CHAPTER 1

SYSTEM COMPONENTS AND THEIR REPRESENTATION

1.1 CONTROL SYSTEM: TERMINOLOGY AND BASIC STRUCTURE

Control system theory evolved as an engineering discipline and due to universality of the principles involved, it is extended to various fields like economy, sociology, biology, medicine, etc. Control theory has played a vital role in the advance of engineering and science. The automatic control has become an integral part of modern manufacturing and industrial processes. For example, numerical control of machine tools in manufacturing industries, controlling pressure, temperature, humidity, viscosity and flow in process industry.

When a number of elements or components are connected in a sequence to perform a specific function, the group thus formed is called a ***system.*** In a system when the output quantity is controlled by varying the input quantity, the system is called ***control system.*** The output quantity is called controlled variable or response and input quantity is called command signal or excitation.

1.1.1 OPEN LOOP SYSTEM

Any physical system which does not automatically correct the variation in its output, is called an ***open loop system***, or control system in which the output quantity has no effect upon the input quantity are called open-loop control system. This means that the output is not fedback to the input for correction.

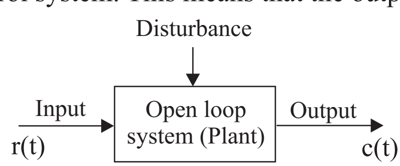


Fig 1.1 : *Open loop system.*

In open loop system the output can be varied by varying the input. But due to external disturbances the system output may change. When the output changes due to disturbances, it is not followed by changes in input to correct the output. In open loop systems the changes in output can be corrected by changing the input manually.

1.1.2 CLOSED LOOP SYSTEM

Control systems in which the output has an effect upon the input quantity in order to maintain the desired output value are called ***closed loop systems.***

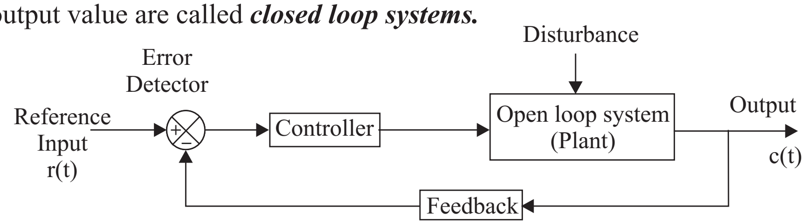


Fig 1.2 : *Closed loop system.*

The open loop system can be modified as closed loop system by providing a feedback. The provision of feedback automatically corrects the changes in output due to disturbances. Hence the closed loop system is also called ***automatic control system.*** The general block diagram of an automatic control system is shown in fig 1.2. It consists of an error detector, a controller, plant (open loop system) and feedback path elements.

The reference signal (or input signal) corresponds to desired output. The feedback path elements samples the output and converts it to a signal of same type as that of reference signal. The feedback signal is proportional to output signal and it is fed to the error detector. The error signal generated by the error detector is the difference between reference signal and feedback signal. The controller modifies and amplifies the error signal to produce better control action. The modified error signal is fed to the plant to correct its output.

Advantages of open loop systems

1. The open loop systems are simple and economical.
2. The open loop systems are easier to construct.
3. Generally the open loop systems are stable.

Disadvantages of open loop systems

1. The open loop systems are inaccurate and unreliable.
2. The changes in the output due to external disturbances are not corrected automatically.

Advantages of closed loop systems

1. The closed loop systems are accurate.
2. The closed loop systems are accurate even in the presence of non-linearities.
3. The sensitivity of the systems may be made small to make the system more stable.
4. The closed loop systems are less affected by noise.

Disadvantages of closed loop systems

1. The closed loop systems are complex and costly.
2. The feedback in closed loop system may lead to oscillatory response.
3. The feedback reduces the overall gain of the system.
4. Stability is a major problem in closed loop system and more care is needed to design a stable closed loop system.

1.1.3 FEEDFORWARD AND FEEDBACK CONTROL THEORY

In automatic control systems, the changes in the controlled output variable due to disturbances are usually corrected automatically by feedback control. An alternative approach for automatic correction of changes in output variable due to disturbances is feedforward control.

In feedforward control the disturbance is measured before it enter the plant. Appropriate corrections to be made at the input are determined using the measured disturbance and input is corrected automatically, so that the corrected input and disturbance enter the plant almost simultaneously. This help in eliminating the effect of disturbance in the output much faster than feedback control, and also reduce the transient error. The feedforward control cannot be implemented alone, because it will not make corrections for non-measurable disturbances. Therefore, a system with feedforward control will also have a feedback control.

Consider the unity feedback control system with an error correction controller in series with the plant as shown in fig 1.3.

Let, G(s) = Open loop transfer function

$G_c(s)$ = Controller transfer function

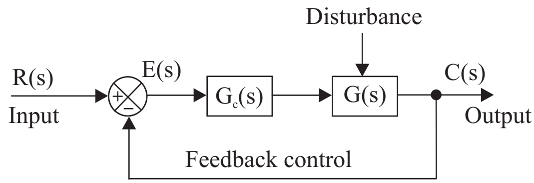


Fig 1.3: *Feedback control system*

Let, N(s) = Disturbance or Noise input

$G_n(s)$ = Disturbance transfer function

Now, a feedforward transfer function $G_f(s)$ can be designed and implemented in the system as shown in fig 1.4.

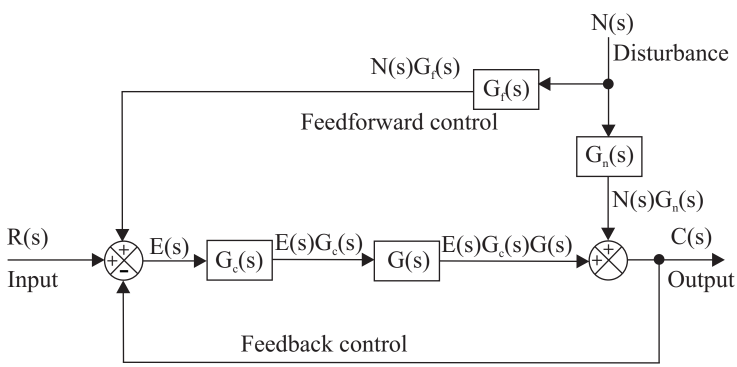


Fig. 1.4: *Feedforward and feedback control system*

The feedforward transfer function can be derived in terms of $G_n(s)$, $G_c(s)$ and G(s) as shown below.

With reference to fig 1.4, the equation for error signal E(s) can be written as shown below.

$$E(s) = R(s) - C(s) + N(s)\,G_f(s) \qquad \text{..... (1.1)}$$

With reference to fig 1.4, the equation for output C(s) can be written as shown below.

$$C(s) = E(s)\,G_c(s)\,G(s) + N(s)\,G_n(s)$$

On substituting for E(s) from equation (1) in the above equation we get,

$$C(s) = [R(s) - C(s) + N(s)\,G_f(s)\,]\,G_c(s)\,G(s) + N(s)\,G_n(s)$$

$$\therefore C(s) = [R(s) - C(s)]\,G_c(s)\,G(s) + N(s)\,G_f(s)\,G_c(s)\,G(s) + N(s)\,G_n(s)$$

$$\therefore C(s) = [R(s) - C(s)]\,G_c(s)\,G(s) + [\,G_f(s)\,G_c(s)\,G(s) + G_n(s)]\,N(s)$$

In the above equation, if , $G_f(s)\,G_c(s)\,G(s) + G_n(s) = 0$,

then the effect of disturbance in the output will be zero.

Therefore, the feedforward transfer function is designed such that,

$$G_f(s)\, G_c(s)\, G(s) + G_n(s) = 0$$

$$\therefore \quad G_f(s) = -\frac{G_n(s)}{G_c(s)G(s)}$$

From the above equation it is clear that, feedforward transfer function $G_f(s)$ can be designed only from the knowledge of disturbance transfer function $G_n(s)$.

The advantage of feedforward control is that it reduces the transient error and so it performs very fast corrections but this control is applicable only if the disturbances are measurable. But, the feedback control can be employed for both measurable and non-measurable disturbances.

1.1.4 EXAMPLES OF CONTROL SYSTEMS

EXAMPLE 1 : TEMPERATURE CONTROL SYSTEM

OPEN LOOP SYSTEM

The electric furnace shown in fig 1.5. is an open loop system. The output in the system is the desired temperature. The temperature of the system is raised by heat generated by the heating element. The output temperature depends on the time during which the supply to heater remains ON.

The ON and OFF of the supply is governed by the time setting of the relay. The temperature is measured by a sensor, which gives an analog voltage corresponding to the temperature of the furnace. The analog signal is converted to digital signal by an Analog - to - Digital converter (A/D converter).

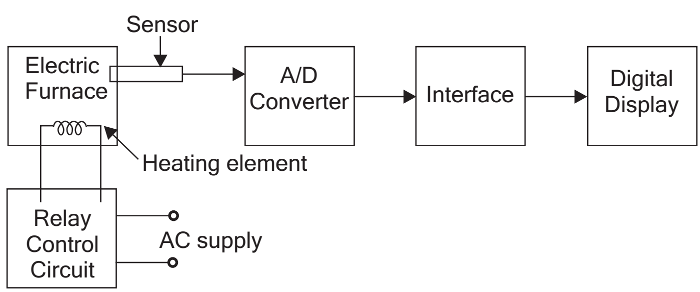


Fig 1.5 : *Open loop temperature control system.*

The digital signal is given to the digital display device to display the temperature. In this system if there is any change in output temperature then the time setting of the relay is not altered automatically.

CLOSED LOOP SYSTEM

The electric furnace shown in fig 1.6 is a closed loop system. The output of the system is the desired temperature and it depends on the time during which the supply to heater remains ON.

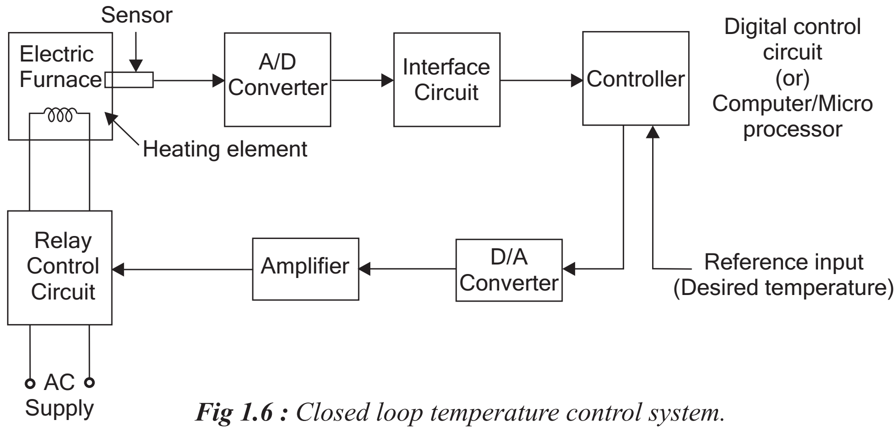


Fig 1.6 : *Closed loop temperature control system.*

The switching ON and OFF of the relay is controlled by a controller which is a digital system or computer. The desired temperature is input to the system through keyboard or as a signal corresponding to desired temperature via ports. The actual temperature is sensed by sensor and converted to digital signal by the A/D converter. The computer reads the actual temperature and compares with desired temperature. If it finds any difference then it sends signal to switch ON or OFF the relay through D/A converter and amplifier. Thus the system automatically corrects any changes in output. Hence it is a closed loop system.

EXAMPLE 2 : TRAFFIC CONTROL SYSTEM

OPEN LOOP SYSTEM

Traffic control by means of traffic signals operated on a time basis constitutes an open-loop control system. The sequence of control signals are based on a time slot given for each signal. The time slots are decided based on a traffic study. The system will not measure the density of the traffic before giving the signals. Since the time slot does not changes according to traffic density, the system is open loop system.

CLOSED LOOP SYSTEM

Traffic control system can be made as a closed loop system if the time slots of the signals are decided based on the density of traffic. In closed loop traffic control system, the density of the traffic is measured on all the sides and the information is fed to a computer. The timings of the control signals are decided by the computer based on the density of traffic. Since the closed loop system dynamically changes the timings, the flow of vehicles will be better than open loop system.

EXAMPLE 3 : NUMERICAL CONTROL SYSTEM

OPEN LOOP SYSTEM

Numerical control is a method of controlling the motion of machine components using numbers. Here, the position of work head tool is controlled by the binary information contained in a disk.

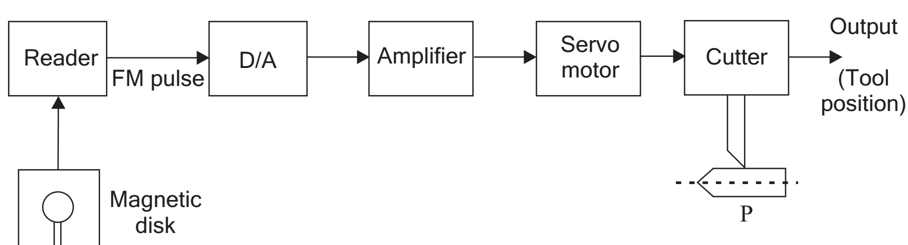


Fig 1.7 : *Open loop numerical control system.*

A magnetic disk is prepared in binary form representing the desired part P (P is the metal part to be machined). The tool will operate on the desired part P. To start the system, the disk is fed through the reader to the D/A converter. The D/A converter converts the FM(frequency modulated) output of the reader to a analog signal. It is amplified and fed to servometer which positions the cutter on the desired part P. The position of the cutter head is controlled by the angular motion of the servometer. This is an open loop system since no feedback path exists between the output and input. The system positions the tool for a given input command. Any deviation in the desired position is not checked and corrected automatically.

CLOSED LOOP SYSTEM

A magnetic disk is prepared in binary form representing the desired part P (P is the metal part to be machined). To start the system, the disk is loaded in the reader. The controller compares the frequency modulated input pulse signal with the feedback pulse signal. The controller is a computer or microprocessor system. The controller carries out mathematical operations on the difference in the pulse signals and generates an error signal. The D/A converter converts the controller output pulse (error signal) into an analog signal . The amplified analog signal rotates the servomotor to position the tool on the job. The position of the cutterhead is controlled according to the input of the servomotor.

The transducer attached to the cutterhead converts the motion into an electrical signal. The analog electrical signal is converted to the digital pulse signal by the A/D converter. Then this signal is compared with the input pulse signal. If there is any difference between these two, the controller sends a signal to the servomotor to reduce it. Thus the system automatically corrects any deviation in the desired output tool position. An advantage of numerical control is that complex parts can be produced with uniform tolerances at the maximum milling speed.

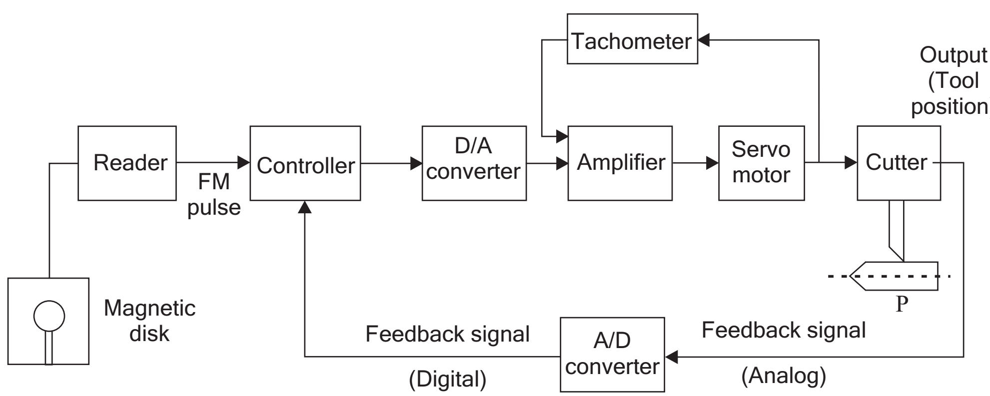


Fig 1.8 : *Closed loop numerical control system.*

EXAMPLE 4 : POSITION CONTROL SYSTEM USING SERVOMOTOR

The position control system shown in fig 1.9 is a closed loop system. The system consists of a servomotor powered by a generator. The load whose position has to be controlled is connected to motor shaft through gear wheels. Potentiometers are used to convert the mechanical motion to electrical signals. The desired load position (θ_R) is set on the input potentiometer and the actual load position (θ_c) is fed to feedback potentiometer. The difference between the two angular positions generates an error signal, which is amplified and fed to generator field circuit. The induced emf of the generator drives the motor. The rotation of the motor stops when the error signal is zero, i.e. when the desired load position is reached.

This type of control systems are called servomechanisms. The ***servo*** or ***servomechanisms*** are feedback control systems in which the output is mechanical position (or time derivatives of position e.g. velocity and acceleration).

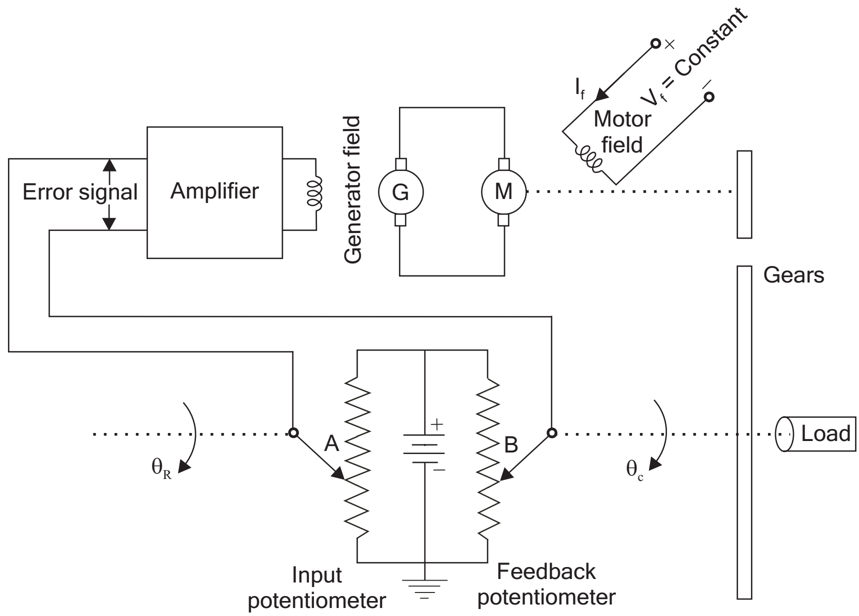


Fig 1.9 : *A position control system (servomechanism).*

1.2 MATHEMATICAL MODELS OF CONTROL SYSTEM

A ***control system*** is a collection of physical objects (components) connected together to serve an objective. The input output relations of various physical components of a system are governed by ***differential equations.*** The mathematical model of a control system constitutes a set of differential equations. The response or output of the system can be studied by solving the differential equations for various input conditions.

The mathematical model of a system is linear if it obeys the principle of superposition and homogenity. This principle implies that if a system model has responses $y_1(t)$ and $y_2(t)$ to any inputs $x_1(t)$ and $x_2(t)$ respectively, then the system response to the linear combination of these inputs $a_1x_1(t) + a_2x_2(t)$ is given by linear combination of the individual outputs $a_1y_1(t) + a_2y_2(t)$, where a_1 and a_2 are constants.

The principle of superposition can be explained diagrammatically as shown in fig 1.10.

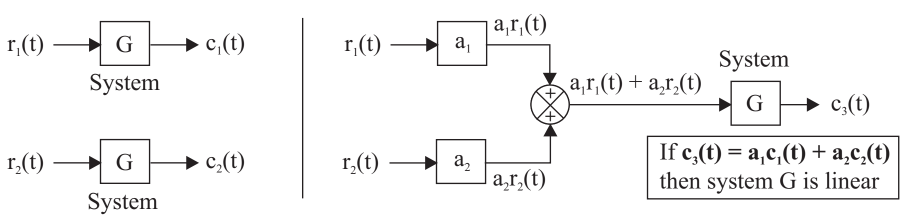


Fig 1.10 : *Principle of linearity and superposition.*

A mathematical model will be linear if the differential equations describing the system has constant coefficients (or the coefficients may be functions of independent variables). If the coefficients of the differential equation describing the system are constants then the model is ***linear time invariant.*** If the coefficients of differential equations governing the system are functions of time then the model is ***linear time varying.***

The differential equations of a linear time invariant system can be reshaped into different form for the convenience of analysis. One such model for single input and single output system analysis is transfer function of the system. The ***transfer function*** of a system is defined as the ratio of Laplace transform of output to the Laplace transform of input with zero initial conditions.

$$\text{Transfer function} = \left.\frac{\text{Laplace Transform of output}}{\text{Laplace Transform of input}}\right|_{\text{with zero initial conditions}}$$

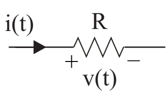
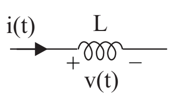
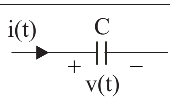
The transfer function can be obtained by taking Laplace transform of the differential equations governing the system with zero initial conditions and rearranging the resulting algebraic equations to get the ratio of output to input.

1.3 ELECTRICAL TRANSFER FUNCTION MODELS

The models of electrical systems can be obtained by using resistor, capacitor and inductor. The current-voltage relation of resistor, inductor and capacitor are given in table-1. For modelling electrical systems, the electrical network or equivalent circuit is formed by using R, L and C and voltage or current source.

The differential equations governing the electrical systems can be formed by writing Kirchoff 's current law equations by choosing various nodes in the network or Kirchoff 's voltage law equations by choosing various closed paths in the network. The transfer function can be obtained by taking Laplace transform of the differential equations and rearranging them as a ratio of output to input.

Table-1.1 : Current-Voltage Relation of R, L and C

Element	Voltage across the element	Current through the element
	$v(t) = Ri(t)$	$i(t) = \frac{v(t)}{R}$
	$v(t) = L\frac{d}{dt}i(t)$	$i(t) = \frac{1}{L}\int v(t)\,dt$
	$v(t) = \frac{1}{C}\int i(t)\,dt$	$i(t) = C\frac{dv(t)}{dt}$

1.3.1 TRANSFER FUNCTION OF ARMATURE CONTROLLED DC MOTOR

The speed of DC motor is directly proportional to armature voltage and inversely proportional to flux in field winding. In armature controlled DC motor the desired speed is obtained by varying the armature voltage. This speed control system is an electro-mechanical control system. The electrical system consists of the armature and the field circuit but for analysis purpose, only the armature circuit is considered because the field is excited by a constant voltage. The mechanical system consists of the rotating part of the motor and load connected to the shaft of the motor. The armature controlled DC motor speed control system is shown in fig 1.11.

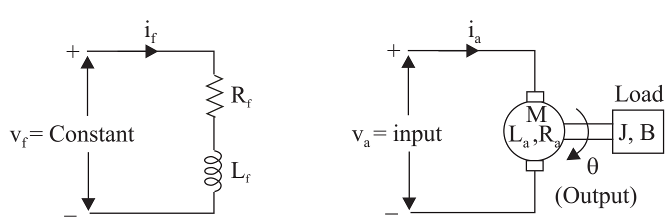


Fig 1.11 : *Armature controlled DC motor.*

Let, R_a = Armature resistance, Ω
L_a = Armature inductance, H
i_a = Armature current, A
v_a = Armature voltage, V
e_b = Back emf, V
K_t = Torque constant, N-m/A
T = Torque developed by motor, N-m
θ = Angular displacement of shaft, rad
ω = Angular velocity, rad/sec
J = Moment of inertia of motor and load, Kg-m²/rad
B = Frictional coefficient of motor and load, N-m/(rad/sec)
K_b = Back emf constant, V/(rad/sec)

The equivalent circuit of armature is shown in fig 1.12.

