the cam ________ with increase in the base circle diameter.
(a) decreases (b) increases
(c) does not change (d) may decrease or increase

7.9 The point on the cam with the maximum pressure angle is known as the
(a) cam centre (b) pitch point (c) trace point (d) prime point

7.10 The path described by the trace point is known as the
(a) pitch curve (b) pitch circle (c) prime circle (d) prime curve

7.11 The most suitable follower motion programme for a high-speed engine is
(a) uniform acceleration and deceleration
(b) uniform velocity
(c) simple harmonic motion
(d) cycloidal

Chapter 8 Friction

8.1 The efficiency of a screw jack depends on
(a) the pitch of the threads (b) the load
(c) both pitch and load (d) neither pitch nor load

8.2 The efficiency of a screw jack increases with a/an
(a) decrease in the load (b) increase in the load
(c) decrease in the pitch (d) increase in the pitch

8.3 The efficiency of a screw jack is

(a) $\eta = \dfrac{\tan\alpha}{\tan(\alpha-\varphi)}$ (b) $\eta = \dfrac{\tan(\alpha+\varphi)}{\tan\alpha}$

(c) $\eta = \dfrac{\tan\alpha}{\tan(\alpha+\varphi)}$ (d) $\eta = \dfrac{\tan(\alpha-\varphi)}{\tan\alpha}$

8.4 The efficiency of a screw jack is maximum when

(a) $\alpha = 45° - \dfrac{\varphi}{4}$ (b) $\alpha = 45° + \dfrac{\varphi}{2}$

(c) $\alpha = 45° + \dfrac{\varphi}{4}$ (d) $\alpha = 45° - \dfrac{\varphi}{2}$

8.5 The maximum efficiency of a screw jack is given by

(a) $\eta = \dfrac{1+\sin\varphi}{1-\sin\varphi}$ (b) $\eta = \dfrac{1-\sin\varphi}{1+\sin\varphi}$

(c) $\eta = \dfrac{1-\sin\varphi}{1+\cos\varphi}$ (d) $\eta = \dfrac{1+\sin\varphi}{1-\cos\varphi}$

8.6 The efficiency of a wedge is

(a) $\eta = \dfrac{\tan \alpha}{\tan (\alpha - 2\varphi)}$ (b) $\eta = \dfrac{\tan (\alpha + 2\varphi)}{\tan \alpha}$

(c) $\eta = \dfrac{\tan \alpha}{\tan (\alpha + 2\varphi)}$ (d) $\eta = \dfrac{\tan (\alpha - 2\varphi)}{\tan \alpha}$

8.7 For flat and conical pivots, the ratio of the friction torque with uniform wear to the friction torque with uniform pressure is

(a) 2/3 (b) 3/2 (c) 4/3 (d) 3/4

8.8 The frictional torque for the same diameter in a conical bearing is ________ than in a flat bearing.

(a) more (b) less

(c) equal (d) may be more or less

8.9 For a safe design, a friction clutch is designed assuming

(a) uniform pressure theory

(b) uniform wear theory

(c) any one of the two

8.10 No force is required for downward motion of a load on a screw jack if

(a) $\alpha < \varphi$ (b) $\alpha > \varphi$ (c) $\alpha > 2\varphi$ (d) $\alpha < 2\varphi$

8.11 In a multiple-friction clutch, the number of active friction surfaces is

(a) $2n$ (b) n (c) $2(n - 1)$ (d) $n - 1$

Chapter 9 Belts, Ropes and Chains

9.1 Which of the following is not a flexible type of connector?

(a) Belt (b) Rope (c) Chain (d) Gear

9.2 In an open or crossed belt drive, the velocity ratio of the two pulleys is

(a) directly proportional to their diameters

(b) directly proportional to the square of their diameters

(c) inversely proportional to their diameters

(d) inversely proportional to the square of their diameters

9.3 Due to slip, the velocity ratio of a belt drive

(a) increases (b) decreases (c) remains same

9.4 The included angle of a pulley for a V-belt is

(a) 50° – 60° (b) 30° – 40° (c) 20° – 30° (d) 40° – 50°

9.5 The crowning of pulleys is done to

(a) increase the tightness of the belt on the pulley

(b) prevent belt running off the pulley

(c) increase the torque transmitted

(d) improve the shape and strength of the pulley

9.6 For maximum power transmission by a belt drive, the maximum tension must be

(a) $2T_c$ (b) $3T_c$ (c) $4T_c$ (d) $5T_c$

9.7 For maximum power transmission, the velocity of the belt is

(a) $\dfrac{T}{\sqrt{m}}$ (b) $\dfrac{T}{\sqrt{2m}}$ (c) $\dfrac{T}{\sqrt{3m}}$ (d) $\dfrac{T}{\sqrt{4m}}$

9.8 The belt drive is designed on the basis of the angle of contact on the
(a) larger pulley (b) smaller pulley (c) any pulley

9.9 The law of belting states that the centre line of the belt when it ________ a pulley must lie in the mid-plane of that pulley.
(a) leaves (b) approaches (c) approaches as well as leaves

9.10 The ratio of tight and slack side tensions in a V-belt or rope is
(a) $e^{\mu\theta \sin\alpha}$ (b) $e^{\mu\theta/\cos\alpha}$ (c) $e^{\mu\theta\cos\alpha}$ (d) $e^{\mu\theta/\sin\alpha}$

9.11 An increase in the initial tension in the belt ________ the power transmitted.
(a) increases (b) decreases (c) does not effect

Chapter 10 Gears

10.1 Two parallel shafts can be connected by ________ gears.
(a) straight spur (b) spiral
(c) cross-helical (d) straight bevel

10.2 Two intersecting shafts can be connected by ________ gears.
(a) straight spur (b) spiral
(c) cross-helical (d) straight bevel

10.3 Two skew shafts can be connected by ________ gears.
(a) straight spur (b) spiral bevel
(c) cross-helical (d) straight bevel

10.4 The size of gears is usually specified by
(a) circular pitch (b) outside diameter
(c) pitch circle diameter (d) inside diameter

10.5 The circular pitch of spur gears is the ratio of the
(a) number of teeth to the pitch diameter
(b) pitch diameter to the number of teeth
(c) circumference of the pitch circle to the number of teeth
(d) circumference of the pitch circle to the diameter of pitch circle

10.6 The module of spur gears is the ratio of the
(a) number of teeth to the pitch diameter
(b) pitch diameter to the number of teeth
(c) circumference of the pitch circle to the number of teeth
(d) circumference of the pitch circle to the diameter of pitch circle

10.7 The pressure angle of spur gears is kept small
(a) to reduce axial thrust on the bearings
(b) to increase the force for power transmission
(c) for both (a) and (b)
(d) none of (a) and (b)

10.8 The contact ratio of gears is always
(a) more than one (b) one (c) less than one (d) zero

10.9 In case of involute gear teeth, the pressure angle is
(a) same at all points of contact
(b) maximum at the engagement of teeth
(c) minimum at the engagement of teeth
(d) zero at the pitch point

10.10 The ratio of circular pitch and the module is
(a) π (b) $1/\pi$ (c) π^2 (d) $1/\pi^2$

10.11 The path of contact in involute tooth profiles is a
(a) parabola (b) circle (c) straight line (d) curve

10.12 Interference occurs in case of
(a) cycloidal profile teeth (b) involute profile teeth
(c) in both of them

10.13 The minimum number of teeth in a rack and pinion for a 20° pair angle teeth is
(a) 20 (b) 18 (c) 22 (d) 24

10.14 The normal circular pitch in helical gears is given by
(a) $p \sin \psi$ (b) $p/\sin \psi$ (c) $p \cos \psi$ (d) $p/\cos \psi$

10.15 The maximum efficiency of spiral gears is given by
(a) $\dfrac{\cos(\theta - \varphi) + 1}{\cos(\theta + \varphi) + 1}$ (b) $\dfrac{\cos(\theta + \varphi) - 1}{\cos(\theta - \varphi) + 1}$
(c) $\dfrac{\cos(\theta + \varphi) + 1}{\cos(\theta - \varphi) - 1}$ (d) $\dfrac{\cos(\theta + \varphi) + 1}{\cos(\theta - \varphi) + 1}$

10.16 The maximum efficiency of a worm and worm wheel is given by
(a) $\dfrac{1 - \sin \varphi}{1 + \sin \varphi}$ (b) $\dfrac{1 + \sin \varphi}{1 - \sin \varphi}$ (c) $\dfrac{1 - \cos \varphi}{1 + \sin \varphi}$ (d) $\dfrac{1 - \sin \varphi}{1 + \cos \varphi}$