By Kirchoff's voltage law, we can write,

$$i_a R_a + L_a \frac{di_a}{dt} + e_b = v_a \quad .....(1.2)$$

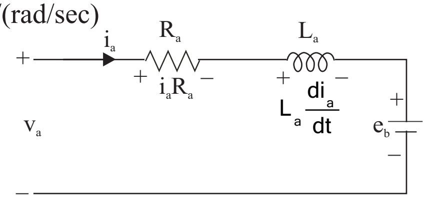


***Fig 1.12 :** Equivalent circuit of armature.*

Torque of DC motor is proportional to the product of flux and current. Since flux is constant in this system, the torque is proportional to i_a alone.

$$T \propto i_a$$

$$\therefore \text{ Torque, } T = K_t\, i_a \quad .....(1.3)$$

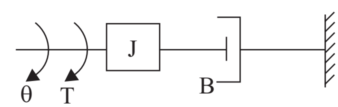


Fig 1.13.

The mechanical system of the motor is shown in fig 1.13.

The differential equation governing the mechanical system of motor is given by,

$$J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} = T \quad .....(1.4)$$

The back emf of DC machine is proportional to speed (angular velocity) of shaft.

$$e_b \propto \omega \quad \text{and} \quad \omega = \frac{d\theta}{dt} \quad ; \quad \therefore\ e_b \propto \frac{d\theta}{dt} \quad \text{or} \quad \text{Back emf, } e_b = K_b\frac{d\theta}{dt} \quad .....(1.5)$$

The Laplace transform of various time domain signals involved in this system are shown below.

$$\mathcal{L}\{v_a\} = V_a(s) \ ; \ \mathcal{L}\{e_b\} = E_b(s) \ ; \ \mathcal{L}\{T\} = T(s) \ ; \ \mathcal{L}\{i_a\} = Ia(s) \ ; \ \mathcal{L}\{\theta\} = \theta(s)$$

The differential equations governing the armature controlled DC motor speed control system are,

$$i_a R_a + L_a\frac{di_a}{dt} + e_b = v_a \quad ; \quad T = K_t i_a \quad ; \quad J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} = T \quad ; \quad e_b = K_b\frac{d\theta}{dt}$$

Taking Laplace transform of the above equations with zero initial conditions we get,

$$I_a(s)\, R_a + L_a s I_a(s) + E_b(s) = V_a(s) \quad .....(1.6)$$

$$T(s) = K_t I_a(s) \quad .....(1.7)$$

$$Js^2\theta(s) + B\, s\, \theta(s) = T(s) \quad .....(1.8)$$

$$E_b(s) = K_b s\theta\,(s) \quad .....(1.9)$$

On equating equations (1.7) and (1.8) we get,

$$K_t I_a(s) = (Js^2 + Bs)\,\theta(s)$$

$$I_a(s) = \frac{(Js^2 + Bs)}{K_t}\,\theta(s) \qquad .....(1.10)$$

Equation (1.16) can be written as,

$$(R_a + sL_a)\,I_a(s) + E_b(s) = V_a(s) \qquad .....(1.11)$$

Substituting for $E_b(s)$ and $I_a(s)$ from equation (1.9) and (1.10) respectively in equation (1.11),

$$(R_a + sL_a)\,\frac{(Js^2 + Bs)}{K_t}\,\theta(s) + K_b s\theta(s) = V_a(s)$$

$$\left[\frac{(R_a + sL_a)(Js^2 + Bs) + K_b K_t s}{K_t}\right]\theta(s) = V_a(s)$$

The required transfer function is $\frac{\theta(s)}{V_a(s)}$

$$\therefore \frac{\theta(s)}{V_a(s)} = \frac{K_t}{(R_a + sL_a)(Js^2 + Bs) + K_b K_t s} \qquad ....(1.12)$$

$$= \frac{K_t}{R_a Js^2 + R_a Bs + L_a Js^3 + L_a Bs^2 + K_b K_t s}$$

$$= \frac{K_t}{s[\,JL_a s^2 + (JR_a + BL_a)s + (BR_a + K_b K_t)\,]}$$

$$= \frac{K_t/JL_a}{s\left[s^2 + \left(\frac{JR_a + BL_a}{JL_a}\right)s + \left(\frac{BR_a + K_b K_t}{JL_a}\right)\right]} \qquad .....(1.13)$$

The transfer function of armature controlled dc motor can be expressed in another standard form as shown below. From equation (1.12) we get,

$$\frac{\theta(s)}{V_a(s)} = \frac{K_t}{(R_a + sL_a)(Js^2 + Bs) + K_b K_t s} = \frac{K_t}{R_a\left(\frac{sL_a}{R_a} + 1\right)Bs\left(1 + \frac{Js^2}{Bs}\right) + K_b K_t s}$$

$$= \frac{K_t/R_a B}{s\left[(1 + sT_a)(1 + sT_m) + \frac{K_b K_t}{R_a B}\right]} \qquad .....(1.14)$$

where, $\frac{L_a}{R_a} = T_a$ = Electrical time constant

$\frac{J}{B} = T_m$ = Mechanical time constant

1.3.2 TRANSFER FUNCTION OF FIELD CONTROLLED DC MOTOR

The speed of a DC motor is directly proportional to armature voltage and inversely proportional to flux. In field controlled DC motor the armature voltage is kept constant and the speed is varied by varying the flux of the machine. Since flux is directly proportional to field current, the flux is varied by varying field current. The speed control system is an electromechanical control system. The electrical system consists of armature and field circuit but for analysis purpose, only field circuit is considered because the armature is excited by a constant voltage. The mechanical system consists of the rotating part of the motor and the load connected to the shaft of the motor. The field controlled DC motor speed control system is shown in fig 1.14.

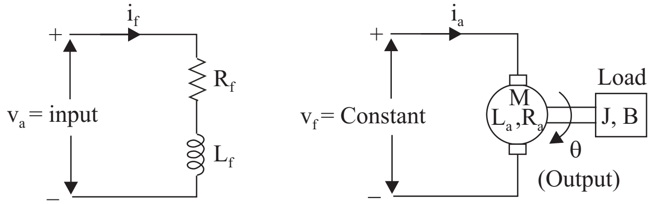


Fig 1.14 : *Field controlled DC motor.*

Let, R_f = Field resistance, Ω
L_f = Field inductance, H
i_f = Field current, A
v_f = Field voltage, V
T = Torque developed by motor, N-m
K_{tf} = Torque constant, N-m/A
J = Moment of inertia of rotor and load, Kg-m²/rad
B = Frictional coefficient of rotor and load, N-m/(rad/sec)

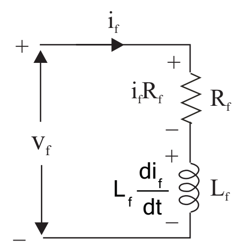


Fig 1.15 : *Equivalent circuit of field.*

The equivalent circuit of field is shown in fig 1.15.

By Kirchoff's voltage law, we can write

$$R_f i_f + L_f \frac{di_f}{dt} = v_f \quad .....(1.15)$$

The torque of DC motor is proportional to product of flux and armature current. Since armature current is constant in this system, the torque is proportional to flux alone, but flux is proportional to field current.

$$T \propto i_f, \quad \therefore \text{Torque, } T = K_{tf}\, i_f \quad .....(1.16)$$

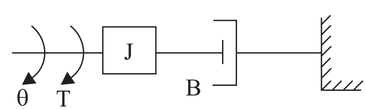


Fig 1.16.

The mechanical system of the motor is shown in fig 1.16. The differential equation governing the mechanical system of the motor is given by,

$$J \frac{d^2\theta}{dt^2} + B \frac{d\theta}{dt} = T \quad .....(1.17)$$

The Laplace transform of various time domain signals involved in this system are shown below.

$\mathcal{L}\{i_f\} = I_f(s)$; $\mathcal{L}\{T\} = T(s)$; $\mathcal{L}\{v_f\} = V_f(s)$; $\mathcal{L}\{\theta\} = \theta(s)$

The differential equations governing the field controlled DC motor are,

$$R_f i_f + L_f \frac{di_f}{dt} = v_f \quad ; \quad T = K_{tf} i_f \quad ; \quad J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} = T$$

On taking Laplace transform of the above equations with zero initial condition we get,

$$R_f I_f(s) + L_f s I_f(s) = V_f(s) \quad .....(1.18)$$

$$T(s) = K_{tf} I_f(s) \quad .....(1.19)$$

$$Js^2\theta(s) + B\, s\theta(s) = T(s) \quad .....(1.20)$$

Equating equations (1.19) and (1.20) we get,

$$K_{tf} I_f(s) = Js^2\theta(s) + B\, s\theta(s)$$

$$I_f(s) = s\,\frac{(Js + B)}{K_{tf}}\,\theta(s) \quad .....(1.21)$$

The equation (1.18) can be written as,

$$(R_f + sL_f)\, I_f(s) = V_f(s) \quad .....(1.22)$$

On substituting for $I_f(s)$ from equation (1.21) in equation (1.22) we get,

$$(R_f + sL_f)\, s\,\frac{(Js + B)}{K_{tf}}\,\theta(s) = V_f(s)$$

$$\frac{\theta(s)}{V_f(s)} = \frac{K_{tf}}{s(R_f + sL_f)(B + sJ)}$$

$$= \frac{K_{tf}}{sR_f\left(1 + \frac{sL_f}{R_f}\right)B\left(1 + \frac{sJ}{B}\right)} = \frac{K_m}{s(1 + sT_f)(1 + sT_m)} \quad .....(1.23)$$

where, $K_m = \frac{K_{tf}}{R_f B}$ = Motor gain constant

$T_f = \frac{L_f}{R_f}$ = Field time constant

$T_m = \frac{J}{B}$ = Mechanical time constant

EXAMPLE 1.1

Obtain the transfer function of the electrical network shown in fig 1.

SOLUTION

In the given network, input is e(t) and output is $v_2(t)$.

Let, Laplace transform of e(t) = $\mathcal{L}\{e(t)\}$ = E(s)

Laplace transform of $v_2(t)$ = $\mathcal{L}\{v_2(t)\}$ = $V_2(s)$

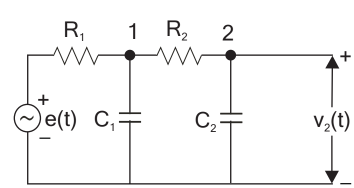
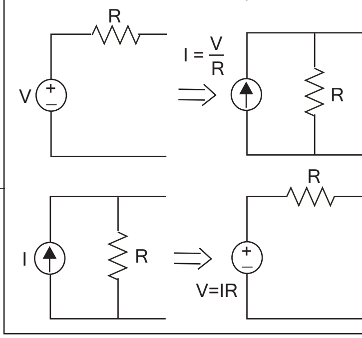


Fig 1.

The transfer function of the network is $\dfrac{V_2(s)}{E(s)}$

Transform the voltage source in series with resistance R_1 into equivalent current source as shown in figure 2. The network has two nodes. Let the node voltages be v_1 and v_2. The Laplace transform of node voltages v_1 and v_2 are $V_1(s)$ and $V_2(s)$ respectively. The differential equations governing the network are given by the Kirchoff's current law equations at these nodes.

Note : *Source transformation*



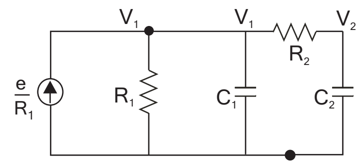


Fig 2.

At node-1, by Kirchoff's current law (refer fig 3)

$$\frac{v_1}{R_1} + C_1\frac{dv_1}{dt} + \frac{v_1 - v_2}{R_2} = \frac{e}{R_1}$$

On taking Laplace transform of above equation with zero initial conditions we get,

$$\frac{V_1(s)}{R_1} + C_1 sV_1(s) + \frac{V_1(s)}{R_2} - \frac{V_2(s)}{R_2} = \frac{E(s)}{R_1}$$

$$V_1(s)\left[\frac{1}{R_1} + sC_1 + \frac{1}{R_2}\right] - \frac{V_2(s)}{R_2} = \frac{E(s)}{R_1} \qquad .....(1)$$

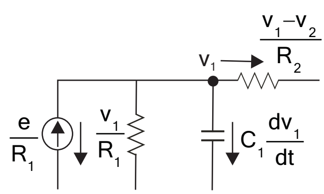


Fig 3.

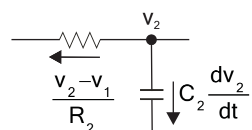


Fig 4.

At node-2, by Kirchoff's current law (refer fig 4)

$$\frac{v_2 - v_1}{R_2} + C_2\frac{dv_2}{dt} = 0$$

On taking Laplace transform of above equation with zero initial conditions we get,

$$\frac{V_2(s)}{R_2} - \frac{V_1(s)}{R_2} + C_2 sV_2(s) = 0$$

$$\frac{V_1(s)}{R_2} = \frac{V_2(s)}{R_2} + C_2 sV_2(s) = \left[\frac{1}{R_2} + sC_2\right]V_2(s)$$

$$\therefore\ V_1(s) = [1 + sC_2R_2]\,V_2(s) \qquad .....(2)$$

Substituting for $V_1(s)$ from equation (2) in equation (1) we get,

$$(1 + sR_2C_2)V_2(s)\left[\frac{1}{R_1} + sC_1 + \frac{1}{R_2}\right] - \frac{V_2(s)}{R_2} = \frac{E(s)}{R_1}$$

$$\left[\frac{(1 + sR_2C_2)(R_2 + R_1 + sC_1R_1R_2) - R_1}{R_1R_2}\right]V_2(s) = \frac{E(s)}{R_1}$$

$$\therefore\ \frac{V_2(s)}{E(s)} = \frac{R_2}{[(1 + sR_2C_2)(R_1 + R_2 + sC_1R_1R_2) - R_1]}$$

RESULT

The (node basis) differential equations governing the electrical network are,

1. $\frac{v_1}{R_1} + C_1 \frac{dv_1}{dt} + \frac{v_1 - v_2}{R_2} = \frac{e}{R_1}$

2. $\frac{v_2 - v_1}{R_2} + C_2 \frac{dv_2}{dt} = 0$

The transfer function of the electrical network is,

$$\frac{V_2(s)}{E(s)} = \frac{R_2}{[(1 + sR_2C_2)(R_1 + R_2 + sC_1R_1R_2) - R_1]}$$

1.4 MECHANICAL TRANSFER FUNCTION MODELS

1.4.1 MECHANICAL TRANSLATIONAL SYSTEMS

The model of mechanical translational systems can be obtained by using three basic elements ***mass, spring and dash-pot.*** These three elements represents three essential phenomena which occur in various ways in mechanical systems.

The weight of the mechanical system is represented by the element ***mass*** and it is assumed to be concentrated at the center of the body. The elastic deformation of the body can be represented by a ***spring.*** The friction existing in rotating mechanical system can be represented by the ***dash-pot.*** The dash-pot is a piston moving inside a cylinder filled with viscous fluid.

When a force is applied to a translational mechanical system, it is opposed by opposing forces due to mass, friction and elasticity of the system. The force acting on a mechanical body are governed by ***Newton's second law of motion.*** For translational systems it states that the sum of forces acting on a body is zero (or Newton's second law states that the sum of applied forces is equal to the sum of opposing forces on a body).

LIST OF SYMBOLS USED IN MECHANICAL TRANSLATIONAL SYSTEM

x = Displacement, m

$v = \frac{dx}{dt}$ = Velocity, m/sec

$a = \frac{dv}{dt} = \frac{d^2x}{dt^2}$ = Acceleration, m/sec^2

f = Applied force, N (Newtons)

f_m = Opposing force offered by mass of the body, N

f_k = Opposing force offered by the elasticity of the body (spring), N

f_b = Opposing force offered by the friction of the body (dash - pot), N

M = Mass, kg

K = Stiffness of spring, N/m

B = Viscous friction co-efficient, N-sec/m

Note : *Lower case letters are functions of time*

FORCE BALANCE EQUATIONS OF IDEALIZED ELEMENTS

Consider an ideal mass element shown in fig 1.17 which has negligible friction and elasticity. Let a force be applied on it. The mass will offer an opposing force which is proportional to acceleration of the body.

Let, f = Applied force

f_m = Opposing force due to mass

Here, $f_m \propto \frac{d^2x}{dt^2}$ or $f_m = M\frac{d^2x}{dt^2}$

By Newton's second law, $\boxed{f = f_m = M\frac{d^2x}{dt^2}}$ .....(1.24)

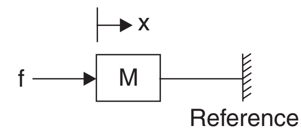


***Fig 1.17 :** Ideal mass element.*

Consider an ideal frictional element dashpot shown in fig 1.18 which has negligible mass and elasticity. Let a force be applied on it. The dash-pot will offer an opposing force which is proportional to velocity of the body.

Let, f = Applied force

f_b = Opposing force due to friction

Here, $f_b \propto \frac{dx}{dt}$ or $f_b = B\frac{dx}{dt}$

By Newton's second law, $\boxed{f = f_b = B\frac{dx}{dt}}$ .....(1.25)

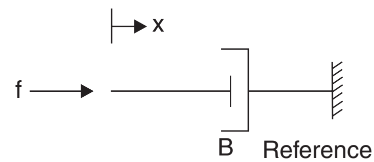


***Fig 1.18 :** Ideal dashpot with one end fixed to reference.*

When the dashpot has displacement at both ends as shown in fig 1.19, the opposing force is proportional to difference between velocity at both ends.

$f_b \propto \frac{d}{dt}(x_1 - x_2)$ or $f_b = B\frac{d}{dt}(x_1 - x_2)$

$\therefore \boxed{f = f_b = B\frac{d}{dt}(x_1 - x_2)}$ .....(1.26)

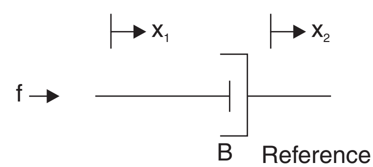


***Fig 1.19 :** Ideal dashpot with displacement at both ends.*

Consider an ideal elastic element spring shown in fig 1.20, which has negligible mass and friction. Let a force be applied on it. The spring will offer an opposing force which is proportional to displacement of the body.

Let, f = Applied force

f_k = Opposing force due to elasticity

Here $f_k \propto x$ or $f_k = K\,x$

By Newton's second law, $\boxed{f = f_k = Kx}$ .....(1.27)

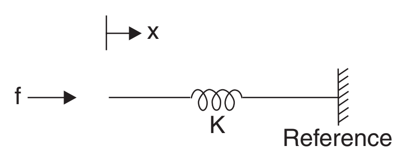


***Fig 1.20 :** Ideal spring with one end fixed to reference.*

When the spring has displacement at both ends as shown in fig 1.21 the opposing force is proportional to difference between displacement at both ends.

$f_k \propto (x_1 - x_2)$ or $f_k = K(x_1 - x_2)$

$\boxed{\therefore\ f = f_k = K(x_1 - x_2)}$ .....(1.28)

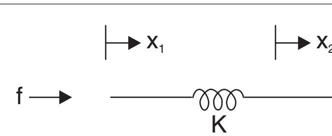


***Fig 1.21 :** Ideal spring with displacement at both ends.*

Guidelines to determine the Transfer Function of Mechanical Translational System

1. In mechanical translational system, the differential equations governing the system are obtained by writing force balance equations at nodes in the system. The nodes are meeting point of elements. Generally the nodes are mass elements in the system. In some cases the nodes may be without mass element.
2. The linear displacement of the masses (nodes) are assumed as x_1, x_2, x_3, etc., and assign a displacement to each mass(node). The first derivative of the displacement is velocity and the second derivative of the displacement is acceleration.
3. Draw the free body diagrams of the system. The free body diagram is obtained by drawing each mass separately and then marking all the forces acting on that mass (node). Always the opposing force acts in a direction opposite to applied force. The mass has to move in the direction of the applied force. Hence the displacement, velocity and acceleration of the mass will be in the direction of the applied force. If there is no applied force then the displacement, velocity and acceleration of the mass will be in a direction opposite to that of opposing force.
4. For each free body diagram, write one differential equation by equating the sum of applied forces to the sum of opposing forces.
5. Take Laplace transform of differential equations to convert them to algebraic equations. Then rearrange the s-domain equations to eliminate the unwanted variables and obtain the ratio between output variable and input variable. This ratio is the transfer function of the system.

Note : *Laplace transform of* $x(t) = \mathcal{L}\{x(t)\} = X(s)$

Laplace transform of $\frac{dx(t)}{dt} = \mathcal{L}\left\{\frac{d}{dt}x(t)\right\} = s\,X(s)$ *(with zero initial conditions)*

Laplace transform of $\frac{d^2x(t)}{dt^2} = \mathcal{L}\left\{\frac{d^2}{dt^2}x(t)\right\} = s^2\,X(s)$ *(with zero initial conditions)*

EXAMPLE 1.2

Write the differential equations governing the mechanical system shown in fig 1. and determine the transfer function.

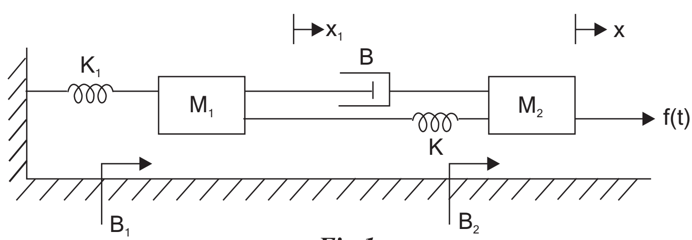


Fig 1.

SOLUTION

In the given system, applied force 'f(t)' is the input and displacement 'x' is the output.

Let, Laplace transform of f(t) $= \mathcal{L}\{f(t)\} = F(s)$

Laplace transform of x $= \mathcal{L}\{x\} = X(s)$

Laplace transform of $x_1 = \mathcal{L}\{x_1\} = X_1(s)$

Hence the required transfer function is $\frac{X(s)}{F(s)}$

The system has two nodes and they are mass M_1 and M_2. The differential equations governing the system are given by force balance equations at these nodes.