Chapter 11 Gear Trains

11.1 In a simple gear train, there is an odd number of idlers. The direction of rotation of the driver and the driven gears will be
(a) opposite
(b) same
(c) depends upon number of teeth of the gears

11.2 In a reverted gear train, the axes of the first and last gear are
(a) parallel (b) co-axial (c) neither parallel nor co-axial

11.3 If the axes of the first and last gear of a compound gear train are co-axial, the gear train is known as
(a) simple (b) epicyclic (c) reverted (d) compound

11.4 In a gear train, the train value is given by
(a) $\dfrac{N_1}{N_n}$ (b) $\dfrac{N_n}{N_1}$ (c) $N_1 \times N_n$ (d) $N_n - N_1$

11.5 The speed ratio of a gear train is
(a) equal to the train value
(b) reciprocal of the train value

11.6 A gear train in which axes of gears have motion are called ________ gear trains.
(a) epicyclic (b) simple (c) compound (d) reverted

11.7 In a clock mechanism, the hour and minute hands are connected by ________ gear train.
(a) simple (b) epicyclic (c) compound (d) reverted

11.8 A differential uses ________ gear train.
(a) simple (b) epicyclic (c) reverted (d) compound

Chapter 12 Static Force Analysis

12.1 A pair of action and reaction forces acting on a body are known as
(a) applied forces (b) constraint forces
(c) accelerating forces (d) inertia forces

12.2 In static equilibrium the vector sum of all the forces acting on the body and all the moments about ________ point is zero.
(a) a fixed (b) a particular (c) any arbitrary (d) a permanent

12.3 If the lines of action of three or more forces intersect at a point, it is known as the ________ point.
(a) equilibrium (b) central (c) zero (d) concurrency

12.4 A part isolated from the mechanism ________ be in equilibrium.
(a) may (b) may or may not (c) must

Chapter 13 Dynamic Force Analysis

13.1 Acceleration of the piston of a reciprocating engine is ________.
(a) $r\omega^2\left(\sin\theta + \frac{\sin 2\theta}{n}\right)$ (b) $r\omega\left(\cos\theta + \frac{\cos 2\theta}{n}\right)$
(c) $r\omega^2\left(\cos\theta + \frac{\cos 2\theta}{4\pi}\right)$ (d) $r\omega^2\left(\cos\theta + \frac{\cos 2\theta}{n}\right)$

13.2 Crank effort is the net force applied at the crankpin ________ to the crank which gives the required turning moment on the crankshaft.
(a) parallel (b) perpendicular (c) at 45° (d) 135°

13.3 In a dynamically equivalent system, a uniformly distributed mass is divided into ________ point masses.
(a) two (b) three (c) four (d) five

13.4 Any distributed mass can be replaced by two point masses to have the same dynamical properties if
(a) the sum of the two masses is equal to the total mass
(b) the combined centre of mass coincides with that of the rod
(c) the moment of inertia of two point masses about the perpendicular axis through their combined centre of mass is equal to that of the rod
(d) all of the above

13.5 The maximum fluctuation of energy is the
(a) ratio of maximum and minimum energies
(b) sum of maximum and minimum energies
(c) difference of maximum and minimum energies
(d) difference of maximum and minimum energies from mean energy

13.6 The maximum fluctuation of energy in a flywheel is equal to
(a) $I\omega(\omega_1 - \omega_2)$ (b) $I\omega^2K$ (c) $2KE$
(d) All (e) none

Chapter 14 Balancing

14.1 Static balancing involves balancing of
(a) forces (b) couples
(c) forces as well as couples (d) masses

14.2 In case of rotating masses, the magnitude of the balancing mass is ________ when the speed of the shaft is doubled.
(a) doubled (b) halved (c) unaffected (d) quadrupled
14.3 For complete dynamic balance, at least ________ mass/masses are necessary.
(a) two (b) three (c) four (d) one
14.4 If a rotating system is dynamically balanced, it is statically
(a) balanced (b) unbalanced (c) partially balanced
14.5 The magnitude of the secondary force is ________ the primary force.
(a) more than (b) less than (c) equal to
14.6 In reciprocating engines, the primary unbalanced force
(a) cannot be balanced (b) can be fully balanced
(c) can be partially balanced
14.7 The primary unbalanced force is maximum when the angle of crank with the line of stroke is ________.
(a) 45° (b) 90° (c) 135° (d) 180°