Let the displacement of mass M_1 be x_1. The free body diagram of mass M_1 is shown in fig 2. The opposing forces acting on mass M_1 are marked as f_{m1}, f_{b1}, f_b, f_{k1} and f_k.

$$f_{m1}=M_1\frac{d^2x_1}{dt^2} \;;\; f_{b1}=B_1\frac{dx_1}{dt} \;;\; f_{k1}=K_1x_1 \;;$$

$$f_b=B\frac{d}{dt}(x_1-x) \;;\; f_k=K(x_1-x)$$

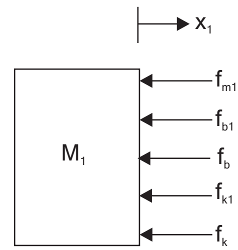


***Fig 2 :** Free body diagram of mass M_1 (node 1).*

By Newton's second law,

$$f_{m1}+f_{b1}+f_b+f_{k1}+f_k=0$$

$$\therefore\; M_1\frac{d^2x_1}{dt^2}+B_1\frac{dx_1}{dt}+B\frac{d}{dt}(x_1-x)+K_1x_1+K(x_1-x)=0$$

On taking Laplace transform of above equation with zero initial conditions we get,

$$M_1s^2X_1(s)+B_1sX_1(s)+Bs[X_1(s)-X(s)]+K_1X_1(s)+K[X_1(s)-X(s)]=0$$

$$X_1(s)\,[M_1s^2+(B_1+B)s+(K_1+K)]-X(s)\,[Bs+K]=0$$

$$X_1(s)\,[M_1s^2+(B_1+B)s+(K_1+K)]=X(s)\,[Bs+K]$$

$$\therefore\; X_1(s)=X(s)\frac{Bs+K}{M_1s^2+(B_1+B)s+(K_1+K)} \qquad \text{......(1)}$$

The free body diagram of mass M_2 is shown in fig 3. The opposing forces acting on M_2 are marked as f_{m2}, f_{b2}, f_b and f_k.

$$f_{m2}=M_2\frac{d^2x}{dt^2} \;;\; f_{b2}=B_2\frac{dx}{dt}$$

$$f_b=B\frac{d}{dt}(x-x_1) \;;\; f_k=K(x-x_1)$$

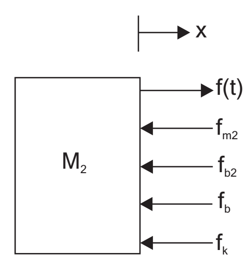


***Fig 3 :** Free body diagram of mass M_2 (node 2).*

By Newton's second law,

$$f_{m2}+f_{b2}+f_b+f_k=f(t)$$

$$M_2\frac{d^2x}{dt^2}+B_2\frac{dx}{dt}+B\frac{d}{dt}(x-x_1)+K(x-x_1)=f(t)$$

On taking Laplace transform of above equation with zero initial conditions we get,

$$M_2s^2X(s)+B_2sX(s)+Bs[X(s)]-X_1(s)]+K[X(s)-X_1(s)]=F(s)$$

$$X(s)[M_2s^2+(B_2+B)s+K]\;-X_1(s)[Bs+K]=F(s) \qquad \text{.....(2)}$$

Substituting for $X_1(s)$ from equation (1) in equation (2) we get,

$$X(s)\,[M_2s^2+(B_2+B)s+K]-X(s)\frac{(Bs+K)^2}{M_1s^2+(B_1+B)s+(K_1+K)}=F(s)$$

$$X(s)\left[\frac{[M_2s^2+(B_2+B)s+K][M_1s^2+(B_1+B)s+(K_1+K)]-(Bs+K)^2}{M_1s^2+(B_1+B)s+(K_1+K)}\right]=F(s)$$

$$\therefore\ \frac{X(s)}{F(s)}=\frac{M_1s^2+(B_1+B)s+(K_1+K)}{[M_1s^2+(B_1+B)s+(K_1+K)][M_2s^2+(B_2+B)s+K]-(Bs+K)^2}$$

RESULT

The differential equations governing the system are,

1. $M_1\frac{d^2x_1}{dt^2}+B_1\frac{dx_1}{dt}+B\frac{d}{dt}(x_1-x)+K_1x_1+K(x_1-x)=0$

2. $M_2\frac{d^2x}{dt^2}+B_2\frac{dx}{dt}+B\frac{d}{dt}(x-x_1)+K(x-x_1)=f(t)$

The transfer function of the system is,

$$\frac{X(s)}{F(s)}=\frac{M_1s^2+(B_1+B)s+(K_1+K)}{[M_1s^2+(B_1+B)s+(K_1+K)][M_2s^2+(B_2+B)s+K]-(Bs+K)^2}$$

EXAMPLE 1.3

Determine the transfer function $\frac{Y_2(s)}{F(s)}$ of the system shown in fig 1.

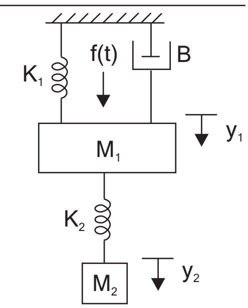


Fig 1.

SOLUTION

Let, Laplace transform of $f(t) = \mathcal{L}\{f(t)\} = F(s)$

Laplace transform of $y_1 = \mathcal{L}\{y_1\} = Y_1(s)$

Laplace transform of $y_2 = \mathcal{L}\{y_2\} = Y_2(s)$

The system has two nodes and they are mass M_1 and M_2. The differential equations governing the system are the force balance equations at these nodes.

The free body diagram of mass M_1 is shown in fig 2.

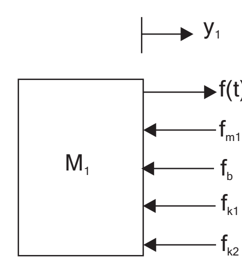


Fig 2.

The opposing forces are marked as f_{m1}, f_b, f_{k1} and f_{k2}

$$f_{m1}=M_1\frac{d^2y_1}{dt^2}\ ;\ f_b=B\frac{dy_1}{dt}\ ;\ f_{k1}=K_1y_1\ ;\ f_{k2}=K_2(y_1-y_2)$$

By Newton's second law, $f_{m1}+f_b+f_{k1}+f_{k2}=f(t)$

$$\therefore\ M_1\frac{d^2y_1}{dt^2}+B\frac{dy_1}{dt}+K_1y_1+K_2(y_1-y_2)=f(t)\ .....(1)$$

On taking Laplace transform of equation (1) with zero initial condition we get,

$$M_1s^2Y_1(s)+BsY_1(s)+K_1Y_1(s)+K_2[Y_1(s)-Y_2(s)]=F(s)$$

$$Y_1(s)[M_1s^2+Bs+(K_1+K_2)]-Y_2(s)K_2=F(s) \quad .....(2)$$

The free body diagram of mass M_2 is shown in fig 3. The opposing forces acting on M_2 are f_{m2} and f_{k2}.

$$f_{m2}=M_2\frac{d^2y_2}{dt^2}\ ;\ f_{k2}=K_2(y_2-y_1)$$

By Newton's second law, $f_{m2}+f_{k2}=0$

$$\therefore\ M_2\frac{d^2y_2}{dt^2}+K_2(y_2-y_1)=0$$

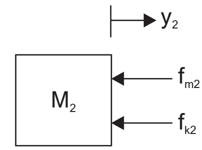


Fig 3.

On taking Laplace transform of above equation we get,

$$M_2s^2Y_2(s)+K_2[Y_2(s)-Y_1(s)]=0$$

$$Y_2(s)\,[M_2s^2+K_2]-Y_1(s)\,K_2=0$$

$$\therefore\ Y_1(s)=Y_2(s)\,\frac{M_2s^2+K_2}{K_2} \quad .....(3)$$

Substituting for $Y_1(s)$ from equation (3) in equation (2) we get,

$$Y_2(s)\left[\frac{M_2s^2+K_2}{K_2}\right][M_1s^2+Bs+(K_1+K_2)]-Y_2(s)\,K_2=F(s)$$

$$Y_2(s)\left[\frac{(M_2s^2+K_2)\,[M_1s^2+Bs+(K_1+K_2)]-K_2^2}{K_2}\right]=F(s)$$

$$\therefore\ \frac{Y_2(s)}{F(s)}=\frac{K_2}{[M_1s^2+Bs+(K_1+K_2)]\,[M_2s^2+K_2]-K_2^2}$$

RESULT

The differential equations governing the system are,

1. $M_1\dfrac{d^2y_1}{dt^2}+B\,\dfrac{dy_1}{dt}+K_1y_1+K_2(y_1-y_2)=f(t)$

2. $M_2\dfrac{d^2y_2}{dt^2}+K_2(y_2-y_1)=0$

The transfer function of the system is,

$$\frac{Y_2(s)}{F(s)}=\frac{K_2}{[M_1s^2+Bs+(K_1+K_2)]\,[M_2s^2+K_2]-K_2^2}$$

EXAMPLE 1.4

Determine the transfer function, $\dfrac{X_1(s)}{F(s)}$ and $\dfrac{X_2(s)}{F(s)}$ for the system shown in fig 1.

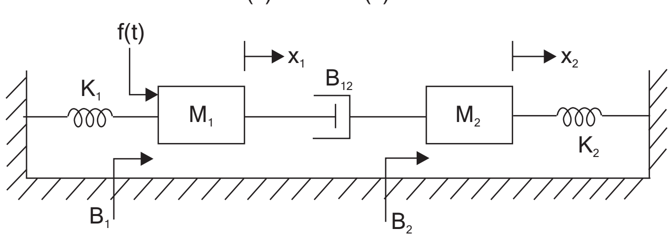


Fig 1.

SOLUTION

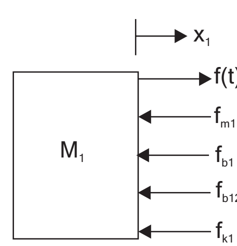


Fig 2.

Let, Laplace transform of f(t) = $\mathcal{L}\{f(t)\}$ = F(s)

Laplace transform of x_1 = $\mathcal{L}\{x_1\}$ = $X_1(s)$

Laplace transform of x_2 = $\mathcal{L}\{x_2\}$ = $X_2(s)$

The system has two nodes and they are mass M_1 and M_2. The differential equations governing the system are the force balance equations at these nodes. The free body diagram of mass M_1 is shown in fig 2. The opposing forces are marked as f_{m1}, f_{b1}, f_{b12} and f_{k1}.

$$f_{m1} = M_1 \frac{d^2x_1}{dt^2} \quad ; \quad f_{b1} = B_1 \frac{dx_1}{dt} \quad ; \quad f_{b12} = B_{12} \frac{d}{dt}(x_1 - x_2) \quad ; \quad f_{k1} = K_1 x_1$$

By Newton's second law, $f_{m1} + f_{b1} + f_{b12} + f_{k1} = f(t)$

$$M_1 \frac{d^2x_1}{dt^2} + B_1 \frac{dx_1}{dt} + B_{12} \frac{d(x_1 - x_2)}{dt} + K_1 x_1 = f(t)$$

On taking Laplace transform of above equation with zero initial conditions we get,

$$M_1 s^2 X_1(s) + B_1 s X_1(s) + B_{12} s[X_1(s) - X_2(s)] + K_1 X_1(s) = F(s)$$

$$X_1(s)[M_1 s^2 + (B_1 + B_{12})s + K_1] - B_{12} s X_2(s) = F(s) \qquad .....(1)$$

The free body diagram of mass M_2 is shown in fig 3. The opposing forces are marked as f_{m2}, f_{b2}, f_{b12} and f_{k2}.

$$f_{m2} = M_2 \frac{d^2x_2}{dt^2} \quad ; \quad f_{b2} = B_2 \frac{dx_2}{dt}$$

$$f_{b12} = B_{12} \frac{d}{dt}(x_2 - x_1) \quad ; \quad f_{k2} = K_2 x_2$$

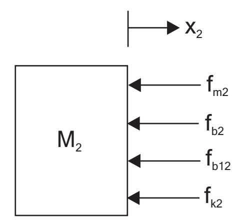


Fig 3.

By Newton's second law, $f_{m2} + f_{b2} + f_{b12} + f_{k2} = 0$

$$M_2 \frac{d^2x_2}{dt^2} + B_2 \frac{dx_2}{dt} + B_{12} \frac{d(x_2 - x_1)}{dt} + K_2 x_2 = f(t) \qquad .....(2)$$

On taking Laplace transform of equation (2) with zero initial conditions we get,

$$M_2 s^2 X_2(s) + B_2 s X_2(s) + B_{12} s[X_2(s) - X_1(s)] + K_2 X_2(s) = 0$$

$$X_2(s)[M_2 s^2 + (B_2 + B_{12})s + K_2] - B_{12} s X_1(s) = 0$$

$$X_2(s)[M_2 s^2 + (B_2 + B_{12})s + K_2] = B_{12} s X_1(s)$$

$$X_2(s) = \frac{B_{12} s X_1(s)}{[M_2 s^2 + (B_2 + B_{12})s + K_2]} \qquad .....(3)$$

Substituting for $X_2(s)$ from equation (3) in equation (1) we get,

$$X_1(s)\,[M_1 s^2 + (B_1 + B_{12})s + K_1] - \frac{(B_{12}s)^2 X_1(s)}{M_2 s^2 + (B_2 + B_{12})s + K_2} = F(s)$$

$$\frac{X_1(s)\left[[M_1 s^2 + (B_1 + B_{12})s + K_1][M_2 s^2 + (B_2 + B_{12})s + K_2] - (B_{12}s)^2 \right]}{M_2 s^2 + (B_2 + B_{12})s + K_2} = F(s)$$

$$\therefore \frac{X_1(s)}{F(s)} = \frac{M_2 s^2 + (B_2 + B_{12})s + K_2}{[M_1 s^2 + (B_1 + B_{12})s + K_1][M_2 s^2 + (B_2 + B_{12})s + K_2] - (B_{12}s)^2}$$

From equation (3) we get,

$$X_1(s) = \frac{[M_2 s^2 + (B_2 + B_{12})s + K_2] X_2(s)}{B_{12} s} \qquad .....(4)$$

Substituting for $X_1(s)$ from equation (4) in equation (1) we get,

$$\frac{X_2(s)\,[M_2 s^2 + (B_2 + B_{12})s + K_2]}{B_{12} s}[M_1 s^2 + (B_1 + B_{12})s + K_1] - B_{12} s X_2(s) = F(s)$$

$$X_2(s)\left[\frac{[M_2s^2+(B_2+B_{12})s+K_2]\,[M_1s^2+(B_1+B_{12})s+K_1]-(B_{12}s)^2}{B_{12}s}\right] = F(s)$$

$$\therefore\ \frac{X_2(s)}{F(s)} = \frac{B_{12}s}{[M_2s^2+(B_2+B_{12})s+K_2]\,[M_1s^2+(B_1+B_{12})s+K_1]-(B_{12}s)^2}$$

RESULT

The differential equations governing the system are,

1. $M_1\frac{d^2x_1}{dt^2}+B_1\frac{dx_1}{dt}+B_{12}\frac{d(x_1-x_2)}{dt}+K_1x_1 = f(t)$

2. $M_2\frac{d^2x_2}{dt^2}+B_2\frac{dx_2}{dt}+B_{12}\frac{d(x_2-x_1)}{dt}+K_2x_2 = 0$

The transfer functions of the system are,

1. $\frac{X_1(s)}{F(s)} = \frac{M_2s^2+(B_2+B_{12})s+K_2}{[M_1s^2+(B_1+B_{12})s+K_1][M_2s^2+(B_2+B_{12})s+K_2]-(B_{12}s)^2}$

2. $\frac{X_2(s)}{F(s)} = \frac{B_{12}s}{[M_2s^2+(B_2+B_{12})s+K_2][M_1s^2+(B_1+B_{12})s+K_1]-(B_{12}s)^2}$

EXAMPLE 1.5

Write the equations of motion in s-domain for the system shown in fig 1. Determine the transfer function of the system.

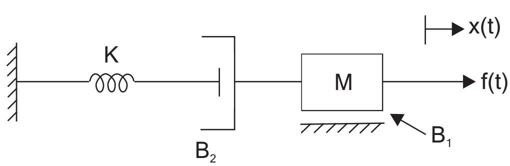


Fig 1.

SOLUTION

Let, Laplace transform of $x(t) = \mathcal{L}\{x(t)\} = X(s)$

Laplace transform of $f(t) = \mathcal{L}\{f(t)\} = F(s)$

Let x_1 be the displacement at the meeting point of spring and dashpot. Laplace transform of x_1 is $X_1(s)$.

The system has two nodes and they are mass M and the meeting point of spring and dashpot. The differential equations governing the system are the force balance equations at these nodes. The equations of motion in the s-domain are obtained by taking Laplace transform of the differential equations.

The free body diagram of mass M is shown in fig 2. The opposing forces are marked as f_m, f_{b1} and f_{b2}.

$$f_m = M\frac{d^2x}{dt^2}\quad ;\quad f_{b1} = B_1\frac{dx}{dt}\quad ;\quad f_{b2} = B_2\frac{d}{dt}(x-x_1)$$

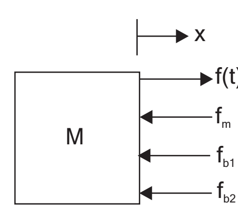


Fig 2.

By Newton's second law the force balance equation is,

$$f_m + f_{b1} + f_{b2} = f(t)$$

$$\therefore\ M\frac{d^2x}{dt^2}+B_1\frac{dx}{dt}+B_2\frac{d}{dt}(x-x_1) = f(t)$$

On taking Laplace transform of the above equation we get,

$$Ms^2X(s) + B_1(s)X(s) + B_2\,s[X(s) - X_1(s)] = F(s)$$

$$[Ms^2 + (B_1 + B_2)s]\,X(s) - B_2\,sX_1(s) = F(s) \qquad .....(1)$$

The free body diagram at the meeting point of spring and dashpot is shown in fig 3. The opposing forces are marked as f_k and f_{b2}.

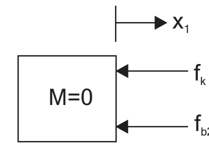


Fig 3.

$$f_{b2} = B_2 \frac{d}{dt}(x_1 - x) \quad ; \quad f_k = Kx_1$$

By Newton's second law, $f_{b2} + f_k = 0$

$$\therefore\ B_2 \frac{d}{dt}(x_1 - x) + Kx_1 = 0$$

On taking Laplace transform of the above equation we get,

$$B_2 s[X_1(s) - X(s)] + K\,X_1(s) = 0$$

$$(B_2 s + K)\,X_1(s) - B_2\,sX(s) = 0$$

$$\therefore\ X_1(s) = \frac{B_2 s}{B_2 s + K} X(s) \qquad .....(2)$$

Substituting for $X_1(s)$ from equation (2) in equation (1) we get,

$$[Ms^2 + (B_1 + B_2)s]\,X(s) - B_2 s\left[\frac{B_2 s}{B_2 s + K}\right] X(s) = F(s)$$

$$X(s)\,\frac{[Ms^2 + (B_1 + B_2)s](B_2 s + K) - (B_2 s)^2]}{B_2 s + K} = F(s)$$

$$\therefore\ \frac{X(s)}{F(s)} = \frac{B_2 s + K}{[Ms^2 + (B_1 + B_2)s](B_2 s + K) - (B_2 s)^2}$$

RESULT

The differential equations governing the system are,

1. $M\frac{d^2x}{dt^2} + B_1\frac{dx}{dt} + B_2\frac{d}{dt}(x - x_1) = f(t)$
2. $B_2\frac{d}{dt}(x_1 - x) + K\,x_1 = 0$

The equations of motion in s-domain are,

1. $[M\,s^2 + (B_1 + B_2)s]\,X(s) - B_2\,sX_1(s) = F(s)$
2. $(B_2 s + K)\,X_1(s) - B_2\,sX(s) = 0$

The transfer function of the system is,

$$\frac{X(s)}{F(s)} = \frac{B_2 s + K}{[M\,s^2 + (B_1 + B_2)s]\,(B_2 s + K) - (B_2 s)^2}$$

1.4.2 MECHANICAL ROTATIONAL SYSTEMS

The model of rotational mechanical systems can be obtained by using three elements, ***moment of inertia*** [J] of mass, ***dash-pot*** with rotational frictional coefficient [B] and ***torsional spring*** with stiffness [K].

The weight of the rotational mechanical system is represented by the moment of inertia of the mass. The moment of inertia of the system or body is considered to be concentrated at the centre of gravity of the body. The elastic deformation of the body can be represented by a spring (torsional spring). The friction existing in rotational mechanical system can be represented by the dash-pot. The dash-pot is a piston rotating inside a cylinder filled with viscous fluid.

When a torque is applied to a rotational mechanical system, it is opposed by opposing torques due to moment of inertia, friction and elasticity of the system. The torques acting on a rotational mechanical body are governed by ***Newton's second law of motion*** for rotational systems. It states that the sum of torques acting on a body is zero (or Newton's law states that the sum of applied torques is equal to the sum of opposing torques on a body).

LIST OF SYMBOLS USED IN MECHANICAL ROTATIONAL SYSTEM

θ = Angular displacement, rad

$\frac{d\theta}{dt}$ = Angular velocity, rad/sec

$\frac{d^2\theta}{dt}$ = Angular acceleration, rad/sec^2

T = Applied torque, N-m

J = Moment of inertia, Kg-m^2/rad

B = Rotational frictional coefficient, N-m/(rad/sec)

K = Stiffness of the spring, N-m/rad

TORQUE BALANCE EQUATIONS OF IDEALISED ELEMENTS

Consider an ideal mass element shown in fig 1.22 which has negligible friction and elasticity. The opposing torque due to moment of inertia is proportional to the angular acceleration.

Let, T = Applied torque.

T_j = Opposing torque due to moment of inertia of the body.

Here $T_j \propto \frac{d^2\theta}{dt^2}$ or $T_j = J\frac{d^2\theta}{dt^2}$

By Newton's second law,

$$\boxed{T = T_j = J\frac{d^2\theta}{dt^2}} \quad .....(1.29)$$

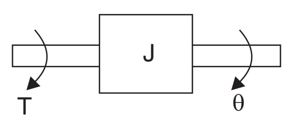


Fig 1.22 : *Ideal rotational mass element.*

Consider an ideal frictional element dash pot shown in fig 1.23 which has negligible moment of inertia and elasticity. Let a torque be applied on it. The dash pot will offer an opposing torque which is proportional to the angular velocity of the body.

Let, T = Applied torque.

T_b = Opposing torque due to friction.

$T_b \propto \frac{d\theta}{dt^2}$ or $T_b = B\frac{d\theta}{dt}$

By Newton's second law, $$\boxed{T = T_b = B\frac{d\theta}{dt}} \quad .....(1.30)$$

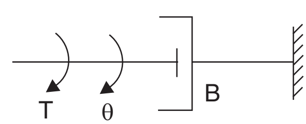


Fig 1.23 : *Ideal rotational dash-pot with one end fixed to reference.*

When the dash pot has angular displacement at both ends as shown in fig 1.24, the opposing torque is proportional to the difference between angular velocity at both ends.

$T_b \propto \frac{d}{dt}(\theta_1 - \theta_2)$ or $T_b = B\frac{d}{dt}(\theta_1 - \theta_2)$

$$\boxed{\therefore\ T = T_b = B\frac{d}{dt}(\theta_1 - \theta_2)} \quad .....(1.31)$$

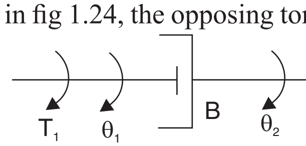


Fig 1.24 : *Ideal dash-pot with angular displacement at both ends.*

Consider an ideal elastic element, torsional spring as shown in fig 1.25, which has negligible moment of inertia and friction. Let a torque be applied on it. The torsional spring will offer an opposing torque which is proportional to angular displacement of the body.

Let, T = Applied torque.

T_k = Opposing torque due to elasticity.

$T_k \propto \theta$ or $T_k = K\theta$

By Newton's second law, $\boxed{T = T_k = K\theta}$ .....(1.32)

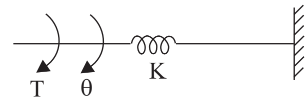


Fig 1.25 : Ideal spring with one end fixed to reference.

When the spring has angular displacement at both ends as shown in fig 1.26 the opposing torque is proportional to difference between angular displacement at both ends.

$T_k \propto (\theta_1 - \theta_2)$ or $T_k = K(\theta_1 - \theta_2)$

$\boxed{\therefore T = T_k = K(\theta_1 - \theta_2)}$ .....(1.33)

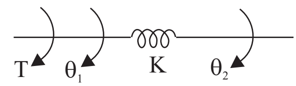


Fig 1.26 : Ideal spring with angular displacement at both ends.