Chapter 15 Brakes and Dynamometers

15.1 Which of the following brakes is commonly used in motor cars?
(a) Band brake (b) Shoe brake
(c) Band and block brake (d) Internal expanding shoe brake
15.2 Brakes commonly used in trains are ________ brakes.
(a) band (b) shoe
(c) band and block (d) internal expanding shoe
15.3 In a self-locking brake, the force required to apply the brake is
(a) minimum (b) zero (c) maximum
15.4 When the frictional force helps the applied force in applying the brake, the brake is
(a) self-locking (b) automatic (c) self-energising
15.5 In an internal expanding shoe brake, more than 50% of the total braking torque is supplied by
(a) leading shoe (b) trailing shoe (c) any of the two
15.6 The ratio of tensions on the tight and slack sides in a band and block brake is given by

(a) $\frac{T_n}{T_o} = \left(\frac{1-\mu \tan\theta}{1+\mu \tan\theta}\right)^n$ (b) $\frac{T_n}{T_o} = \left(\frac{1+\mu \tan\theta}{1-\mu \tan\theta}\right)^n$

(c) $\frac{T_n}{T_o} = \left(\frac{1+\mu \tan\theta}{1-\mu \tan\theta}\right)^{1/n}$ (d) $\frac{T_n}{T_o} = \left(\frac{1-\mu \tan\theta}{1-\mu \tan\theta}\right)^{1/n}$

15.7 The tractive resistance during the propulsion of a wheeled vehicle depends on
(a) road resistance (b) aerodynamic resistance
(c) gradient resistance (d) all the above.

Chapter 16 Governors

16.1 A ________ governor is a spring-loaded governor.
(a) Watt (b) Hartnell (c) Porter (d) Proell
16.2 The height of a Watt governor is
(a) g/ω^3 (b) ω^2/g (c) $g\omega^2$ (d) g/ω^2

16.3 The ratio of the height of a Porter governor to that of a Watt governor when the lengths of the links and the arms are the same is

(a) $\frac{M + m}{M}$ (b) $\frac{M + m}{m}$ (c) $\frac{M}{M + m}$ (d) $\frac{m}{M + m}$

16.4 A Hartnell governor is a/an ________ governor.
(a) dead weight (b) pendulum type
(c) inertia (d) spring-loaded

16.5 The frictional resistance at the sleeve ________ the sensitivity of the governor.
(a) does not affect (b) increases
(c) decreases (d) may increase or decrease

16.6 The governor is said to be ________ when the speed of the engine fluctuates continuously above and below the mean speed.
(a) isochronous (b) hunting
(c) insensitive (d) stable

16.7 If the controlling force of a spring-controlled governor is expressed as $a.r + b$, where r is the radius of rotation and a and b are constants, it is a/an ________ governor.
(a) isochronous (b) centrifugal
(c) dead-weight (d) inertia

16.8 In a governor if the equilibrium speed is constant for all radii of rotation of balls, the governor is said to be
(a) stable (b) unstable (c) inertia (d) isochronous

16.9 The force resisting the outward movement of balls is known as ________ of the governor.
(a) effort (b) centripetal force
(c) controlling force (d) inertia force

16.10 In a Wilson–Hartnell governor, the balls are connected by
(a) one spring (b) two springs in series
(c) two parallel springs (d) four springs

16.11 The effort of a governor is the force exerted by the governor on the
(a) balls (b) sleeve (c) upper links (d) lower links

16.12 The condition of isochronism can be realised in a ________ governor.
(a) Watt (b) Porter (c) Proell (d) Harnell

Chapter 17 Gyroscope

17.1 The magnitude of the gyroscopic couple applied to a disc of moment of inertia I, spinning with an angular velocity ω and having an angular velocity of precession ω_p is
(a) $I^2\omega\omega_p$ (b) $I\omega^2\omega_p$ (c) $I\omega\omega_p^2$ (d) $I\omega\omega_p$

17.2 The gyroscopic acceleration is given by

(a) $\frac{\delta\omega}{\delta t}$ (b) $\omega\frac{\delta\theta}{\delta t}$ (c) $r\frac{\delta\theta}{\delta t}$ (d) $r\frac{\delta\omega}{\delta t}$

17.3 If the air screw of an aeroplane rotates clockwise when viewed from the rear and the aeroplane takes a right turn, the gyrosocopic effect will
(a) tend to raise the tail and depress the nose
(b) tend to raise the nose and depress the tail
(c) tilt the aeroplane about spin axis
(d) none of above

17.4 The axis of spin, the axis of precession and the axis of gyroscopic torque are in
(a) two parallel planes (b) two perpendicular planes
(c) three perpendicular planes (d) three parallel planes

17.5 The effect of gyroscopic torque on the naval ship when it is rolling and the rotor is spinning about the longitudinal axis is
(a) to raise the bow and lower the stern
(b) to lower the bow and raise the stern
(c) to turn the ship to one side
(d) none of the above

Chapter 18 Vibrations

18.1 A reduction in amplitude of successive oscillations indicate ________ vibrations.
(a) free (b) force (c) damped (d) natural

18.2 The particles of a body move ________ its axis in longitudinal vibrations.
(a) in a circle about (b) parallel to
(c) perpendicular to (d) away from

18.3 The particles of a body move ________ its axis in torsional vibrations.
(a) in a circle about (b) parallel to
(c) perpendicular to (d) away from

18.4 In a spring-mass system, if the mass is halved and the spring stiffness is doubled, the natural frequency is
(a) halved (b) doubled (c) unchanged (d) quadrupled

18.5 In free vibrations, the velocity vector leads the displacement vector by
(a) π (b) $\pi/2$ (c) $\pi/3$ (d) $2\pi/3$

18.6 In free vibrations, the acceleration vector leads the displacement vector by
(a) π (b) $\pi/2$ (c) $\pi/3$ (d) $2\pi/3$

18.7 The amplitude ratio of two successive oscillations of a damped vibratory system is
(a) more than one (b) less than one
(c) equal to one (d) variable

18.8 An over-damped system
(a) does not vibrate at all
(b) vibrates with frequency more than the natural frequency of system
(c) vibrates with frequency less than the natural frequency of system
(d) vibrates with frequency equal than the natural frequency of system

18.9 The ratio of the amplitude of the steady-state response of forced vibrations to the static deflection under the action of a static force is known as
(a) damping ratio (b) damping factor
(c) transmissibility (d) magnification factor

18.10 The frequency of damped vibrations is always ________ the natural frequency.
(a) equal to (b) more than (c) less than (d) double

18.11 If ω/ω_n is more than $\sqrt{2}$ in a vibration isolation system then for all values of the damping factor, the transmissibility is
(a) less than $\sqrt{2}$ (b) more than $\sqrt{2}$
(c) less than unity (d) more than unity

18.12 Resonance is a phenomenon in which the frequency of the exciting force is ________ to the natural frequency of the system.
(a) double (b) half (c) equal (d) thrice

18.13 At resonance, the amplitude of vibration is
(a) very large (b) small
(c) zero (d) depends upon frequency

18.14 At a certain speed, revolving shafts tend to vibrate violently in transverse directions. The speed is known as
(a) whirling speed (b) critical speed (c) whipping speed
(d) all of these (e) none of these

18.15 The critical speed of a rotating shaft with a mass at the centre is ________ the natural frequency of transverse vibration of the system.
(a) equal (b) less than
(c) more than (d) dependent upon

18.16 A torsional vibratory system having two rotors connected by a shaft has
(a) one node (b) two nodes (c) three nodes (d) no node

18.17 A torsional vibratory system having three rotors connected by a shaft has
(a) one node (b) two nodes (c) three nodes (d) no node

Chapter 19 Automatic Control

19.1 A block diagram is a symbolic outline of a system in which various components or operations are represented by ________ in an ordered sequence.
(a) circles (b) rectangles
(c) triangles (d) parallelograms

19.2 In a first-order system, the response is given by ________.
(a) $y = \left(e^{-\frac{t}{T}} - 1\right)$ (b) $y = x - e^{-\frac{t}{T}}$
(c) $y = x\left(1 - e^{-\frac{t}{T}}\right)$ (d) $y = x\left(1 - xe^{-\frac{t}{T}}\right)$

19.3 The transfer function is the operational relationship of the output and the
(a) command (b) response (c) input (d) error

ANSWERS

Chapter 1

1.1 (b)	1.2 (c)	1.3 (a)	1.4 (b)	1.5 (c)	1.6 (a)
1.7 (c)	1.8 (a)	1.9 (b)	1.10 (c)	1.11 (b)	