Guidelines to determine the Transfer Function of Mechanical Rotational System

1. In mechanical rotational system, the differential equations governing the system are obtained by writing torque balance equations at nodes in the system. The nodes are meeting point of elements. Generally the nodes are mass elements with moment of inertia in the system. In some cases the nodes may be without mass element.
2. The angular displacement of the moment of inertia of the masses (nodes) are assumed as θ_1, θ_2, θ_3, etc., and assign a displacement to each mass (node). The first derivative of angular displacement is angular velocity and the second derivative of the angular displacement is angular acceleration.
3. Draw the free body diagrams of the system. The free body diagram is obtained by drawing each moment of inertia of mass separately and then marking all the torques acting on that body. Always the opposing torques acts in a direction opposite to applied torque.
4. The mass has to rotate in the direction of the applied torque. Hence the angular displacement, velocity and acceleration of the mass will be in the direction of the applied torque. If there is no applied torque then the angular displacement, velocity and acceleration of the mass is in a direction opposite to that of opposing torque.
5. For each free body diagram write one differential equation by equating the sum of applied torques to the sum of opposing torques.
6. Take Laplace transform of differential equation to convert them to algebraic equations. Then rearrange the s-domain equations to eliminate the unwanted variables and obtain the relation between output variable and input variable. This ratio is the transfer function of the system.

Note :

Laplace transform of $\theta = \mathcal{L}\{\theta\} = \theta(s)$

Laplace transform of $\dfrac{d\theta}{dt} = \mathcal{L}\left\{\dfrac{d\theta}{dt}\right\} = s\,\theta(s)$ *(with zero initial conditions)*

Laplace transform of $\dfrac{d^2\theta}{dt^2} = \mathcal{L}\left\{\dfrac{d^2\theta}{dt^2}\right\} = s^2\,\theta(s)$ *(with zero initial conditions)*

EXAMPLE 1.6

Write the differential equations governing the mechanical rotational system shown in fig 1. Obtain the transfer function of the system.

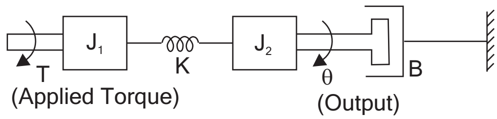


Fig 1.

SOLUTION

In the given system, applied torque T is the input and angular displacement θ is the output.

Let, Laplace transform of $T = \mathcal{L}\{T\} = T(s)$

Laplace transform of $\theta = \mathcal{L}\{\theta\} = \theta(s)$

Laplace transform of $\theta_1 = \mathcal{L}\{\theta_1\} = \theta_1(s)$

Hence the required transfer function is $\dfrac{\theta(s)}{T(s)}$

The system has two nodes and they are masses with moment of inertia J_1 and J_2. The differential equations governing the system are given by torque balance equations at these nodes.

Let the angular displacement of mass with moment of inertia J_1 be θ_1. The free body diagram of J_1 is shown in fig 2. The opposing torques acting on J_1 are marked as T_{j1} and T_k.

$$T_{j1} = J_1 \frac{d^2\theta_1}{dt^2} \quad ; \quad T_k = K(\theta_1 - \theta)$$

By Newton's second law, $T_{j1} + T_k = T$

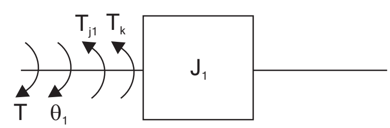


***Fig 2 :** Free body diagram of mass with moment of inertia J_1.*

$$J_1 \frac{d^2\theta_1}{dt^2} + K(\theta_1 - \theta) = T$$

$$J_1 \frac{d^2\theta_1}{dt^2} + K\theta_1 - K\theta = T \qquad .....(1)$$

On taking Laplace transform of equation (1) with zero initial conditions we get,

$$J_1 s^2\theta_1(s) + K\theta_1(s) - K\theta(s) = T(s)$$

$$(J_1 s^2 + K)\theta_1(s) - K\theta(s) = T(s) \qquad .....(2)$$

The free body diagram of mass with moment of inertia J_2 is shown in fig 3. The opposing torques acting on J_2 are marked as T_{j2}, T_b and T_k.

$$T_{j2} = J_2 \frac{d^2\theta}{dt^2} \quad ; \quad T_b = B\frac{d\theta}{dt} \quad ; \quad T_k = K(\theta - \theta_1)$$

By Newton's second law, $T_{j2} + T_b + T_k = 0$

$$\therefore \; J_2 \frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} + K(\theta - \theta_1) = 0$$

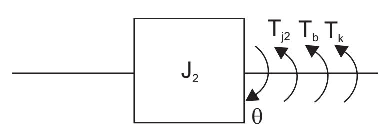


***Fig 3 :** Free body diagram of mass with moment of inertia J_2.*

$$J_2 \frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} + K\theta - K\theta_1 = 0$$

On taking Laplace transform of above equation with zero initial conditions we get,

$$J_2 s^2\theta(s) + B\,s\,\theta(s) + K\,\theta(s) - K\theta_1(s) = 0$$

$$(J_2 s^2 + Bs + K)\,\theta(s) - K\theta_1(s) = 0$$

$$\theta_1(s) = \frac{(J_2 s^2 + Bs + K)}{K}\,\theta(s) \qquad .....(3)$$

Substituting for $\theta_1(s)$ from equation (3) in equation (2) we get,

$$(J_1s^2+K)\frac{(J_2s^2+Bs+K)}{K}\theta(s)-K\theta(s)=T(s)$$

$$\left[\frac{(J_1s^2+K)(J_2s^2+Bs+K-K^2)}{K}\right]\theta(s)=T(s)$$

$$\therefore\ \frac{\theta(s)}{T(s)}=\frac{K}{(J_1s^2+K)(J_2s^2+Bs+K)-K^2}$$

RESULT

The differential equations governing the system are,

1. $J_1\frac{d^2\theta_1}{dt^2}+K\theta_1-K\theta=T$
2. $J_2\frac{d^2\theta}{dt^2}+B\frac{d\theta}{dt}+K\theta-K\theta_1=0$

The transfer function of the system is,

$$\frac{\theta(s)}{T(s)}=\frac{K}{(J_1s^2+K)(J_2s^2+Bs+K)-K^2}$$

EXAMPLE 1.7

Write the differential equations governing the mechanical rotational system shown in fig 1. and determine the transfer function $\theta(s)/T(s)$.

SOLUTION

In the given system, the torque T is the input and the angular displacement θ is the output.

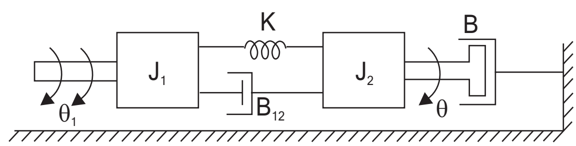


Fig 1.

Let, Laplace transform of $T=\mathcal{L}\{T\}=T(s)$

Laplace transform of $\theta=\mathcal{L}\{\theta\}=\theta(s)$

Laplace transform of $\theta_1=\mathcal{L}\{\theta_1\}=\theta_1(s)$

Hence the required transfer function is $\frac{\theta(s)}{T(s)}$

The system has two nodes and they are masses with moment of inertia J_1 and J_2. The differential equations governing the system are given by torque balance equations at these nodes.

Let the angular displacement of mass with moment of inertia J_1 be θ_1. The free body diagram of J_1 is shown in fig 2. The opposing torques acting on J_1 are marked as T_{j1}, T_{b12} and T_k.

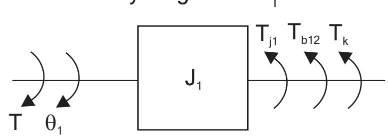


Fig 2 : *Free body diagram of mass with moment of inertia J_1.*

$$T_{j1}=J_1\frac{d^2\theta_1}{dt^2}\quad;\quad T_{b12}=B_{12}\frac{d}{dt}(\theta_1-\theta)\quad;\quad T_k=K(\theta_1-\theta)$$

By Newton's second law, $T_{j1}+T_{b12}+T_k=T$

$$J_1\frac{d^2\theta_1}{dt^2}+B_{12}\frac{d}{dt}(\theta_1-\theta)+K(\theta_1-\theta)=T$$

On taking Laplace transform of above equation with zero initial conditions we get,

$$J_1s^2\theta_1(s)+s\,B_{12}[\theta_1(s)-\theta(s)]+K\theta_1(s)-K\theta(s)=T(s)$$

$$\theta_1(s)\,[J_1s^2+s\,B_{12}+K]-\theta(s)\,[s\,B_{12}+K]=T(s) \qquad .....(1)$$

The free body diagram of mass with moment of inertia J_2 is shown in fig 3. The opposing torques are marked as T_{j2}, T_{b12}, T_b and T_k.

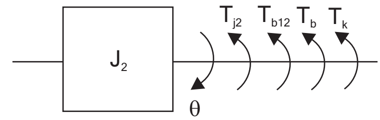


Fig 3 : *Free body diagram of mass with moment of inertia J_2.*

$$T_{j2} = J_2 \frac{d^2\theta}{dt^2} \quad ; \quad T_{b12} = B_{12} \frac{d}{dt}(\theta - \theta_1)$$

$$T_b = B \frac{d\theta}{dt} \quad ; \quad T_k = K(\theta - \theta_1)$$

By Newton's second law, $T_{j2} + T_{b12} + T_b + T_k = 0$

$$J_2 \frac{d^2\theta}{dt^2} + B_{12} \frac{d}{dt}(\theta - \theta_1) + B\frac{d\theta}{dt} + K(\theta - \theta_1) = 0$$

$$J_2 \frac{d^2\theta}{dt^2} - B_{12}\frac{d\theta_1}{dt} + \frac{d\theta}{dt}(B_{12} + B) + K\theta - K\theta_1 = 0$$

On taking Laplace transform of above equation with zero initial conditions we get,

$$J_1 s^2\theta(s) - B_{12}\, s\theta_1(s) + s\theta(s)\,[B_{12} + B] + K\theta(s) - K\theta_1(s) = 0$$

$$\theta(s)\,[s^2J_2 + s(B_{12} + B) + K] - \theta_1(s)\,[sB_{12} + K] = 0$$

$$\theta_1(s) = \frac{[\,s^2J_2 + s(B_{12} + B) + K\,]}{[sB_{12} + K]}\,\theta(s) \qquad .....(2)$$

Substituting for $\theta_1(s)$ from equation (2) in equation (1) we get,

$$[\,J_1s^2 + sB_{12} + K\,]\,\frac{[J_2s^2 + s(B_{12} + B) + K]\,\theta(s)}{(sB_{12} + K)} - (sB_{12} + K)\,\theta(s) = T(s)$$

$$\left[\frac{(J_1s^2 + sB_{12} + K)\,[J_2s^2 + s(B_{12} + B) + K] - (sB_{12} + K)^2}{(sB_{12} + K)}\right]\theta(s) = T(s)$$

$$\therefore \quad \frac{\theta(s)}{T(s)} = \frac{(sB_{12} + K)}{(J_1s^2 + sB_{12} + K)\,[J_2s^2 + s(B_{12} + B) + K] - (sB_{12} + K)^2}$$

RESULT

The differential equations governing the system are,

1. $J_1\frac{d^2\theta_1}{dt^2} + B_{12}\frac{d}{dt}(\theta_1 - \theta) + K(\theta_1 - \theta) = T$

2. $J_2\frac{d^2\theta_1}{dt^2} - B_{12}\frac{d\theta_1}{dt} + \frac{d\theta}{dt}(B_{12} + B) + K(\theta - \theta_1) = 0$

The transfer function of the system is,

$$\frac{\theta(s)}{T(s)} = \frac{(sB_{12} + K)}{(J_1s^2 + sB_{12} + K)\,[J_2s^2 + s(B_{12} + B) + K] - (sB_{12} + K)^2}$$

1.5 ELECTRICAL ANALOGOUS OF MECHANICAL TRANSLATIONAL SYSTEMS

Systems remain ***analogous*** as long as the differential equations governing the systems or transfer functions are in identical form. The electric analogue of any other kind of system is of greater importance since it is easier to construct electrical models and analyse them.

The three basic elements mass, dash-pot and spring that are used in modelling mechanical translational systems are analogous to resistance, inductance and capacitance of electrical systems.

The input force in mechanical system is analogous to either voltage source or current source in electrical systems. The output velocity (first derivative of displacement) in mechanical system is analogous to either current or voltage in an element in electrical system.

Since the electrical systems has two types of inputs either voltage or current source, there are two types of analogies : ***force-voltage analogy*** and ***force-current analogy***.

FORCE-VOLTAGE ANALOGY

The force balance equations of mechanical elements and their analogous electrical elements in force-voltage analogy are shown in table-1.2. The table-1.3 shows the list of analogous quantities in force-voltage analogy.

The following points serve as guidelines to obtain electrical analogous of mechanical systems based on force-voltage analogy.

1. In electrical systems the elements in series will have same current, likewise in mechanical systems, the elements having same velocity are said to be in series.
2. The elements having same velocity in mechanical system should have the same analogous current in electrical analogous system.
3. Each node (meeting point of elements) in the mechanical system corresponds to a closed loop in electrical system. A mass is considered as a node.
4. The number of meshes in electrical analogous is same as that of the number of nodes (masses) in mechanical system. Hence the number of mesh currents and system equations will be same as that of the number of velocities of nodes (masses) in mechanical system.

Table- 1.2 : Analogous Elements in Force-Voltage Analogy

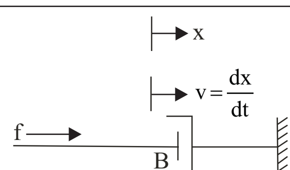
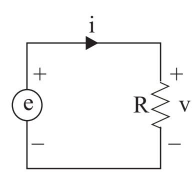
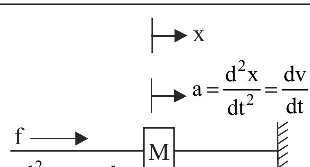
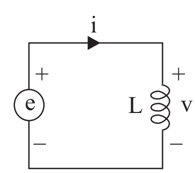
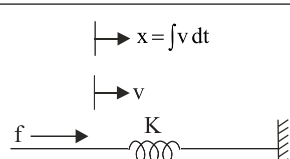
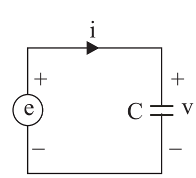
Mechanical system	Electrical system
Input : Force Output : Velocity	Input : Voltage source Output : Current through the element
 $f = B\frac{dx}{dt} = Bv$	 e = v and v=Ri $\therefore$ e = Ri
 $f = M\frac{d^2x}{dt^2} = M\frac{dv}{dt}$	 $e = v$ and $v = L\frac{di}{dt}$ $\therefore e = L\frac{di}{dt}$
 $f = Kx = K\int v\,dt$	 $e = v$ and $v = \frac{1}{C}\int i\,dt$ $\therefore e = \frac{1}{C}\int i\,dt$

Table -1.3 : Analogous Quantities in Force-Voltage Analogy

Item	Mechanical system	Electrical system (mesh basis system)
Independent variable (input)	Force, f	Voltage, e, v
Dependent variable	Velocity, v	Current, i
(output)	Displacement, x	Charge, q
Dissipative element	Frictional coefficient of dashpot, B	Resistance, R
Storage element	Mass, M	Inductance, L
	Stiffness of spring, K	Inverse of capacitance, 1/C
Physical law	Newton's second law $\sum f = 0$	Kirchoff's voltage law $\sum v = 0$
Changing the level of independent variable	Lever $\frac{f_1}{f_2} = \frac{l_1}{l_2}$	Transformer $\frac{e_1}{e_2} = \frac{N_1}{N_2}$

Table-1.4 : Analogous Elements in Force-Current Analogy

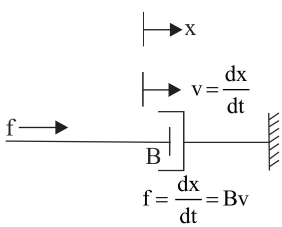
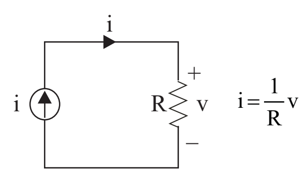
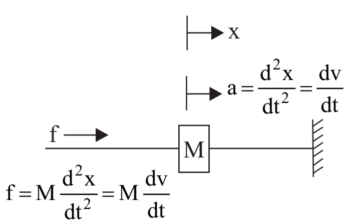
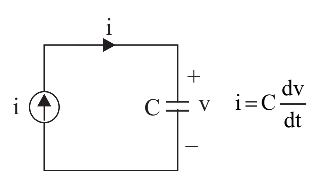
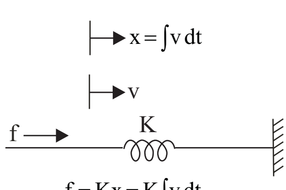
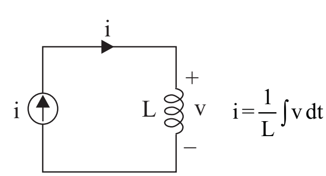
Mechanical system	Electrical system
Input : Force Output : Velocity	Input : Current source Output : Voltage across the element
	
	
	

Table-1.5 : Analogous Quantities in Force-Current Analogy

Item	Mechanical system	Electrical system (node basis system)
Independent variable (input)	Force, f	Current, i
Dependent variable (output)	Velocity, v	Voltage, v
	Displacement, x	Flux, ϕ
Dissipative element	Frictional coefficient of dashpot, B	Conductance G=1/R
Storage element	Mass, M	Capacitance, C
	Stiffness of spring, K	Inverse of inductance, 1/L
Physical law	Newton's second law $\sum f = 0$	Kirchoff's current law $\sum i = 0$
Changing the level of independent variable	Lever $\frac{f_1}{f_2} = \frac{l_1}{l_2}$	Transformer $\frac{i_1}{i_2} = \frac{N_2}{N_1}$

5. The mechanical driving sources (force) and passive elements connected to the node (mass) in mechanical system should be represented by analogous elements in a closed loop in analogous electrical system.
6. The element connected between two (nodes) masses in mechanical system is represented as a common element between two meshes in electrical analogous system.

FORCE-CURRENT ANALOGY

The force balance equations of mechanical elements and their analogous electrical elements in force-current analogy are shown in table-1.4. The table-1.5 shows the list of analogous quantities in force-current analogy.

The following points serve as guidelines to obtain electrical analogous of mechanical systems based on force-current analogy.

1. In electrical systems elements in parallel will have same voltage, likewise in mechanical systems, the elements having same force are said to be in parallel.
2. The elements having same velocity in mechanical system should have the same analogous voltage in electrical analogous system.
3. Each node (meeting point of elements) in the mechanical system corresponds to a node in electrical system. A mass is considered as a node.
4. The number of nodes in electrical analogous is same as that of the number of nodes (masses) in mechanical system. Hence the number of node voltages and system equations will be same as that of the number of velocities of (nodes) masses in mechanical system.
5. The mechanical driving sources (forces) and passive elements connected to the node (mass) in mechanical system should be represented by analogous elements connected to a node in electrical system.
6. The element connected between two nodes (masses) in mechanical system is represented as a common element between two nodes in electrical analogous system.

EXAMPLE 1.8

Write the differential equations governing the mechanical system shown in fig 1. Draw the force-voltage and force-current electrical analogous circuits and verify by writing mesh and node equations.

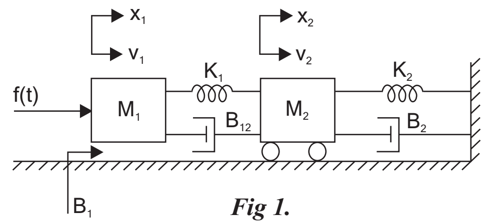


Fig 1.

SOLUTION

The given mechanical system has two nodes (masses). The differential equations governing the mechanical system are given by force balance equations at these nodes. Let the displacements of masses M_1 and M_2 be x_1 and x_2 respectively. The corresponding velocities be v_1 and v_2.

The free body diagram of M_1 is shown in fig 2. The opposing forces are marked as f_{m1}, f_{b1}, f_{b12} and f_{k1}.

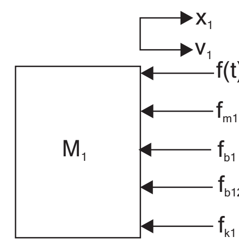


Fig 2.

$$f_{m1} = M_1 \frac{d^2x_1}{dt^2} \quad ; \quad f_{b1} = B_1 \frac{dx_1}{dt}$$

$$f_{b12} = B_{12} \frac{d}{dt}(x_1 - x_2) \quad ; \quad f_{k1} = K_1(x_1 - x_2)$$

By Newton's second law, $f_{m1} + f_{b1} + f_{b12} + f_{k1} = f(t)$

$$\therefore\ M_1 \frac{d^2x_1}{dt^2} + B_1 \frac{dx_1}{dt} + B_{12} \frac{d}{dt}(x_1 - x_2) + K_1(x_1 - x_2) = f(t) \qquad ......(1)$$

The free body diagram of M_2 is shown in fig 3.The opposing forces are marked as f_{m2}, f_{b2}, f_{b12}, f_{k1} and f_{k2} .

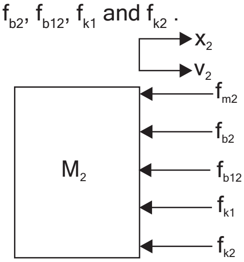


Fig 3.

$$f_{m2} = M_2 \frac{d^2x_2}{dt^2} \quad ; \quad f_{b2} = B_2 \frac{dx_2}{dt} \quad ; \quad f_{b12} = B_{12} \frac{d}{dt}(x_2 - x_1)$$

$$f_{k1} = K_1(x_2 - x_1) \quad ; \quad f_{k2} = K_2 x_2$$

By Newton's second law, $f_{m2} + f_{b2} + f_{k2} + f_{b12} + f_{k1} = 0$

$$M_2 \frac{d^2x_2}{dt^2} + B_2 \frac{dx_2}{dt} + K_2 x_2 + B_{12} \frac{d}{dt}(x_2 - x_1) + K_1(x_2 - x_1) = 0 \qquad .....(2)$$

On replacing the displacements by velocity in the differential equations (1) and (2) of the mechanical system we get,

$$\left(\text{i.e., } \frac{d^2x}{dt^2} = \frac{dv}{dt} \quad ; \quad \frac{dx}{dt} = v \quad \text{and} \quad x = \int v\, dt \right)$$

$$M_1 \frac{dv_1}{dt} + B_1 v_1 + B_{12}(v_1 - v_2) + K_1 \int (v_1 - v_2)\, dt = f(t) \qquad .....(3)$$

$$M_2 \frac{dv_2}{dt} + B_2 v_2 + K_2 \int v_2 dt + B_{12}(v_2 - v_1) + K_1 \int (v_2 - v_1)\, dt = 0 \qquad .....(4)$$

FORCE-VOLTAGE ANALOGOUS CIRCUIT

The given mechanical system has two nodes (masses). Hence the force-voltage analogous electrical circuit will have two meshes.

The force applied to mass, M_1 is represented by a voltage source in first mesh. The elements M_1, B_1, K_1 and B_{12} are connected to first node. Hence they are represented by analogous element in mesh-1 forming a closed path. The elements K_1, B_{12}, M_2, K_2, and B_2 are connected to second node. Hence they are represented by analogous element in mesh-2 forming a closed path.

The elements K_1 and B_{12} are common between node-1 and 2 and so they are represented by analogous element as common elements between two meshes. The force-voltage electrical analogous circuit is shown in fig 4.

The electrical analogous elements for the elements of mechanical system are given below.