Chapter 2

2.1 (b)	2.2 (a)	2.3 (a)	2.4 (b)	2.5 (c)	2.6 (c)
2.7 (b)	2.8 (b)	2.9 (a)	2.10 (c)		

Chapter 3

3.1 (b)	3.2 (a)	3.3 (c)	3.4 (b)	3.5 (b)	3.6 (d)
3.7 (b)					

Chapter 4

4.1 (c)	4.2 (c)	4.3 (a)	4.4 (a)

Chapter 5

5.1 (b)	5.2 (a)	5.3 (a)

Chapter 6

6.1 (a)	6.2 (b)	6.3 (c)	6.4 (b)	6.5 (b)	6.6 (d)
6.7 (c)	6.8 (c)	6.9 (c)	6.10 (b)	6.11 (b)	6.12 (a)

Chapter 7

7.1 (c)	7.2 (b)	7.3 (a)	7.4 (c)	7.5 (d)	7.6 (c)
7.7 (b)	7.8 (a)	7.9 (b)	7.10 (a)	7.11 (d)	

Chapter 8

8.1 (a)	8.2 (d)	8.3 (c)	8.4 (d)	8.5 (b)	8.6 (c)
8.7 (d)	8.8 (a)	8.9 (b)	8.10 (b)	8.11 (d)	

Chapter 9

9.1 (d)	9.2 (c)	9.3 (b)	9.4 (b)	9.5 (b)	9.6 (b)
9.7 (c)	9.8 (b)	9.9 (b)	9.10 (d)	9.11 (a)	

Chapter 10

10.1 (a)	10.2 (d)	10.3 (c)	10.4 (c)	10.5 (c)	10.6 (b)
10.7 (c)	10.8 (a)	10.9 (a)	10.10 (a)	10.11 (c)	10.12 (b)
10.13 (b)	10.14 (c)	10.15 (d)	10.16 (a)		

Chapter 11

11.1 (b)	11.2 (b)	11.3 (c)	11.4 (b)	11.5 (b)	11.6 (a)
11.7 (d)	11.8 (b)				

Chapter 12

12.1 (b)	12.2 (c)	12.3 (d)	12.4 (c)

Chapter 13

13.1 (b)	13.2 (b)	13.3 (a)	13.4 (c)	13.5 (c)	13.6 (d)

Chapter 14

14.1 (a)	14.2 (c)	14.3 (a)	14.4 (a)	14.5 (b)	14.6 (c)
14.7 (d)					

Chapter 15

15.1 (d)	15.2 (b)	15.3 (b)	15.4 (c)	15.5 (a)	15.6 (b)
15.7 (d)					

Chapter 16

16.1 (b)	16.2 (d)	16.3 (b)	16.4 (d)	16.5 (c)	16.6 (b)
16.7 (a)	16.8 (d)	16.9 (c)	16.10 (c)	16.11 (b)	16.12 (d)

Chapter 17

17.1 (d)	17.2 (b)	17.3 (a)	17.4 (c)	17.5 (d)

Chapter 18

18.1 (c)	18.2 (b)	18.3 (a)	18.4 (b)	18.5 (b)	18.6 (a)
18.7 (b)	18.8 (a)	18.9 (d)	18.10 (c)	18.11 (c)	18.12 (c)
18.13 (a)	18.14 (d)	18.15 (a)	18.16 (a)	18.17 (b)	

Chapter 19

19.1 (b)	19.2 (c)	19.3 (c)

Appendix B

IMPORTANT RELATIONS AND RESULTS

1. For degree of freedom of mechanisms,
   - *Kutzback's* criterion, $F = 3\,(N-1) - 2P_1 - 1P_2$
   - *Gruebler's* criterion, $F = 3\,(N-1) - 2P_1$
   - *Author's* criterion, $F = N - (2L+1)$ and $P_1 = N + (L-1)$
2. The number of Instantaneous-centres in a mechanism, $N = n\,(n-1)/2$
3. The angle of the output link of a four-link mechanism, $\varphi = 2\tan^{-1}\left[\dfrac{-B \pm \sqrt{B^2 - 4AC}}{2A}\right]$

   where $2k = a^2 - b^2 + c^2 + d^2$, $A = k - a\,(d-c)\cos\theta - cd$
   $B = -2ac\sin\theta$ and $C = k - a\,(d+c)\cos\theta + cd$
4. The angle of the coupler link of four-link mechanism, $\beta = 2\tan^{-1}\left[\dfrac{-E \pm \sqrt{E^2 - 4DF}}{2D}\right]$