$f(t) \rightarrow e(t)$	$M_1 \rightarrow L_1$	$B_1 \rightarrow R_1$	$K_1 \rightarrow 1/C_1$
$v_1 \rightarrow i_1$	$M_2 \rightarrow L_2$	$B_2 \rightarrow R_2$	$K_2 \rightarrow 1/C_2$
$v_2 \rightarrow i_2$		$B_{12} \rightarrow R_{12}$	

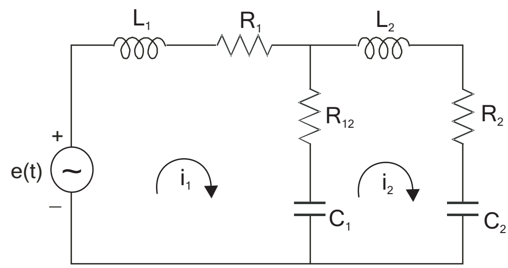


Fig 4 : *Force-voltage electrical analogous circuit.*

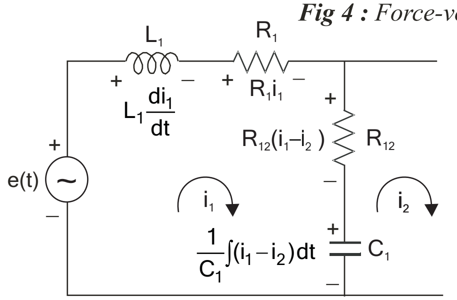


Fig 5 : *Mesh-1 of analogous circuit.*

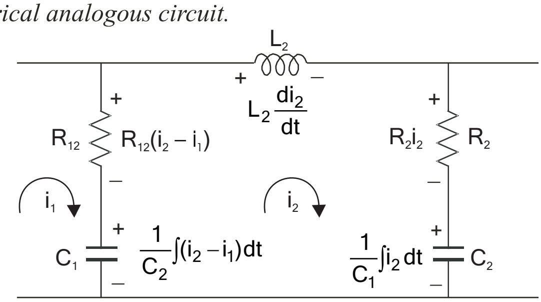


Fig 6 : *Mesh-2 of analogous circuit.*

The mesh basis equations using Kirchoff's voltage law for the circuit shown in fig 4 are given below (Refer fig 5 and 6).

$$L_1 \frac{di_1}{dt} + R_1 i_1 + R_{12}(i_1 - i_2) + \frac{1}{C_1}\int (i_1 - i_2)\, dt = e(t) \qquad .....(5)$$

$$L_2 \frac{di_2}{dt} + R_2 i_2 + \frac{1}{C_2}\int i_2\, dt + R_{12}(i_2 - i_1) + \frac{1}{C_1}\int (i_2 - i_1)\, dt = 0 \qquad .....(6)$$

It is observed that the mesh basis equations (5) and (6) are similar to the differential equations (3) and (4) governing the mechanical system.

FORCE-CURRENT ANALOGOUS CIRCUIT

The given mechanical system has two nodes (masses). Hence the force-current analogous electrical circuit will have two nodes.

The force applied to mass M_1 is represented as a current source connected to node-1 in analogous electrical circuit. The elements M_1, B_1, K_1 and B_{12} are connected to first node. Hence they are represented by analogous elements connected to node-1 in analogous electrical circuit. The elements K_1, B_{12}, M_2, K_2, and B_2 are connected to second node. Hence they are represented by analogous elements as elements connected to node-2 in analogous electrical circuit.

The elements K_1 and B_{12} are common between node-1 and 2 and so they are represented by analogous elements as common element between two nodes in analogous circuit. The force-current electrical analogous circuit is shown in fig 7.

The electrical analogous elements for the elements of mechanical system are given below.

$f(t) \rightarrow i(t)$	$M_1 \rightarrow C_1$	$B_1 \rightarrow 1/R_1$	$K_1 \rightarrow 1/L_1$
$v_1 \rightarrow v_1$	$M_2 \rightarrow C_2$	$B_2 \rightarrow 1/R_2$	$K_2 \rightarrow 1/L_2$
$v_2 \rightarrow v_2$	$B_{12} \rightarrow 1/R_{12}$		

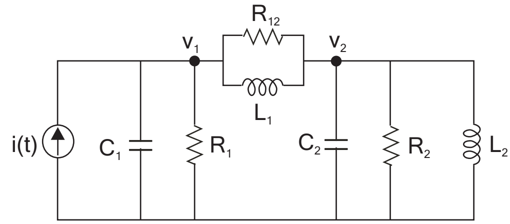


Fig 7 : *Force-voltage electrical analogous circuit.*

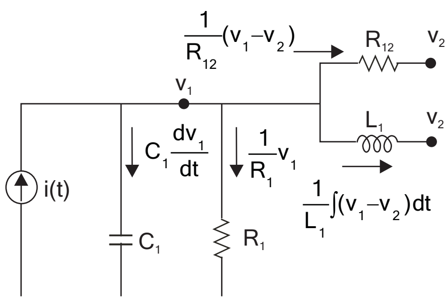


Fig 8 : *Node-1 of analogous circuit.*

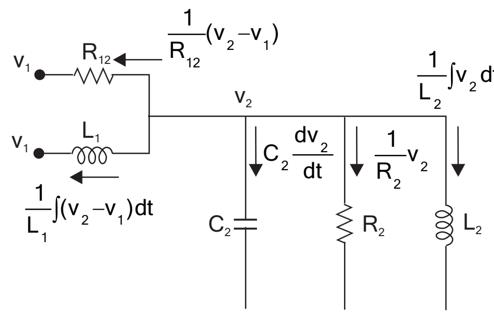


Fig 9 : *Node-2 of analogous circuit.*

The node basis equations using Kirchoff 's current law for the circuit shown in fig 7 are given below (Refer fig 8 and 9).

$$C_1\frac{dv_1}{dt}+\frac{1}{R_1}v_1+\frac{1}{R_{12}}(v_1-v_2)\,dt+\frac{1}{L_1}\int(v_1-v_2)=i(t) \qquad .....(7)$$

$$C_2\frac{dv_2}{dt}+\frac{1}{R_2}v_2+\frac{1}{L_2}\int v_2\,dt+\frac{1}{R_{12}}(v_2-v_1)+\frac{1}{L_1}\int(v_2-v_1)\,dt=0 \qquad .....(8)$$

It is observed that the node basis equations (7) and (8) are similar to the differential equations (3) and (4) governing the mechanical system.

EXAMPLE 1.9

Write the differential equations governing the mechanical system shown in fig1. Draw the force-voltage and force-current electrical analogous circuits and verify by writing mesh and node equations.

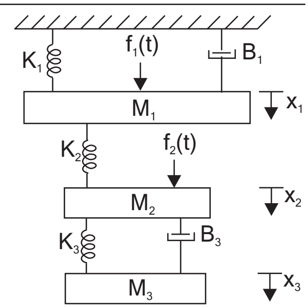


Fig 1.

SOLUTION

The given mechanical system has three nodes masses. The differential equations governing the mechanical system are given by force balance equations at these nodes. Let the displacements of masses M_1, M_2 and M_3 be x_1, x_2 and x_3 respectively. The corresponding velocities be v_1, v_2 and v_3.

The free body diagram of M_1 is shown in fig 2. The opposing forces are marked as f_{m1}, f_{b1}, f_{k2} and f_{k1}.

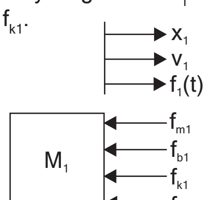


Fig 2.

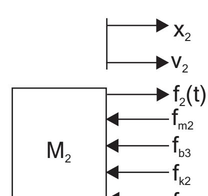


Fig 3.

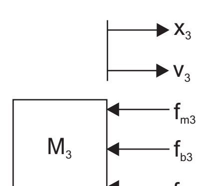


Fig 4.

$$f_{m1}=\frac{M_1 d^2x_1}{dt^2} \quad ; \quad f_{b1}=B_1\frac{dx_1}{dt} \quad ; \quad f_{k2}=K_2(x_1-x_2) \quad ; \quad f_{k1}=K_1x_1$$

By Newton's second law, $f_{m1}+f_{b1}+f_{k2}+f_{k1}=f_1(t)$

$$M_1\frac{d^2x_1}{dt^2}+B_1\frac{dx_1}{dt}+K_2(x_1-x_2)+K_1x_1=f_1(t) \qquad .....(1)$$

Free body diagram of M_2 is shown in fig 3. The opposing forces are marked as f_{m2}, f_{b3}, f_{k2} & f_{k3}.

$$f_{m2}=M_2\frac{d^2x_2}{dt^2} \quad ; \quad f_{b3}=B_3\frac{d}{dt}(x_2-x_3) \quad ; \quad f_{k2}=K_2(x_2-x_1) \quad ; \quad f_{k3}=K_3(x_2-x_3)$$

By Newton's second law, $f_{m2}+f_{b3}+f_{k2}+f_{k3}=f_2(t)$

$$M_2\frac{d^2x_2}{dt^2}+B_3\frac{d}{dt}(x_2-x_3)+K_2(x_2-x_1)+K_3(x_2-x_3)=f_2(t) \qquad .....(2)$$

The free body diagram of M_3 is shown in fig 4. The opposing forces are marked as f_{m3}, f_{b3} and f_{k3}.

$$f_{m3}=M_3\frac{d^2x_3}{dt^2} \quad ; \quad f_{b3}=B_3\frac{d}{dt}(x_3-x_2) \quad ; \quad f_{k3}=K_3(x_3-x_2)$$

By Newton's second law,

$$M_3\frac{d^2x_3}{dt^2}+B_3\frac{d}{dt}(x_3-x_2)+K_3(x_3-x_2)=0 \qquad .....(3)$$

On replacing the displacements by velocity in the differential equations (1), (2) and (3) governing the mechanical system we get,

$$\left(\text{i.e., }\frac{d^2x}{dt^2}=\frac{dv}{dt} \quad ; \quad \frac{dx}{dt}=v \text{ and } x=\int v\,dt\right)$$

$$M_1\frac{dv_1}{dt}+B_1v_1+K_1\int v_1dt+K_2\int (v_1-v_2)\,dt=f_1(t) \qquad .....(4)$$

$$M_2\frac{dv_2}{dt}+B_3(v_2-v_3)+K_2\int (v_2-v_1)\,dt+K_3\int (v_2-v_3)\,dt=f_2(t) \qquad .....(5)$$

$$M_3\frac{dv_3}{dt}+B_3(v_3-v_2)+K_3\int (v_3-v_2)\,dt=0 \qquad .....(6)$$

FORCE-VOLTAGE ANALOGOUS CIRCUIT

The given mechanical system has three nodes (masses). Hence the force-voltage analogous electrical circuit will have three meshes. The force applied to mass, M_1 is represented by a voltage source in first mesh and the force applied to mass, M_2 is represented by a voltage source in second mesh.

The elements M_1, B_1, K_1 and K_2 are connected to first node. Hence they are represented by analogous element in mesh-1 forming a closed path. The elements M_2, B_3, K_2 and K_3 are connected to second node. Hence they are represented by analogous element in mesh-2 forming a closed path. The elements M_3, K_3 and B_3 are connected to third node. Hence they are represented by analogous element in mesh-3 forming a closed path.

The element K_2 is common between node-1 and 2 and so it is represented by analogous element as common element between mesh 1 and 2. The elements K_3 and B_3 are common between node-2 and 3 and so they are represented by analogous elements as common elements between mesh-2 and 3. The force-voltage electrical analogous circuit is shown in fig 5.

The electrical analogous elements for the elements of mechanical system are given below.

$f_1(t) \rightarrow e_1(t)$	$v_1 \rightarrow i_1$	$M_1 \rightarrow L_1$	$B_1 \rightarrow R_1$	$K_1 \rightarrow 1/C_1$
$f_2(t) \rightarrow e_2(t)$	$v_2 \rightarrow i_2$	$M_2 \rightarrow L_2$	$B_3 \rightarrow R_3$	$K_2 \rightarrow 1/C_2$
	$v_3 \rightarrow i_3$	$M_3 \rightarrow L_3$		$K_3 \rightarrow 1/C_3$

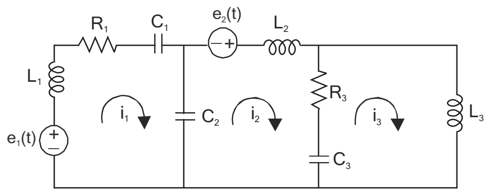


Fig 5 : Force-voltage electrical analogous circuit.

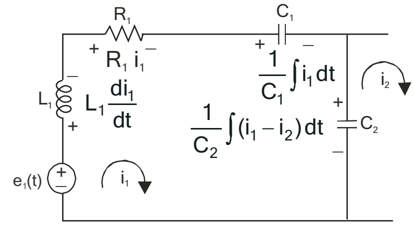


Fig 6 : Mesh-1 analogous circuit.

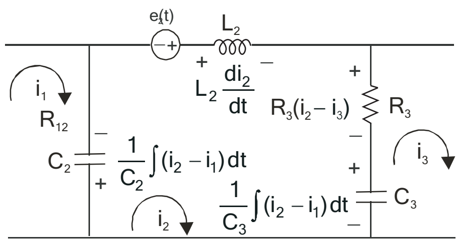


Fig 7 : Mesh-2 of analogous circuit.

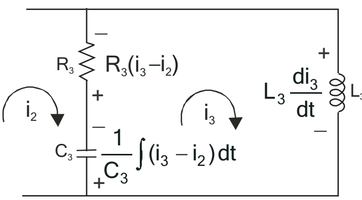


Fig 8 : Mesh-3 of analogous circuit.

The mesh basis equations using Kirchoff's voltage law for the circuit shown in fig 5 are given below (Refer fig 6, 7, 8).

$$L_1\frac{di_1}{dt} + R_1 i_1 + \frac{1}{C_1}\int i_1 dt + \frac{1}{C_2}\int (i_1 - i_2)\,dt = e_1(t) \qquad .....(7)$$

$$L_2\frac{di_2}{dt} + R_3(i_2 - i_3) + \frac{1}{C_3}\int (i_2 - i_3)\,dt + \frac{1}{C_2}\int (i_2 - i_1)\,dt = e_2(t) \qquad .....(8)$$

$$L_3\frac{di_3}{dt} + R_3(i_3 - i_2) + \frac{1}{C_3}\int (i_3 - i_2)\,dt = 0 \qquad .....(9)$$

It is observed that the mesh equations (7), (8) and (9) are similar to the differential equations (4), (5) and (6) governing the mechanical system.

FORCE-CURRENT ANALOGOUS CIRCUIT

The given mechanical system has three nodes (masses). Hence the force-current analogous electrical circuit will have three nodes.

The force applied to mass M_1 is represented as a current source connected to node-1 in analogous electrical circuit. The force applied to mass M_2 is represented as a current source connected to node-2 in analogous electrical circuit.

The elements M_1, B_1, K_1 and K_2 are connected to first node. Hence they are represented by analogous elements as elements connected to node-1 in analogous electrical circuit. The elements M_2, B_3, K_2 and K_3 are connected to second node. Hence they are represented by analogous elements as elements connected to node-2 in analogous electrical circuit. The elements M_3, B_3 and K_3 are connected to third node. Hence they are represented by analogous elements as elements connected to node-3 in analogous electrical circuit.

The element K_2 is common between node-1 and 2 and so it is represented by analogous element as common element between node-1 and 2 in analogous circuit. The elements B_3 and K_3 are common between node-2 and 3 and so they are represented by analogous elements as common elements between node-2 and 3. The force-current electrical analogous circuit is shown in fig 9.

The electrical analogous elements for the elements of mechanical system are given below.

$f_1(t) \rightarrow i_1(t)$	$v_1 \rightarrow v_1$	$M_1 \rightarrow C_1$	$B_1 \rightarrow 1/R_1$	$K_1 \rightarrow 1/L_1$
$f_2(t) \rightarrow i_2(t)$	$v_2 \rightarrow v_2$	$M_2 \rightarrow C_2$	$B_3 \rightarrow 1/R_3$	$K_2 \rightarrow 1/L_2$
	$v_3 \rightarrow v_3$	$M_3 \rightarrow C_3$		$K_3 \rightarrow 1/L_3$

The node basis equations using Kirchoff's current law for the circuit shown in fig 9. are given below. (Refer fig10, 11,12).

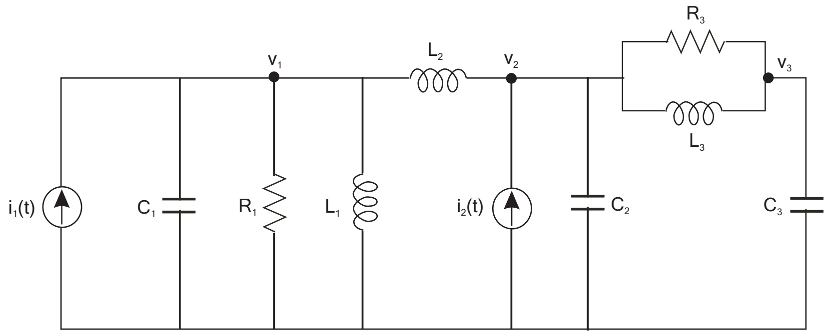


Fig 9 : *Force-current electrical analogous circuit.*

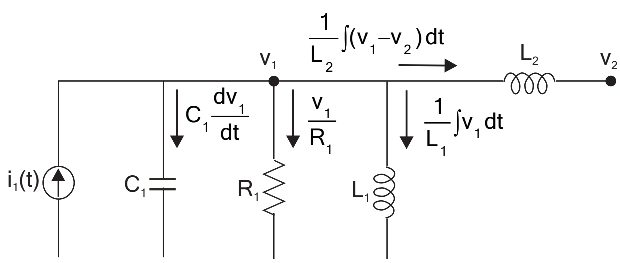


Fig 10 : *Node-1 of analogous circuit.*

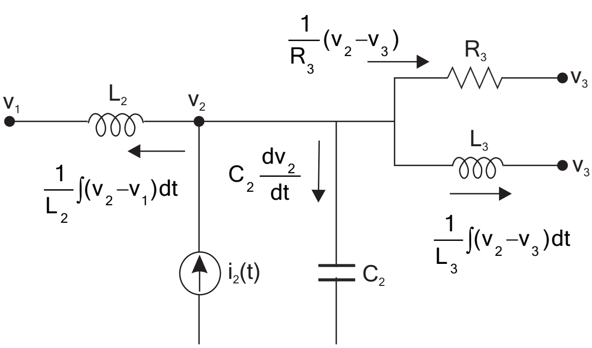


Fig 11 : *Node-2 of analogous circuit.*

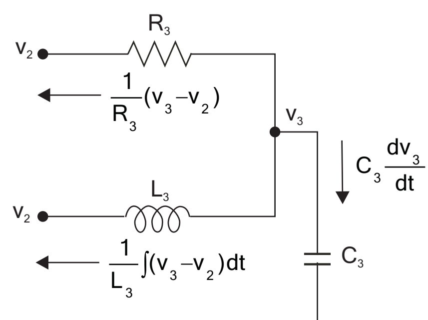


Fig 12 : *Node-3 of analogous circuit.*

$$C_1\frac{dv_1}{dt} + \frac{1}{R_1}v_1 + \frac{1}{L_1}\int v_1 dt + \frac{1}{L_2}\int (v_1 - v_2)\,dt = i_1(t) \quad .....(10)$$

$$C_2\frac{dv_2}{dt} + \frac{1}{R_3}(v_2 - v_3) + \frac{1}{L_3}\int (v_2 - v_3)\,dt + \frac{1}{L_2}\int (v_2 - v_1)\,dt = i_2(t) \quad .....(11)$$

$$C_3\frac{dv_3}{dt} + \frac{1}{R_3}(v_3 - v_2) + \frac{1}{L_3}\int (v_3 - v_2)\,dt = 0 \quad .....(12)$$

It is observed that node basis equations (10), (11) and (12) are similar to the differential equations (4), (5) and (6) governing the mechanical system.

EXAMPLE 1.10

Write the differential equations governing the mechanical system shown in fig 1. Draw force-voltage and force-current electrical analogous circuits and verify by writing mesh and node equations.

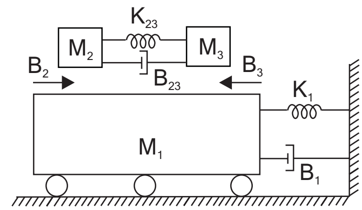


Fig 1.

SOLUTION

The given mechanical system has three nodes (masses). The differential equations governing the mechanical system are given by force balance equations at these nodes. Let the displacements of masses M_1, M_2 and M_3 be x_1, x_2 and x_3 respectively. The corresponding velocities be v_1, v_2 and v_3.

The free body diagram of M_1 is shown in fig 2. The opposing forces are marked as f_{b1}, f_{k1}, f_{b2}, f_{b3}, and f_{m1}.

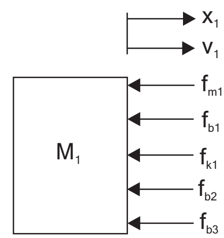


Fig 2.

$$f_{m1} = M_1 \frac{d^2x_1}{dt^2} \quad ; \quad f_{b1} = B_1 \frac{dx_1}{dt} \quad ; \quad f_{k1} = K_1 x_1$$

$$f_{b2} = B_2 \frac{d}{dt}(x_1 - x_2) \quad ; \quad f_{b3} = B_3 \frac{d}{dt}(x_1 - x_3)$$

By Newton's second law, $f_{m1} + f_{b1} + f_{k1} + f_{b2} + f_{b3} = 0$

$$M_1 \frac{d^2x_1}{dt^2} + B_1 \frac{dx_1}{dt} + K_1 x_1 + B_2 \frac{d}{dt}(x_1 - x_2) + B_3 \frac{d}{dt}(x_1 - x_3) = 0 \qquad .....(1)$$

The free body diagram of M_2 is shown in fig 3. The opposing forces are marked as f_{m2}, f_{b2}, f_{b23} and f_{k23}.

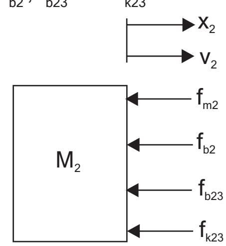


Fig 3.

$$f_{m2} = M_2 \frac{d^2x_2}{dt^2} \quad ; \quad f_{b2} = B_2 \frac{d}{dt}(x_2 - x_1)$$

$$f_{b23} = B_{23} \frac{d}{dt}(x_2 - x_3) \quad ; \quad f_{k23} = K_{23}(x_2 - x_3)$$

By Newton's second law, $f_{m2} + f_{b2} + f_{b23} + f_{k23} = 0$

$$M_2 \frac{d^2x_2}{dt^2} + B_2 \frac{d}{dt}(x_2 - x_1) + B_{23} \frac{d}{dt}(x_2 - x_3) + K_{23}(x_2 - x_3) = 0 \qquad ......(2)$$

The free body diagram of M_3 is shown in fig 4. The opposing forces are marked as f_{m3}, f_{b3}, f_{b23}, and f_{k23}.