   where $2k' = a^2 + b^2 - c^2 + d^2$, $D = k' - a(d+b)\cos\theta + bd$
   $E = 2ab\sin\theta$ and $F = k' - a(d-b)\cos\theta - bd$
5. The angular velocities of the output and coupler links of a four-link mechanism,

   $$\omega_c = \frac{a\omega_\alpha \sin(\beta-\theta)}{c\sin(\beta-\varphi)} \text{ and } \omega_b = -\frac{a\omega_\alpha \sin(\varphi-\theta)}{b\sin(\varphi-\beta)}$$
6. The angular accelerations of the output and coupler links of a four-link mechanism,

   $$a_c = \frac{a\alpha_a \sin(\beta-\theta) - a\omega_a^2\cos(\beta-\theta) - b\omega_b^2 + c\omega_c^2\cos(\beta-\varphi)}{c\sin(\beta-\varphi)}$$

   and $$a_b = \frac{a\alpha_a \sin(\varphi-\theta) - a\omega_a^2\cos(\varphi-\theta) - b\omega_b^2\cos(\varphi-\beta) + c\omega_c^2}{b\sin(\beta-\varphi)}$$
7. The displacement of the slider of a slider-crank mechanism, $d = \dfrac{-C_1 \pm \sqrt{C_1^2 - 4C_2}}{2}$

   where $C_1 = -2a\cos\theta$ and $C_2 = a^2 - b^2 + e^2 - 2ae\sin\theta$
8. The angle of the coupler link of a slider-crank mechanism, $\beta = \sin^{-1}\dfrac{e - a\sin\theta}{b}$
9. The velocities of the slider and the coupler of a slider-crank mechanism,

   $$\dot{d} = \frac{a\omega_a \sin(\beta-\theta)}{\cos\beta} \quad\text{and}\quad \omega_b = \frac{a\omega_a\cos\theta}{b\cos\beta}$$

10. The accelerations of the slider and the coupler link of a slider-crank mechanism,

$$\ddot{d} = \frac{a\alpha_a \sin(\beta - \theta) - a\omega_a^2 \cos(\beta - \theta) - b\omega_b^2}{\cos\beta}$$

and $$\alpha_b = \frac{a\alpha_a \cos\theta - a\omega_a^2 \sin\theta - b\omega_b^2 \sin\beta}{b\cos\beta}$$

11. *Freudenstein's* equation is

$$\frac{d}{a}\cos\varphi - \frac{d}{c}\cos\theta + \frac{a^2 - b^2 + c^2 + d^2}{2ac} = \cos(\theta - \varphi) = \cos(\varphi - \theta)$$

12. For n accuracy positions in the range $x_o \le x \le x_{n+1}$, the Chebychev spacing given by

$$x_i = \frac{x_{n+1} + x_o}{2} - \frac{x_{n+1} - x_o}{2}\cos\frac{(2i-1)\pi}{2n} \text{ where } i = 1, 2, 3 \ldots n$$

13. In a simple harmonic motion of follower,

$$v_{\max} = \frac{h}{2}\frac{\pi\omega}{\varphi} \text{ at } \theta = \frac{\varphi}{2} \quad \text{and} \quad f_{\max} = \frac{h}{2}\left(\frac{\pi\omega}{\varphi}\right)^2 \text{ at } \theta = 0^\circ$$

14. In constant acceleration and deceleration of follower,

$$f = \frac{4h\omega^2}{\varphi^2} \text{ and } v_{\max} = \frac{2h\omega}{\varphi} \text{ at } \theta = \varphi/2$$

15. In constant velocity of the follower, $v = \dfrac{h\omega}{\varphi}$

16. In cycloidal motion, $v_{\max} = \dfrac{2h\omega}{\varphi}$ at $\theta = \dfrac{\varphi}{2}$ and $f_{\max} = \dfrac{2h\pi\omega^2}{\varphi^2}$ at $\theta = \dfrac{\varphi}{4}$

17. When a body slides up the plane, $\eta = \dfrac{\cot(\alpha + \theta) - \cot\theta}{\cot\alpha - \cot\theta}$

    If the direction of the applied force is horizontal, $\eta = \dfrac{\tan\alpha}{\tan(\alpha + \varphi)}$