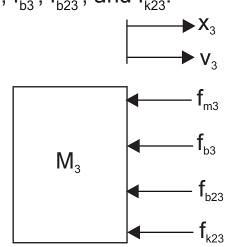


Fig 4.

$$f_{m3} = M_3 \frac{d^2x_3}{dt^2} \quad ; \quad f_{b3} = B_3 \frac{d}{dt}(x_3 - x_1)$$

$$f_{b23} = B_{23} \frac{d}{dt}(x_3 - x_2) \quad ; \quad f_{k23} = K_{23}(x_3 - x_2)$$

By Newton's second law, $f_{m3} + f_{b3} + f_{b23} + f_{k23} = 0$

$$M_3 \frac{d^2x_3}{dt^2} + B_3 \frac{d}{dt}(x_3 - x_1) + B_{23} \frac{d}{dt}(x_3 - x_2) + K_{23}(x_3 - x_2) = 0 \qquad .....(3)$$

On replacing the displacements by velocity in the differential equations (1), (2) and (3) governing the mechanical system we get,

$$\left(\text{i.e.,} \ \frac{d^2x}{dt^2} = \frac{dv}{dt}, \ \frac{dx}{dt} = v \ \text{ and } \ x = \int v\,dt \right)$$

$$M_1 \frac{dv_1}{dt} + B_1 v_1 + K_1 \int v_1 dt + B_2(v_1 - v_2) + B_3(v_1 - v_3) = 0 \qquad .....(4)$$

$$M_2 \frac{dv_2}{dt} + B_2(v_2 - v_1) + B_{23}(v_2 - v_3) + K_{23} \int (v_2 - v_3)\,dt = 0 \qquad .....(5)$$

$$M_3 \frac{dv_3}{dt} + B_3(v_3 - v_1) + B_{23}(v_3 - v_2) + K_{23} \int (v_3 - v_2)\,dt = 0 \qquad .....(6)$$

FORCE-VOLTAGE ANALOGOUS CIRCUIT

The given mechanical system has three nodes (masses). Hence the force-voltage analogous electrical circuit will have three meshes. Since there is no applied force in mechanical system there will not be any voltage source in analogous electrical circuit.

The elements M_1, K_1, B_1, B_3 and B_2 are connected to first node. Hence they are represented by analogous elements in mesh-1 forming a closed path. The elements M_2, K_{23}, B_{23} and B_2 are connected to second node. Hence they are represented by analogous elements in mesh-2 forming a closed path. The elements M_3, K_{23} , B_{23} and B_3 are connected to third node. Hence they are represented by analogous elements in mesh-3 forming a closed path.

The elements K_{23} and B_{23} are common between node-2 and 3 and so they are represented by analogous element as common elements between mesh-2 and 3. The element B_2 is common between node-1 and 2 and so it is represented by analogous element as common element between mesh-1 and 2. The element B_3 is common between node-1 and 3 and so it is represented by analogous element between mesh-1 and 3. The force-voltage electrical analogous circuit is shown in fig 5.

The electrical analogous elements for the elements of mechanical system are given below.

$v_1 \rightarrow i_1$	$M_1 \rightarrow L_1$	$K_1 \rightarrow 1/C_1$	$B_2 \rightarrow R_2$
$v_2 \rightarrow i_2$	$M_2 \rightarrow L_2$	$K_{23} \rightarrow 1/C_{23}$	$B_3 \rightarrow R_3$
$v_3 \rightarrow i_3$	$M_3 \rightarrow L_3$	$B_1 \rightarrow R_1$	$B_{23} \rightarrow R_{23}$

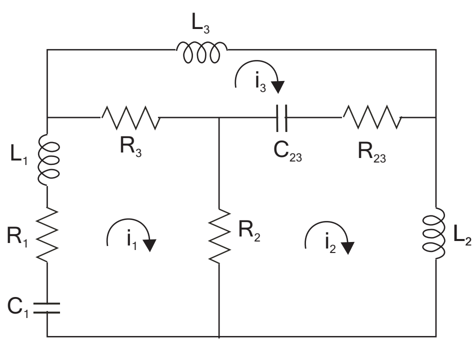


Fig 5 : Force-voltage electrical analogous circuit.

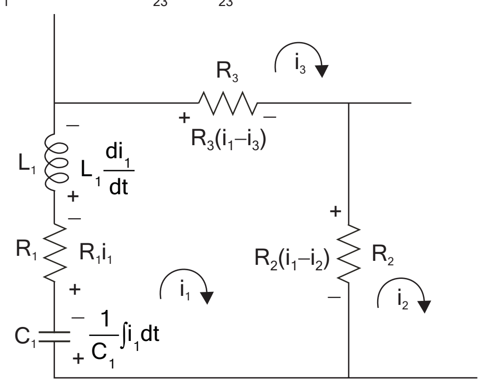


Fig 6 : Mesh-1 of analogous circuit.

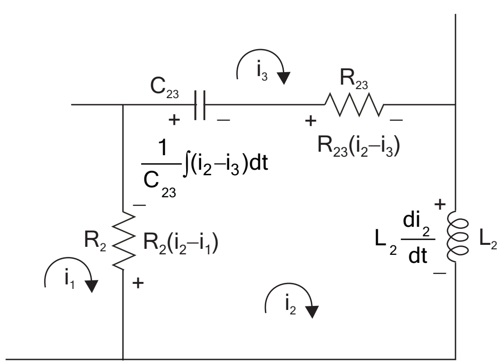


Fig 7 : Mesh-2 of analogous circuit.

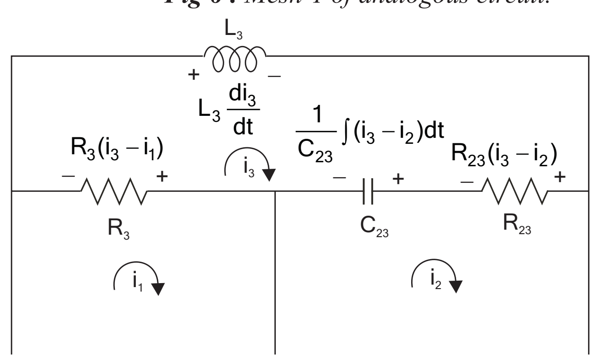


Fig 8 : Mesh-3 of analogous circuit..

The mesh basis equations using Kirchoff's voltage law for the circuit shown in fig 5 are given below. (Refer fig 6, 7 and 8).

$$L_1\frac{di_1}{dt}+R_1i_1+\frac{1}{C_1}\int i_1dt+R_2(i_1-i_2)+R_3(i_1-i_3)=0 \qquad .....(7)$$

$$L_2\frac{di_2}{dt}+R_2(i_2-i_1)+\frac{1}{C_{23}}\int (i_2-i_3)\,dt+R_{23}(i_2-i_3)=0 \qquad .....(8)$$

$$L_3 \frac{di_3}{dt} + R_3(i_3 - i_1) + \frac{1}{C_{23}} \int (i_3 - i_2)\,dt + R_{23}(i_3 - i_2) = 0 \qquad .....(9)$$

It is observed that the mesh basis equations (7), (8) and (9) are similar to the differential equations (4), (5) and (6) governing the mechanical system.

FORCE-CURRENT ANALOGOUS CIRCUIT

The given mechanical system has three nodes (masses). Hence the force-current analogous electrical circuit will have three nodes. Since there is no applied force in mechanical system there will not be any current source in analogous electrical circuit.

The elements M_1, K_1, B_1, B_2 and B_3 are connected to first node. Hence they are represented by analogous elements as elements connected to node-1 in analogous electrical circuit. The elements M_2, K_{23}, B_{23} and B_2 are connected to second node. Hence they are represented by analogous elements as elements connected to node-2 in analogous electrical circuit. The elements M_3, K_{23} , B_{23} and B_3 are connected to third node. Hence they are represented by analogous elements as elements connected to node-3 in analogous electrical circuit.

The elements K_{23} and B_{23} are common between node-2 and 3 and so they are represented by analogous element as common elements between node-2 and 3 in electrical analogous circuit. The element B_2 is common between node-1 and 2 and so it is represented by analogous element as common element between node-1 and 2 in electrical analogous circuit. The element B_3 is common between node-1 and 3 and so it is represented by analogous element as common element between node-1 and 3 in electrical analogous circuit. The force-current electrical analogous circuit is shown in fig 9.

The electrical analogous elements for the elements of mechanical system are given below.

$v_1 \rightarrow v_1$	$M_1 \rightarrow C_1$	$K_1 \rightarrow 1/L_1$	$B_2 \rightarrow 1/R_2$
$v_2 \rightarrow v_2$	$M_2 \rightarrow C_2$	$K_{23} \rightarrow 1/L_{23}$	$B_3 \rightarrow 1/R_3$
$v_3 \rightarrow v_3$	$M_3 \rightarrow C_3$	$B_1 \rightarrow 1/R_1$	$B_{23} \rightarrow 1/R_{23}$

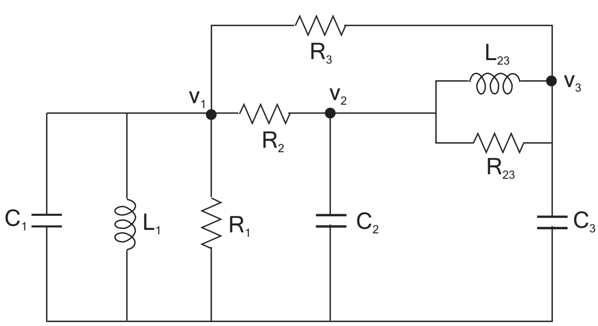


Fig 9 : *Force-current electrical analogous circuit.*

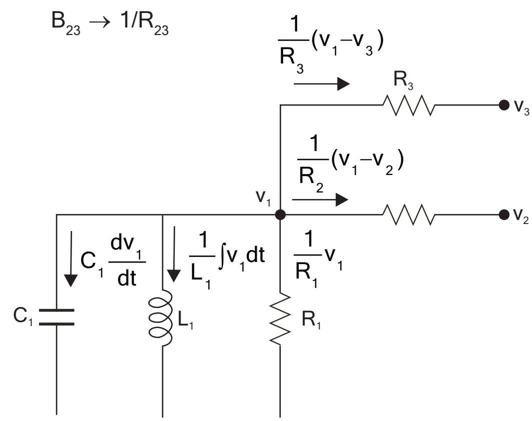


Fig 10 : *Node-1 of analogous circuit.*

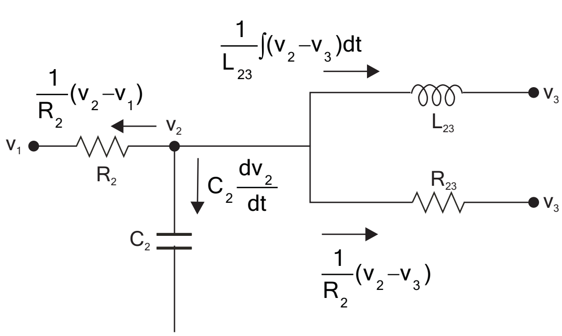


Fig 11 : *Node-2 of analogous circuit.*

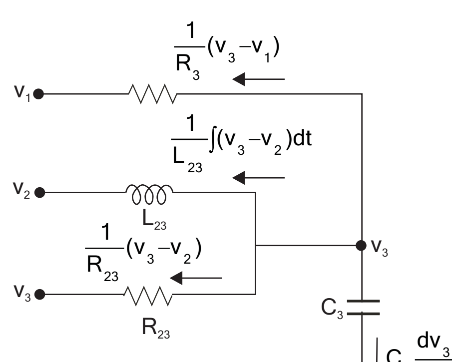


Fig 12 : *Node-3 of analogous circuit.*

The node basis equations using Kirchoff's current law for the circuit shown in fig 9 are given below. (Refer fig 10, 11 and 12).

$$C_1\frac{dv_1}{dt}+\frac{1}{R_1}v_1+\frac{1}{L_1}\int v_1dt+\frac{1}{R_2}(v_1-v_2)+\frac{1}{R_3}(v_1-v_3)=0 \quad .....(10)$$

$$C_2\frac{dv_2}{dt}+\frac{1}{R_2}(v_2-v_1)+\frac{1}{L_{23}}\int (v_2-v_3)\,dt+\frac{1}{R_{23}}(v_2-v_3)=0 \quad .....(11)$$

$$C_3\frac{dv_3}{dt}+\frac{1}{R_3}(v_3-v_1)+\frac{1}{L_{23}}\int (v_3-v_2)\,dt+\frac{1}{R_{23}}(v_3-v_2)=0 \quad .....(12)$$

It is observed that the node basis equations (10), (11) and (12) are similar to the differential equations (4), (5) and (6) governing the mechanical system.

EXAMPLE 1.11

Write the differential equations governing the mechanical system shown in fig 1. Draw the force-voltage and force-current electrical analogous circuits and verify by writing mesh and node equations.

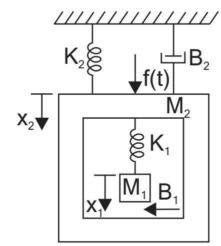


Fig 1.

SOLUTION

The given mechanical system has two nodes (masses). The differential equations governing the mechanical system are given by force balance equations at these nodes. Let the displacement of masses M_1 and M_2 be x_1 and x_2 respectively. The corresponding velocities be v_1 and v_2.

The free body diagram of M_1 is shown in fig 2. The opposing forces are marked as f_{m1}, f_{b1} and f_{k1}.

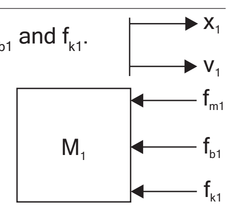


Fig 2.

$$f_{m1}=M_1\frac{d^2x_1}{dt^2} \quad ; \quad f_{b1}=B_1\frac{d(x_1-x_2)}{dt} \quad ; \quad f_{k1}=K_1(x_1-x_2)$$

By Newton's second law, $f_{m1}+f_{b1}+f_{k1}=0$

$$M_1\frac{d^2x_1}{dt^2}+B_1\frac{d(x_1-x_2)}{dt}+K_1(x_1-x_2)=0 \quad .....(1)$$

The free body diagram of M_2 is shown in fig 3. The opposing forces are marked as f_{m2}, f_{b2}, f_{b1}, f_{k2} and f_{k1}.

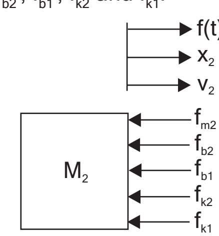


Fig 3.

$$f_{m2}=M_2\frac{d^2x_2}{dt^2} \quad ; \quad f_{b2}=B_2\frac{dx_2}{dt} \quad ; \quad f_{b1}=B_1\frac{d}{dt}(x_2-x_1)$$

$$f_{k2}=K_2x_2 \quad ; \quad f_{k1}=K_1(x_2-x_1)$$

By Newton's second law, $f_{m2}+f_{b2}+f_{k2}+f_{b1}+f_{k1}=f(t)$

$$M_2\frac{d^2x_2}{dt^2}+B_2\frac{dx_2}{dt}+K_2x_2+B_1\frac{d}{dt}(x_2-x_1)+K_1(x_2-x_1)=f(t) \quad .....(2)$$

On replacing the displacements by velocity in the differential equations (1) and (2) governing the mechanical system we get,

$$\left(\text{i.e., } \frac{d^2x}{dt^2}=\frac{dv}{dt} \;,\; \frac{dx}{dt}=v \text{ and } x=\int vdt\right)$$

$$M_1\frac{dv_1}{dt}+B_1(v_1-v_2)+K_1\int (v_1-v_2)\,dt=0 \quad .....(3)$$

$$M_2\frac{dv_2}{dt}+B_2v_2)+K_2\int v_2dt+B_1(v_2-v_1)+K_1\int (v_2-v_1)\,dt=f(t) \quad .....(4)$$

FORCE-VOLTAGE ANALOGOUS CIRCUIT

The given mechanical system has two nodes (masses). Hence the force voltage analogous electrical circuit will have two meshes. The force applied to mass, M_2 is represented by a voltage source in second mesh.

The elements M_1, K_1 and B_1 are connected to first node. Hence they are represented by analogous element in mesh 1 forming a closed path. The elements M_2, K_2, B_2, B_1 and K_1 are connected to second node. Hence they are represented by analogous element in mesh 2 forming a closed path.

The elements B_1 and K_1 are common between node 1 and 2 and so they are represented as common elements between mesh 1 and 2. The force-voltage electrical analogous circuit is shown in fig 4.

The electrical analogous elements for the elements of mechanical system are given below.

$f(t) \rightarrow e(t)$ $v_1 \rightarrow i_1$ $M_1 \rightarrow L_1$ $K_1 \rightarrow 1/C_1$ $B_1 \rightarrow R_1$
$v_2 \rightarrow i_2$ $M_2 \rightarrow L_2$ $K_2 \rightarrow 1/C_2$ $B_2 \rightarrow R_2$

The mesh basis equations using Kirchoff's voltage law for the circuit shown in fig 4. are given below, (refer fig 5 and 6).

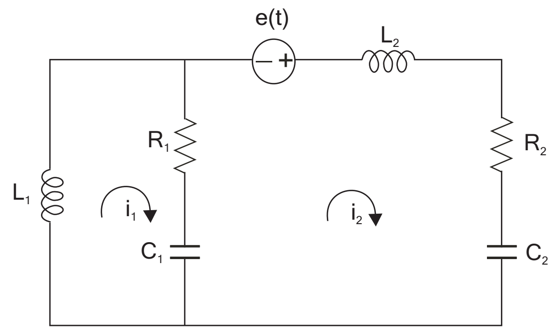


Fig 4 : *Force-voltage electrical analogous circuit.*

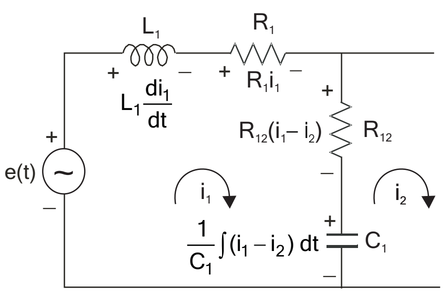


Fig 5 : *Mesh-1 of analogous circuit.*

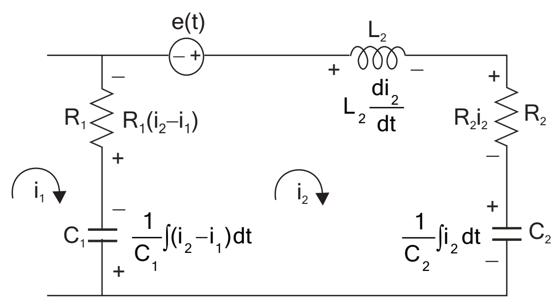


Fig 6 : *Mesh-2 of analogous circuit.*

$$L_1\frac{di_1}{dt} + R_1(i_1 - i_2) + \frac{1}{C_1}\int (i_1 - i_2)\,dt = 0 \qquad .....(5)$$

$$L_2\frac{di_2}{dt} + R_2 i_2 + \frac{1}{C_2}\int i_2 dt + \frac{1}{C_1}\int (i_2 - i_1)\,dt + R_1(i_2 - i_1) = e(t) \qquad .....(6)$$

It is observed that the mesh basis equations (5) and (6) are similar to the differential equations (3) and (4) governing the mechanical system.

FORCE-CURRENT ANALOGOUS CIRCUIT

The given mechanical system has two nodes (masses). Hence the force-current analogous electrical circuit will have two nodes. The force applied to mass M_2 is represented as a current source connected to node-2 in analogous electrical circuit.

The elements M_1, K_1 and B_1 are connected to first node. Hence they are represented by analogous elements as elements connected to node-1 in analogous electrical circuit. The elements M_2, K_2, B_2, B_1 and K_1 are connected to second node. Hence they are represented by analogous elements as elements connected to node-1 in analogous electrical circuit.

The elements K_1 and B_1 is common to node-1 and 2 and so they are represented by analogous element as common elements between two nodes in analogous circuit. The force-current electrical analogous circuit is shown in fig 7.

The electrical analogous elements for the elements of mechanical system are given below.

$f(t) \rightarrow i(t)$ $\quad v_1 \rightarrow v_1$ $\quad M_1 \rightarrow C_1$ $\quad B_1 \rightarrow 1/R_1$ $\quad K_1 \rightarrow 1/L_1$

$v_2 \rightarrow v_2$ $\quad M_2 \rightarrow C_2$ $\quad B_2 \rightarrow 1/R_2$ $\quad K_2 \rightarrow 1/L_2$

The node basis equations using Kirchoff 's current law for the circuit shown in fig.7, are given below, (Refer fig 8 and 9).

$$C_1\frac{dv_1}{dt} + \frac{1}{R_1}(v_1 - v_2) + \frac{1}{L_1}\int (v_1 - v_2)\,dt = 0 \qquad .....(7)$$

$$C_2\frac{dv_2}{dt} + \frac{1}{R_2}v_2 + \frac{1}{L_2}\int v_2 dt + \frac{1}{R_1}(v_2 - v_1) + \frac{1}{L_1}\int (v_2 - v_1)\,dt = i(t) \qquad .....(8)$$

It is observed that the node basis equations (7) and (8) are similar to the differential equations (3) and (4) governing the mechanical system.

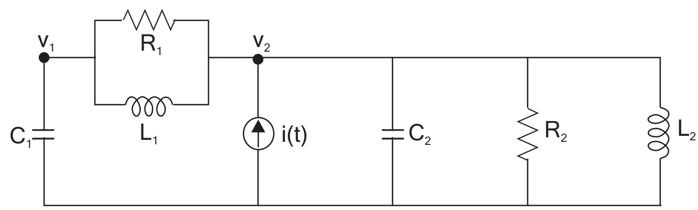


Fig 7 : *Force-current electrical analogous circuit.*

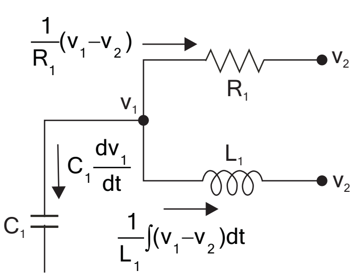


Fig 8 : *Node-1 of analogous circuit.*

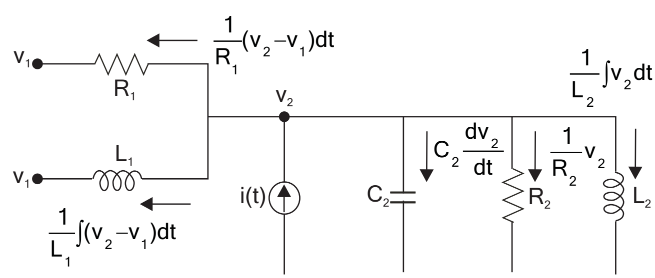


Fig 9 : *Node-2 of analogous circuit.*

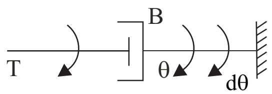
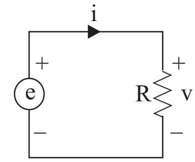
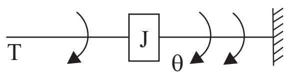
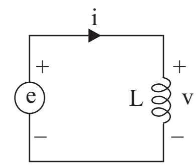
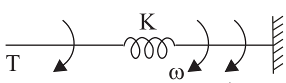
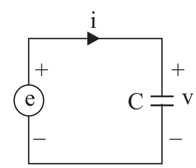
1.6 ELECTRICAL ANALOGOUS OF MECHANICAL ROTATIONAL SYSTEMS

The three basic elements moment of inertia, rotational dashpot and torsional spring that are used in modelling mechanical rotational systems are analogous to resistance, inductance and capacitance of electrical systems. The input torque in mechanical system is analogous to either voltage source or current source in electrical systems. The output angular velocity (first derivative of angular displacement) in mechanical rotational system is analogous to either current or voltage in an element in electrical system. Since the electrical systems has two types of inputs either voltage source or current source, there are two types of analogies: ***torque-voltage analogy and torque-current analogy***.

TORQUE-VOLTAGE ANALOGY

The torque balance equations of mechanical rotational elements and their analogous electrical elements in torque-voltage analogy are shown in table-1.6. The table-1.7 shows the list of analogous quantities in torque-voltage analogy.