18. When the body moves down the plane, $\eta = \dfrac{\cot\alpha - \cot\theta}{\cot(\varphi - \alpha) + \cot\theta}$

    If the direction of the applied force is horizontal, $\eta = \dfrac{\tan(\varphi - \alpha)}{\tan\alpha}$

19. For flat collars, friction torque is

$$T = \frac{2\mu F(R_o^3 - R_i^3)}{3(R_o^2 - R_i^2)} \text{ with uniform pressure theory}$$

$$= \frac{\mu F}{2}(R_o^2 + R_i^2) \text{ with uniform wear theory}$$

20. For conical collars, friction torque $= \dfrac{\text{friction torque for flat collares}}{\sin\alpha}$

21. When the belt is on the point of slipping on the pulleys, $\dfrac{T_1}{T_2} = e^{\mu\theta}$ for flat belt drive, and $\dfrac{T_1}{T_2} = e^{\mu\theta/\sin\alpha}$ for V-belt drive

22. Power transmitted in belts, $P = (T_1 - T_2)\ v$

23. Initial tension in the belt, $T_o = \dfrac{T_1 + T_2}{2}$

24. Path of contact in gears $= \left[\sqrt{R_a^2 - R^2 \cos^2 \varphi} - R \sin \varphi\right] + \left[\sqrt{r_a^2 - r^2 \cos^2 \varphi} - r \sin \varphi\right]$

25. Arc of contact $= \dfrac{\text{Path of contact}}{\cos \varphi}$

26. The minimum number of teeth on the wheel, $T = \dfrac{2a_w}{\sqrt{1 + \dfrac{1}{G}\left(\dfrac{1}{G} + 2\right)\sin^2 \varphi} - 1}$

27. Maximum efficiency of worm gear, $\eta_{max} = \dfrac{1 - \sin \varphi}{1 + \sin \varphi}$

28. Inertia force on the piston, $F_b = mf = mr\omega^2 \left(\cos \theta + \dfrac{\cos 2\theta}{n}\right)$

29. Turning moment on the piston $= Fr\left(\sin \theta + \dfrac{\sin 2\theta}{2\sqrt{n^2 - \sin^2 \theta}}\right)$

30. In flywheels, maximum fluctuation of energy, $e = \dfrac{1}{2} I(\omega_1^2 - \omega_2^2) = I\omega^2 K$

and coefficient of fluctuation of speed, $K = \dfrac{e}{I\omega^2} = \dfrac{e}{2E}$

31. In a reciprocating engine,

Primary accelerating force $= mr\omega^2 \cos\theta$

Secondary accelerating force $= mr\omega^2 \cos(2\theta)/n$

32. In a block brake, if the angle of contact is more than 40°, $\mu' = \mu\left(\dfrac{4 \sin(\theta/2)}{\theta + \sin \theta}\right)$

33. In a band and block brake, $\dfrac{T_n}{T_o} = \left(\dfrac{1 + \mu \tan \theta}{1 - \mu \tan \theta}\right)^n$

34. In a Watt governor, height of governor, $h = \dfrac{895}{N^2}$ m

35. In a Hartnell governor, stiffness of spring, $s = 2\left(\dfrac{a}{b}\right)^2 \left(\dfrac{F_2 - F_1}{r_2 - r_1}\right)$

36. In a Wilson–Hartnell governor, $\dfrac{F_2 - F_1}{r_2 - r_1} = 4s + \dfrac{S_a}{2}\left(\dfrac{b}{a}\dfrac{y}{x}\right)^2$

37. Damping factor in a vibrating system, $\zeta = c/c_c$

38. The frequency of an undamped system ($\zeta = 0$), $\omega_n = \sqrt{g/\Delta}$

39. In an underdamped system ($\zeta < 1$), $\omega_d = \sqrt{1 - \zeta^2}\,\omega_n$ and $T_d = 2\pi/\omega_d$

40. At critical damping $\xi = 1$, $\omega_d = 0$ and $T_d = \infty$

41. Transfer function,

∞ In open loop, $TF = \dfrac{\theta_0}{\theta_i} = F_4(D)\, F_3(D)\, F_1(D) = KG(D)$

∞ In closed loop, $TF = \dfrac{\theta_0}{\theta_i} = \dfrac{KG(D)}{1 + KG(D)} = \dfrac{\text{Open loop TF}}{1 + \text{Open loop TF}}$

INDEX