TABLE-1.6 : Analogous Element of Torque-Voltage Analogy

Mechanical rotational system	Electrical system
Input : Torque Output : Angular velocity	Input : Voltage source Output : Current through the element
 $T = B\frac{d\theta}{dt} = B\omega$ $\omega = \frac{d\theta}{dt}$	 $e = v$; $v = Ri$ $\therefore\ e = Ri$
 $T = J\frac{d^2\theta}{dt^2} = j\frac{d\omega}{dt}$ $\propto = \frac{d^2\theta}{dt^2} = \frac{d\omega}{dt}$	 $e = v$; $v = L\frac{di}{dt}$ $\therefore e = L\frac{di}{dt}$
 $T = K\theta = K\int\omega\, dt$ $\theta = \int\omega\, dt$	 $e = v$; $v = \frac{1}{C}\int i\, dt$ $\therefore e = \frac{1}{C}\int i\, dt$

The following points serve as guidelines to obtain electrical analogous of mechanical rotational systems based on torque-voltage analogy.

1. In electrical systems the elements in series will have same current, likewise in mechanical systems, the elements having same angular velocity are said to be in series.
2. The elements having same angular velocity in mechanical system should have analogous same current in electrical analogous system.
3. Each node (meeting point of elements) in the mechanical system corresponds to a closed loop in electrical system. The moment of inertia of mass is considered as a node.
4. The number of meshes in electrical analogous is same as that of the number of nodes (moment of inertia of mass) in mechanical system. Hence the number of mesh currents and system equations will be same as that of the number of angular velocities of nodes (moment of inertia of mass) in mechanical system.
5. The mechanical driving sources (Torque) and passive elements connected to the node (moment of inertia of mass) in mechanical system should be represented by analogous element in a closed loop in analogous electrical system.
6. The element connected between two nodes (moment of inertia) in mechanical system is represented as a common element between two meshes in electrical analogous system.

Table-1.7 : Analogous Quantities in Torque-Voltage Analogy

Item	Mechanical rotational system	Electrical system (mesh basis system)
Independent variable (input)	Torque, T	Voltage, e, v
Dependent variable (output)	Angular Velocity, ω	Current, i
	Angular displacement, θ	Charge, q
Dissipative element	Rotational coefficient of dashpot, B	Resistance, R
Storage element	Moment of inertia, J	Inductance, L
	Stiffness of spring, K	Inverse of capacitance, 1/C
Physical law	Newton's second law $\sum T = 0$	Kirchoff's voltage law $\sum v = 0$
Changing the level of independent variable	Gear $\frac{T_1}{T_2} = \frac{n_1}{n_2}$	Transformer $\frac{e_1}{e_2} = \frac{N_1}{N_2}$

TORQUE-CURRENT ANALOGY

The torque balance equations of mechanical elements and their analogous electrical elements in torque-current analogy are shown in table-1.8. The table-1.9 shows the list of analogous quantities in torque-current analogy.

The following points serve as guidelines to obtain electrical analogous of mechanical rotational systems based on Torque-current analogy.

1. In electrical systems the elements in parallel will have same voltage, likewise in mechanical systems, the elements having same torque are said to be in parallel.
2. The elements having same angular velocity in mechanical system should have analogous same voltage in electrical analogous system.
3. Each node (meeting point of elements) in the mechanical system corresponds to a node in electrical system. The moment of inertia of mass is considered as a node.
4. The number of nodes in electrical analogous is same as that of the number of nodes (moment of inertia of mass) in mechanical system. Hence the number of node voltages and system equations will be same as that of the number of angular velocities of nodes (moment of inertia of mass) in mechanical system.
5. The mechanical driving sources (Torque) and passive elements connected to the node in mechanical system should be represented by analogous element connected to a node in analogous electrical system.
6. The element connected between two nodes (moment of inertia of mass) in mechanical system is represented as a common element between two nodes in electrical analogous system.

TABLE-1.8 : Analogous Elements in Torque-Current Analogy

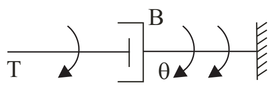
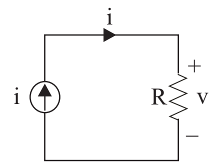
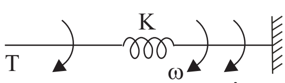
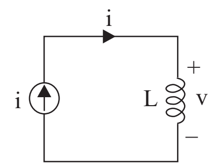
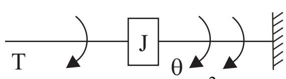
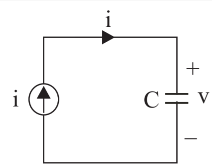
Mechanical rotational system	Electrical system
Input : Torque Output : Angular velocity	Input : Current source Output : Voltage across the element
 $T = B\frac{d\theta}{dt} = B\omega$ $\quad \omega = \frac{d\theta}{dt}$	 $i = \frac{1}{R}v$
 $T = K\theta = K\int \omega\, dt$ $\quad \theta = \int \omega\, dt$	 $i = \frac{1}{L}\int v\, dt$
 $T = J\frac{d^2\theta}{dt^2} = J\frac{d\omega}{dt}$ $\quad \propto = \frac{d^2\theta}{dt^2} = \frac{d\omega}{dt}$	 $i = C\frac{dv}{dt}$

Table-1.9 : Analogous Quantities in Torque-Current Analogy

Item	Mechanical rotational system	Electrical system (node basis system)
Independent variable (input)	Torque, T	Current, i
Dependent variable (output)	Angular Velocity, ω	Voltage, v
	Angular displacement, θ	Flux, ϕ
Dissipative element	Rotational frictional coefficient of dashpot, B	Conductance, G = 1/R
Storage element	Moment of inertia, J	Capacitance, C
	Stiffness of spring, K	Inverse of inductance, 1/L
Physical law	Newton's second law $\sum T = 0$	Kirchoff 's current law $\sum i = 0$
Changing the level of independent variable	Gear $\frac{T_1}{T_2} = \frac{n_1}{n_2}$	Transformer $\frac{i_1}{i_2} = \frac{N_2}{N_1}$

EXAMPLE 1.12

Write the differential equations governing the mechanical rotational system shown in fig 1. Draw the torque-voltage and torque-current electrical analogous circuits and verify by writing mesh and node equations.

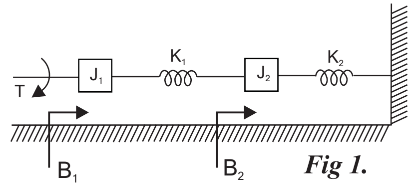


Fig 1.

SOLUTION

The given mechanical rotational system has two nodes (moment of inertia of masses). The differential equations governing the mechanical rotational system are given by torque balance equations at these nodes.

Let the angular displacements of J_1 and J_2 be θ_1 and θ_2 respectively. The corresponding angular velocities be ω_1 and ω_2.

The free body diagram of J_1 is shown in fig 2. The opposing torques are marked as T_{j1}, T_{b1} and T_{k1}.

$$T_{j1} = J_1 \frac{d^2\theta_1}{dt^2} \quad ; \quad T_{b1} = B_1 \frac{d\theta_1}{dt} \quad ; \quad T_{k1} = K_1(\theta_1 - \theta_2)$$

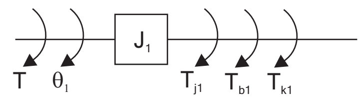


Fig 2.

By Newton's second law, $T_{j1} + T_{b1} + T_{k1} = T$

$$J_1 \frac{d^2\theta_1}{dt^2} + B_1 \frac{d\theta_1}{dt} + K_1(\theta_1 - \theta_2) = T \qquad .....(1)$$

The free body diagram of J_2 is shown in fig 3. The opposing torques are marked as T_{j2}, T_{b2}, T_{k2} and T_{k1}.

$$T_{j2} = J_2 \frac{d^2\theta_2}{dt^2} \quad ; \quad T_{b2} = B_2 \frac{d\theta_2}{dt}$$

$$T_{k2} = K_2\theta_2 \quad ; \quad T_{k1} = K_1(\theta_2 - \theta_1)$$

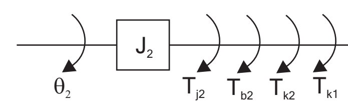


Fig 3.

By Newton's second law, $T_{j2} + T_{b2} + T_{k2} + T_{k1} = 0$

$$J_2 \frac{d^2\theta_2}{dt^2} + B_2 \frac{d\theta_2}{dt} + K_2\theta_2 + K_1(\theta_2 - \theta_1) = 0 \qquad .....(2)$$

On replacing the angular displacements by angular velocity in the differential equations (1) and (2) governing the mechanical rotational system we get,

$$\left(\text{i.e., } \frac{d^2\theta}{dt^2} = \frac{d\omega}{dt} \ ; \ \frac{d\theta}{dt} = \omega \ \text{ and } \ \theta = \int \omega\, dt \right)$$

$$J_1 \frac{d\omega_1}{dt} + B_1\omega_1 + K_1 \int (\omega_1 - \omega_2)\, dt = T \qquad .....(3)$$

$$J_2 \frac{d\omega_2}{dt} + B_2\omega_2 + K_2 \int \omega_2\, dt + K_1 \int (\omega_2 - \omega_1)\, dt = 0 \qquad .....(4)$$

TORQUE-VOLTAGE ANALOGOUS CIRCUIT

The given mechanical system has two nodes (J_1 and J_2). Hence the torque-voltage analogous electrical circuit will have two meshes. The torque applied to J_1 is represented by a voltage source in first mesh. The elements J_1, B_1 and K_1 are connected to first node. Hence they are represented by analogous element in mesh-1 forming a closed path. The elements J_2, B_2, K_2 and K_1 are connected to second node. Hence they are represented by analogous elements in mesh-2 forming a closed path.

The element K_1 is common between node-1 and 2 and so it is represented by analogous element as common element between two meshes. The torque-voltage electrical analogous circuit is shown in fig 4.

The electrical analogous elements for the elements of mechanical rotational system are given below.

$T \rightarrow e(t)$	$J_1 \rightarrow L_1$	$B_1 \rightarrow R_1$	$K_1 \rightarrow 1/C_1$
$\omega_1 \rightarrow i_1$	$J_2 \rightarrow L_2$	$B_2 \rightarrow R_2$	$K_2 \rightarrow 1/C_2$
$\omega_2 \rightarrow i_2$			

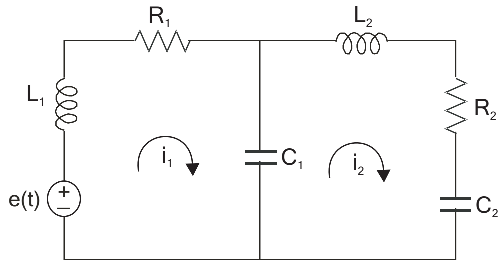


Fig 4 : *Torque-voltage electrical analogous circuit.*

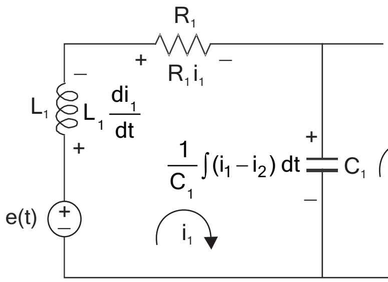


Fig 5 : *Mesh-1 of analogous circuit.*

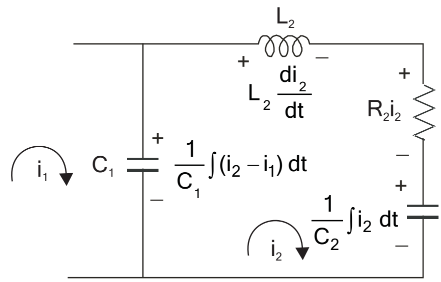


Fig 6 : *Mesh-2 of analogous circuit.***.**

The mesh basis equations using Kirchoff 's voltage law for the circuit shown in fig 4 are given below (Refer fig 5 and 6).

$$L_1 \frac{di_1}{dt} + R_1 i_1 + \frac{1}{C_1}\int (i_1 - i_2) = e(t) \qquad .....(5)$$

$$L_2 \frac{di_2}{dt} + R_2 i_2 + \frac{1}{C_2}\int i_2 dt + \frac{1}{C_2}\int (i_2 - i_1) dt = 0 \qquad .....(6)$$

It is observed that the mesh basis equations (5) and (6) are similar to the differential equations (3) and (4) governing the mechanical system.

TORQUE-CURRENT ANALOGOUS CIRCUIT

The given mechanical system has two nodes (J_1 and J_2). Hence the torque-current analogous electrical circuit will have two nodes. The torque applied to J_1 is represented as a current source connected to node-1 in analogous electrical circuit.

The elements J_1, B_1 and K_1 are connected to first node. Hence they are represented by analogous elements as elements connected to node-1 in analogous electrical circuit. The elements J_2, B_2, K_2 and K_1 are connected to second node. Hence they are represented by analogous elements as elements connected to node-2 in analogous electrical circuit.

The element K_1 is common between node-1 and 2. So it is represented by analogous element as common element between node-1 and 2. The torque-current electrical analogous circuit is shown in fig 7.

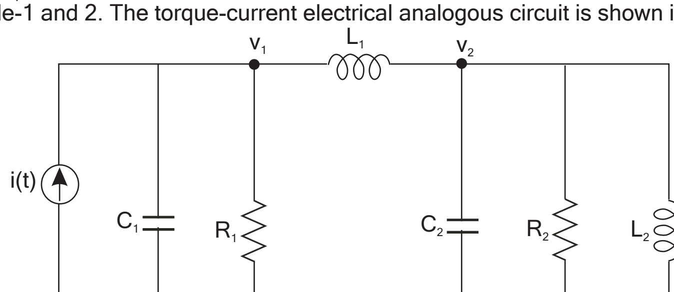


Fig 7 : *Torque-current electrical analogous circuit.*

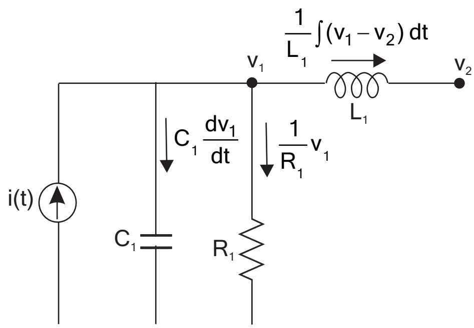


Fig 8 : Node-1 of analogous circuit.

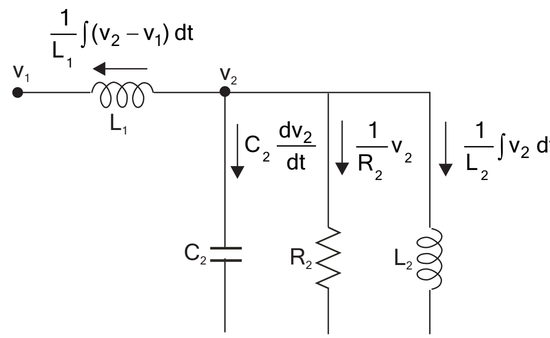


Fig 9 : Node-2 of analogous circuit.

The electrical analogous elements for the elements of mechanical rotational system are given below.

$T \rightarrow i(t)$	$B_1 \rightarrow 1/R_1$	$\omega_1 \rightarrow v_1$	$J_1 \rightarrow C_1$	$K_1 \rightarrow 1/L_1$
	$B_2 \rightarrow 1/R_2$	$\omega_2 \rightarrow v_2$	$J_2 \rightarrow C_2$	$K_2 \rightarrow 1/L_2$

The node basis equations using Kirchoff's current law for the circuit shown in fig 7 are given below (Refer fig 8 and 9).

$$C_1\frac{dv_1}{dt} + \frac{1}{R_1}v_1 + \frac{1}{L_1}\int (v_1 - v_2)\,dt = i(t) \quad .....(7)$$

$$C_1\frac{dv_2}{dt} + \frac{1}{R_2}v_2 + \frac{1}{L_2}\int v_2\,dt + \frac{1}{L_1}\int (v_2 - v_1)\,dt = 0 \quad .....(8)$$

It is observed that the mesh basis equations (5) and (6) are similar to the differential equations (3) and (4) governing the mechanical system.

EXAMPLE 1.13

Write the differential equations governing the mechanical rotational system shown in fig 1. Draw the torque-voltage and torque-current electrical analogous circuits and verify by writing mesh and node equations.

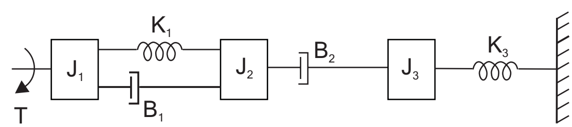


Fig 1.

SOLUTION

The given mechanical rotational system has three nodes (moment of inertia of masses). The differential equations governing the mechanical rotational system are given by torque balance equations at these nodes.

Let the angular displacements of J_1, J_2 and J_3 be θ_1, θ_2 and θ_3 respectively. The corresponding angular velocities be ω_1, ω_2 and ω_3.

The free body diagram of J_1 is shown in fig 2. The opposing torques are marked as T_{j1}, T_{b1} and T_{k1}.

$$T_{j1} = J_1\frac{d^2\theta_1}{dt^2} \quad ; \quad T_{b1} = B_1\frac{d(\theta_1 - \theta_2)}{dt}$$

$$T_{k1} = K_1(\theta_1 - \theta_2)$$

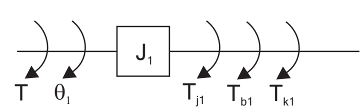


Fig 2.

By Newton's second law, $T_{j1} + T_{b1} + T_{k1} = T$

$$J_1\frac{d^2\theta_1}{dt^2} + B_1\frac{d(\theta_1 - \theta_2)}{dt} + K_1(\theta_1 - \theta_2) = T \quad .....(1)$$

The free body diagram of J_2 is shown in fig 3. The opposing torques are marked as T_{j2}, T_{b2}, T_{b1} and T_{k1}.

$$T_{j2} = J_2\frac{d^2\theta_2}{dt^2} \quad ; \quad T_{b2} = B_2\frac{d(\theta_2 - \theta_3)}{dt}$$

$$T_{k1} = K_1(\theta_2 - \theta_1) \quad ; \quad T_{b1} = B_1\frac{d(\theta_2 - \theta_1)}{dt}$$

By Newton's second law, $T_{j2} + T_{b2} + T_{b1} + T_{k1} = 0$

$$J_2\frac{d^2\theta_2}{dt^2} + B_2\frac{d(\theta_2 - \theta_3)}{dt} + B_1\frac{d(\theta_2 - \theta_1)}{dt} + K_1(\theta_2 - \theta_1) = 0 \qquad .....(2)$$

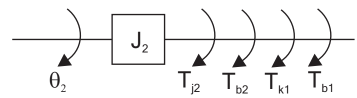


Fig 3.

The free body diagram of J_3 is shown in fig 4. The opposing torques are marked as T_{j3}, T_{b2}, and T_{k3}.

$$T_{j3} = J_3\frac{d^2\theta_3}{dt^2} \quad ; \quad T_{b2} = B_2\frac{d(\theta_3 - \theta_2)}{dt} \quad ; \quad T_{k3} = K_3\theta_3$$

By Newton's second law, $T_{j3} + T_{b2} + T_{k3} = 0$

$$\therefore\ J_3\frac{d^2\theta_3}{dt^2} + B_2\frac{d(\theta_3 - \theta_2)}{dt} + K_3\theta_3 = 0 \qquad .....(3)$$

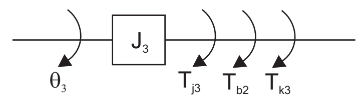


Fig 4.

On replacing the angular displacements by angular velocity in the differential equations (1) and (2) governing the mechanical rotational system we get,

$$\left(\text{i.e.,}\ \frac{d^2\theta}{dt^2} = \frac{d\omega}{dt} \quad ; \quad \frac{d\theta}{dt} = \omega \quad \text{and} \quad \theta = \int \omega\, dt\right)$$

$$J_1\frac{d\omega_1}{dt} + B_1(\omega_1 - \omega_2) + K_1\int(\omega_1 - \omega_2)\, dt = T \qquad .....(4)$$

$$J_2\frac{d\omega_2}{dt} + B_1(\omega_2 - \omega_1) + B_2(\omega_2 - \omega_3) + K_1\int(\omega_2 - \omega_1)\, dt = 0 \qquad .....(5)$$

$$J_3\frac{d\omega_3}{dt} + B_2(\omega_3 - \omega_2) + K_3\int \omega_3 dt = 0 \qquad .....(6)$$

TORQUE-VOLTAGE ANALOGOUS CIRCUIT

The given mechanical system has three nodes (J_1, J_2 and J_3). Hence the torque-voltage analogous electrical circuit will have three meshes. The torque applied to J_1 is represented by a voltage source in first mesh.

The elements J_1, K_1 and B_1 are connected to first node. Hence they are represented by analogous element in mesh-1 forming a closed path. The elements J_2, B_2, B_1 and K_1 are connected to second node. Hence they are represented by analogous element in mesh-2 forming a closed path. The element J_3, B_2 and K_3 are connected to third node. Hence they are represented by analogous element in mesh-3 forming a closed path.

The elements K_1 and B_1 are common between the nodes-1 and 2 and so they are represented by analogous element as common between mesh-1 and 2. The element B_2 is common between the nodes-2 and 3 and so it is represented by analogous element as common element between the mesh-2 and 3. The torque-voltage electrical analogous circuit is shown in fig 5.

The electrical analogous elements for the elements of mechanical rotational system are given below.

$T \rightarrow e(t)$	$\omega_1 \rightarrow i_1$	$J_1 \rightarrow L_1$	$B_1 \rightarrow R_1$	$K_1 \rightarrow 1/C_1$
	$\omega_2 \rightarrow i_2$	$J_2 \rightarrow L_2$	$B_2 \rightarrow R_2$	$K_3 \rightarrow 1/C_3$
	$\omega_3 \rightarrow i_3$	$J_3 \rightarrow L_3$		

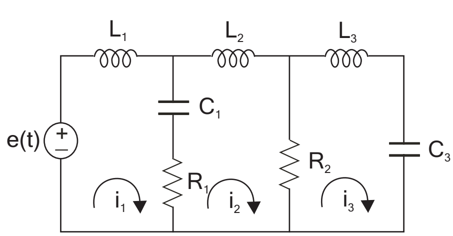


Fig 5 : *Torque-voltage electrical analogous circuit.*

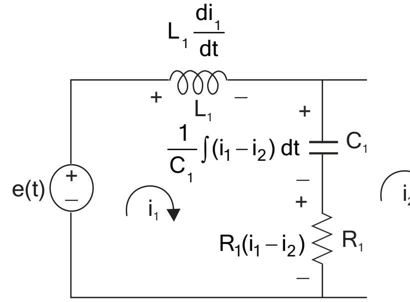


Fig 6 : *Mesh-1 of analogous circuit.*

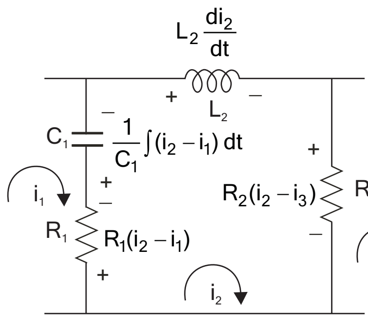


Fig 7 : Mesh-2 of analogous circuit.

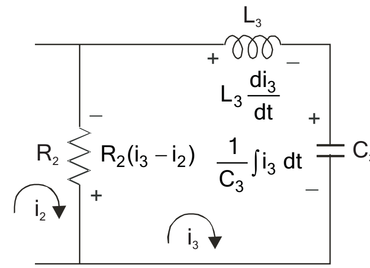


Fig 8 : Mesh-3 of analogous circuit.

The mesh basis equations using Kirchoff's voltage law for the circuit shown in fig 5 are given below (Refer fig 6, 7 and 8).

$$L_1 \frac{di_1}{dt} + R_1(i_1 - i_2) + \frac{1}{C_1}\int (i_1 - i_2)\,dt = e(t) \quad .....(7)$$

$$L_2 \frac{di_2}{dt} + R_1(i_2 - i_1) + R_2(i_2 - i_3) + \frac{1}{C_1}\int (i_2 - i_1)\,dt = 0 \quad .....(8)$$

$$L_3 \frac{di_3}{dt} + R_2(i_3 - i_2) + \frac{1}{C_3}\int i_3\,dt = 0 \quad .....(9)$$

It is observed that the mesh basis equations (7), (8) and (9) are similar to the differential equations (4), (5) and (6) governing the mechanical system.

TORQUE-CURRENT ANALOGOUS CIRCUIT

The given mechanical system has three nodes (J_1, J_2 and J_3). Hence the torque-current analogous electrical circuit will have three nodes. The torque applied to J_1 is represented as a current source connected to node-1 in analogous electrical circuit.

The elements K_1, J_1 and B_1 are connected to first node. Hence they are represented by analogous elements as elements connected to node-1 in analogous electrical circuit. The elements J_2, B_2, B_1 and K_1 are connected to second node. Hence they are represented by analogous elements as elements connected to node-2 in analogous electrical circuit. The elements J_3, B_2, and K_3 are connected to third node. Hence they are represented by analogous elements as elements connected to node-3 in analogous electrical circuit.

The elements K_1 and B_1 are common between node-1 and 2 and so they are represented by analogous element as common elements between node-1 and 2. The element B_2 is common between node-2 and 3 and so it is represented as common element between node-2 and 3 in analogous circuit. The torque-current electrical analogous circuit is shown in fig 9.

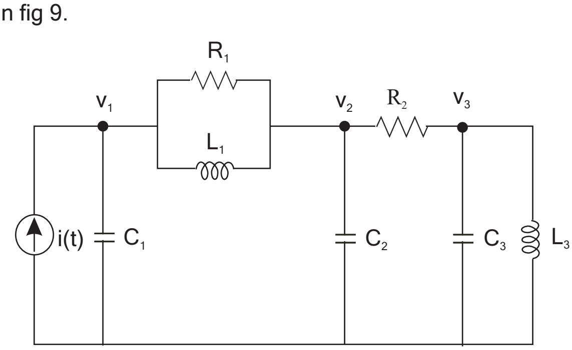


Fig 9 : Torque-current electrical analogous circuit.

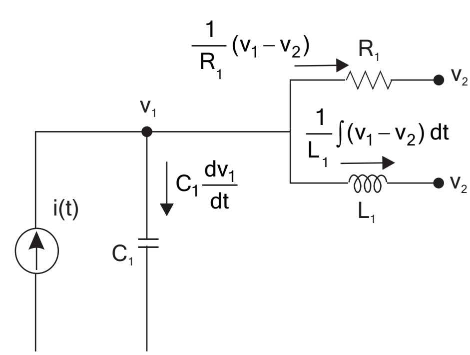


Fig 10 : Node-1 of analogous circuit.

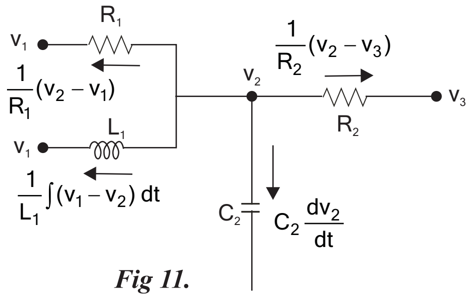


Fig 11.

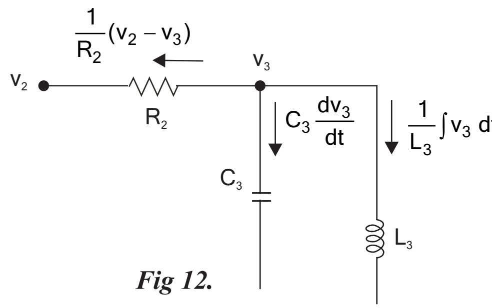


Fig 12.

The electrical analogous elements for the elements of mechanical rotational system are given below.

$T \rightarrow i(t)$	$\omega_1 \rightarrow v_1$	$J_1 \rightarrow C_1$	$B_1 \rightarrow 1/R_1$	$K_1 \rightarrow 1/L_1$
	$\omega_2 \rightarrow v_2$	$J_2 \rightarrow C_2$	$B_2 \rightarrow 1/R_2$	$K_3 \rightarrow 1/L_3$
	$\omega_3 \rightarrow v_3$	$J_3 \rightarrow C_3$		

The node basis equations using Kirchoff's current law for the circuit shown in fig 9 are given below (Refer fig 10, 11 and 12).

$$C_1\frac{dv_1}{dt}+\frac{1}{R_1}(v_1-v_2)+\frac{1}{L_1}\int(v_1-v_2)\,dt=i(t) \qquad .....(10)$$

$$C_2\frac{dv_2}{dt}+\frac{1}{R_1}(v_2-v_1)+\frac{1}{R_2}(v_2-v_3)+\frac{1}{L_1}\int(v_2-v_1)\,dt=0 \qquad .....(11)$$

$$C_3\frac{dv_3}{dt}+\frac{1}{R_2}(v_3-v_2)+\frac{1}{L_3}\int v_3\,dt=0 \qquad .....(12)$$

It is observed that the node basis equations (10), (11) and (12) are similar to the differential equations (4), (5) and (6) governing the mechanical system.

1.7 BLOCK DIAGRAM MODELS

A control system may consist of a number of components. In control engineering to show the functions performed by each component, we commonly use a diagram called the block diagram. A ***block diagram*** of a system is a pictorial representation of the functions performed by each component and of the flow of signals. Such a diagram depicts the interrelationships that exist among the various components. The elements of a block diagram are ***block***, ***branch point*** and ***summing point.***

BLOCK

In a block diagram all system variables are linked to each other through functional blocks. The ***functional block*** or simply ***block*** is a symbol for the mathematical operation on the input signal to the block that produces the output. The transfer functions of the components are usually entered in the corresponding blocks, which are connected by arrows to indicate the direction of the flow of signals. Figure 1.27 shows the block diagram of functional block.

The arrowhead pointing towards the block indicates the input, and the arrowhead leading away from the block represents the output. Such arrows are referred to as signals. The output signal from the block is given by the product of input signal and transfer function in the block.

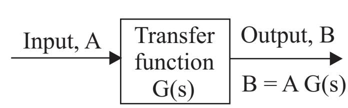


***Fig 1.27 :** Functional block.*

SUMMING POINT

Summing points are used to add two or more signals in the system. Referring to figure 1.28, a circle with a cross is the symbol that indicates a summing operation.

The plus or minus sign at each arrowhead indicates whether the signal is to be added or subtracted. It is important that the quantities being added or subtracted have the same dimensions and the same units.

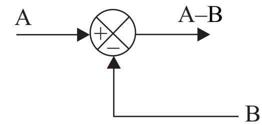


***Fig 1.28 :** Summing point.*

BRANCH POINT

A ***branch point*** is a point from which the signal from a block goes concurrently to other blocks or summing points.

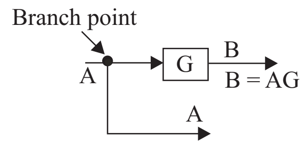


***Fig 1.29 :** Branch point.*

CONSTRUCTING BLOCK DIAGRAM FOR CONTROL SYSTEMS

A control system can be represented diagramatically by block diagram. The differential equations governing the system are used to construct the block diagram. By taking Laplace transform the differential equations are converted to algebraic equations. The equations will have variables and constants. From the working knowledge of the system the input and output variables are identified and the block diagram for each equation can be drawn. Each equation gives one section of block diagram. The output of one section will be input for another section. The various sections are interconnected to obtain the overall block diagram of the system.

EXAMPLE 1.14

Construct the block diagram of armature controlled dc motor.

SOLUTION

The differential equations governing the armature controlled dc motor are (refer section 1.7),

$$V_a = i_a R_a + L_a \frac{di_a}{dt} + e_b \qquad .....(1)$$

$$T = K_t i_a \qquad .....(2)$$

$$T = J\frac{d\omega}{dt} + B\omega \qquad .....(3)$$

$$e_b = K_b \omega \qquad .....(4)$$

$$\omega = \frac{d\theta}{dt} \qquad .....(5)$$

On taking Laplace transform of equation (1) we get,

$$V_a(s) = I_a(s)R_a + L_a s\, I_a(s) + E_b(s) \qquad .....(6)$$

In equation (6), $V_a(s)$ and $E_b(s)$ are inputs and $I_a(s)$ is the output. Hence the equation (6) is rearranged and the block diagram for this equation is shown in fig 1.

$$V_a(s) - E_b(s) = I_a(s)\,[R_a + s\,L_a]$$

$$\therefore\ I_a(s) = \frac{1}{R_a + s\,L_a}\,[V_a(s) - E_b(s)]$$

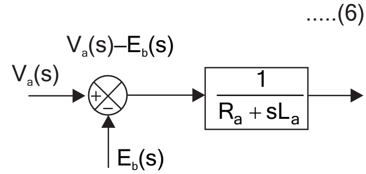


Fig 1.

On taking Laplace transform of equation (2) we get,

$$T(s) = K_t\, I_a(s) \qquad .....(7)$$

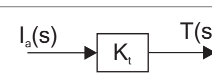


Fig 2.

In equation (7), $I_a(s)$ is the input and $T(s)$ is the output. The block diagram for this equation is shown in fig 2.

On taking Laplace transform of equation (3) we get,

$$T(s) = Js\,\omega(s) + B\,\omega(s) \qquad .....(8)$$

In equation (8), T(s) is the input and ω(s) is the output. Hence the equation (8) is rearranged and the block diagram for this equation is shown in fig (3).

$$T(s) = (Js + B)\,\omega(s)$$

$$\therefore\ \omega(s) = \frac{1}{Js + B}\,T(s)$$

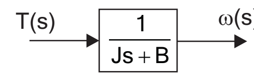


Fig 3.

On taking Laplace transform of equation (4) we get,

$$E_b(s) = K_b\,\omega(s) \qquad .....(9)$$

In equation (9), ω(s) is the input and $E_b(s)$ is the output. The block diagram for this equation is shown in fig 4.

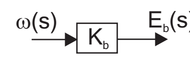


Fig 4.

On taking Laplace transform of equation (5) we get,

$$\omega(s) = s\,\theta(s) \qquad .....(10)$$

In equation (10), ω(s) is the input and θ(s) is the output. Hence equation (10) is rearranged and the block diagram for this equation is shown in fig 5.

$$\theta(s) = \frac{1}{s}\,\omega(s)$$

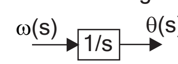


Fig 5.

The overall block diagram of armature controlled dc motor is obtained by connecting the various sections shown in fig 1 to fig 5. The overall block diagram is shown in fig 6.

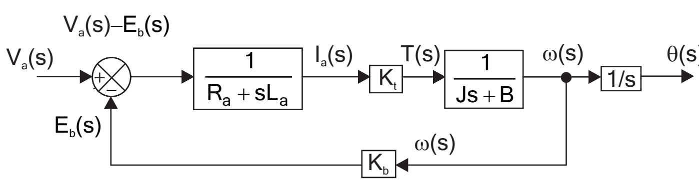


Fig 6 : *Block diagram of armature controlled dc motor.*

EXAMPLE 1.15

Construct the block diagram of field controlled dc motor.

SOLUTION

The differential equations governing the field controlled dc motor are (refer section 1.8),

$$v_t = R_f i_f + L_f \frac{di_f}{dt} \qquad .....(1)$$

$$T = K_{tf} i_f \qquad .....(2)$$

$$T = J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} \qquad .....(3)$$

On taking Laplace transform of equation (1) we get,

$$V_f(s) = R_f I_f(s) + L_f s\, I_f(s) \qquad .....(4)$$

In equation (4), $V_f(s)$ is the input and $I_f(s)$ is the output. Hence the equation (4) is rearranged and the block diagram for this equation is shown in fig 1.

$$V_f(s) = I_f(s)\,[R_f + sL_f]$$

$$\therefore\; I_f(s) = \frac{1}{R_f + sL_f}\, V_f(s)$$

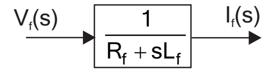


Fig 1.

On taking Laplace transform of equation (2) we get,

$$T(s) = K_{tf} I_f(s) \qquad .....(5)$$

In equation (5), $I_f(s)$ is the input and $T(s)$ is the output. The block diagram for this equation is shown in fig 2.

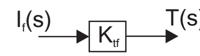


Fig 2.

On taking Laplace transform of equation (3) we get,

$$T(s) = J\,s^2\,\theta(s) + B\,s\,\theta(s) \qquad .....(6)$$

In equation (6), $T(s)$ is input and $\theta(s)$ is the output. Hence equation (6) is rearranged and the block diagram for this equation is shown in fig 3.

$$T(s) = (Js^2 + Bs)\,\theta(s)$$

$$\therefore\; \theta(s) = \frac{1}{Js^2 + Bs}\, T(s)$$

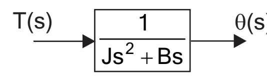


Fig 3.

The overall block diagram of field controlled dc motor is obtained by connecting the various section shown in fig 1 to fig 3. The overall block diagram is shown in fig 4.

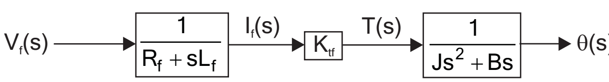


Fig 4 : *Block diagram of field controlled dc motor.*

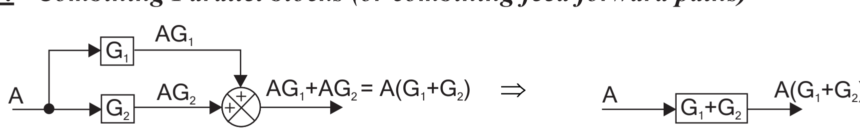
BLOCK DIAGRAM REDUCTION

The block diagram can be reduced to find the overall transfer function of the system. The following rules can be used for block diagram reduction. The rules are framed such that any modification made on the diagram does not alter the input-output relation.

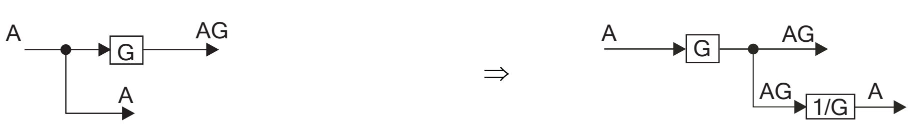
RULES OF BLOCK DIAGRAM ALGEBRA

Rule-1 : Combining the blocks in cascade

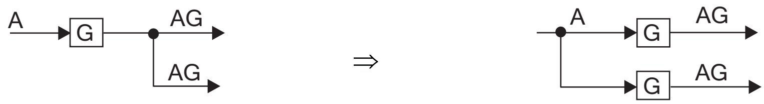
Rule-2 : Combining Parallel blocks (or combining feed forward paths)



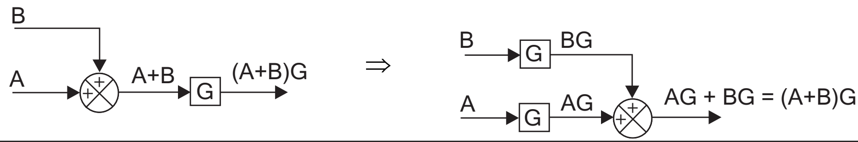
Rule-3 : Moving the branch point ahead of the block



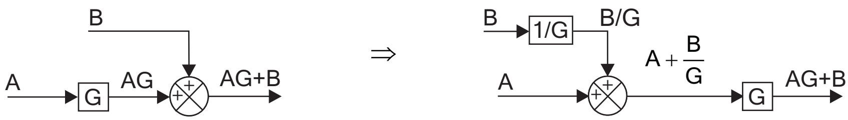
Rule-4 : ***Moving the branch point before the block***



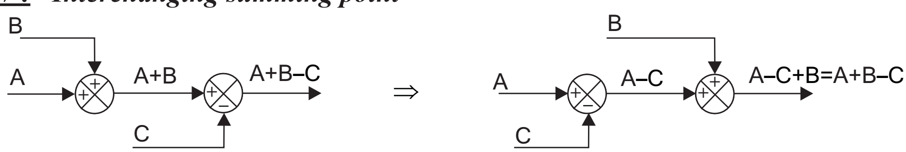
Rule-5 : ***Moving the summing point ahead of the block***



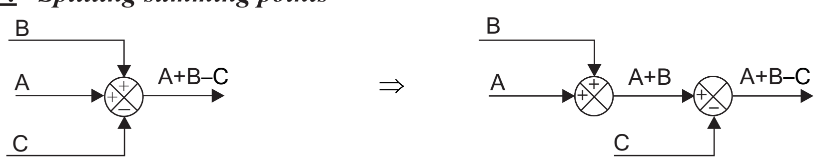
Rule-6 : ***Moving the summing point before the block***



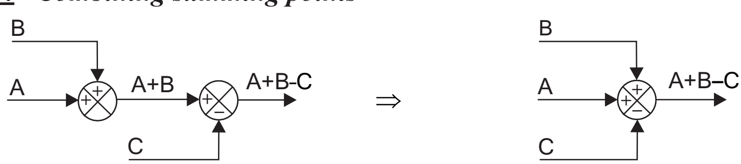
Rule-7 : ***Interchanging summing point***



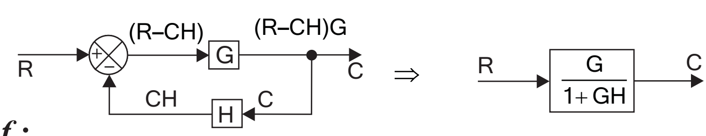
Rule-8 : ***Splitting summing points***



Rule-9 : ***Combining summing points***



Rule-10 : ***Elimination of (negative) feedback loop***

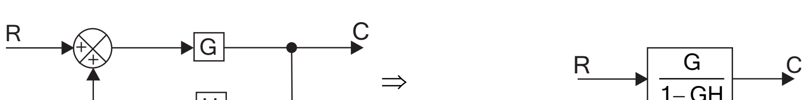


Proof :

$$C = (R - CH)G \quad \Rightarrow \quad C = RG - CHG \quad \Rightarrow \quad C + CHG = RG$$

$$\therefore C(1 + HG) = RG \quad \Rightarrow \quad \frac{C}{R} = \frac{G}{1 + GH}$$

Rule-11 : ***Elimination of (positive) feedback loop***



EXAMPLE 1.16

Reduce the block diagram shown in fig 1 and find C/R.

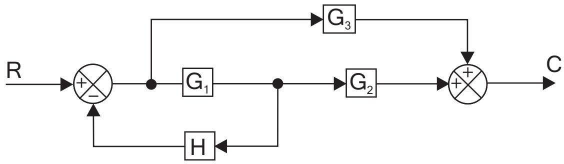
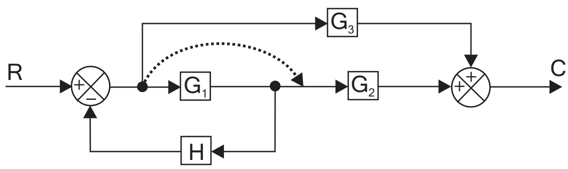


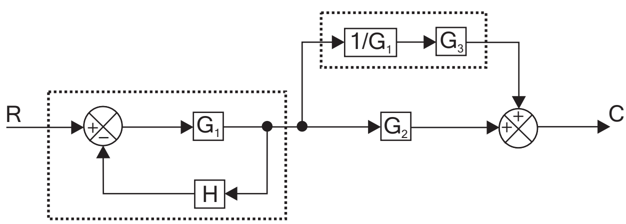
Fig 1.

SOLUTION

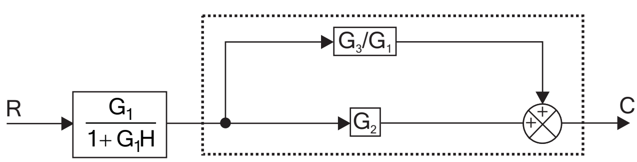
Step 1: Move the branch point after the block.



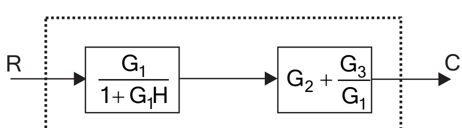
Step 2: Eliminate the feedback path and combining blocks in cascade.



Step 3: Combining parallel blocks



Step 4: Combining blocks in cascade



$$\frac{C}{R} = \left(\frac{G_1}{1+G_1H}\right)\left(G_2 + \frac{G_3}{G_1}\right) = \left(\frac{G_1}{1+G_1H}\right)\left(\frac{G_1G_2+G_3}{G_1}\right) = \frac{G_1G_2+G_3}{1+G_1H}$$

RESULT

The overall transfer function of the system, $\frac{C}{R} = \frac{G_1G_2+G_3}{1+G_1H}$

EXAMPLE 1.17

Using block diagram reduction technique find closed loop transfer function of the system whose block diagram is shown in fig 1.

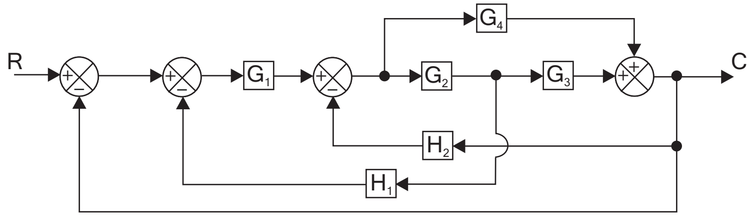
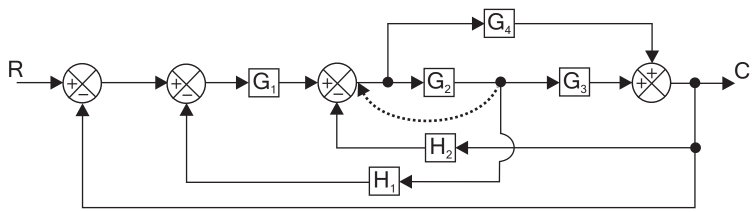


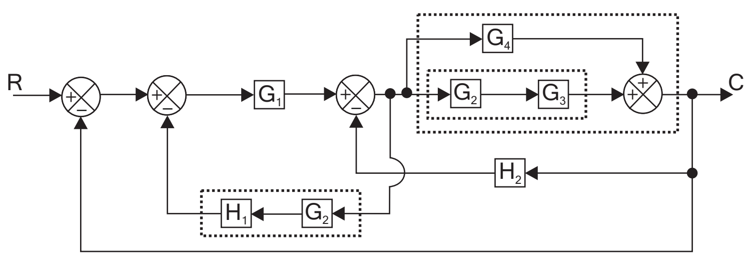
Fig 1.

SOLUTION

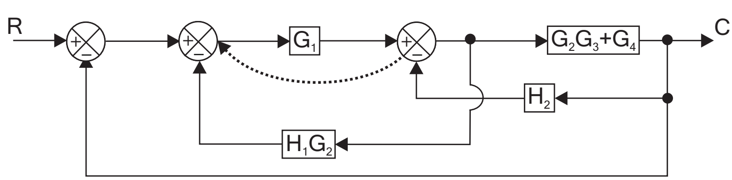
Step 1: Moving the branch point before the block



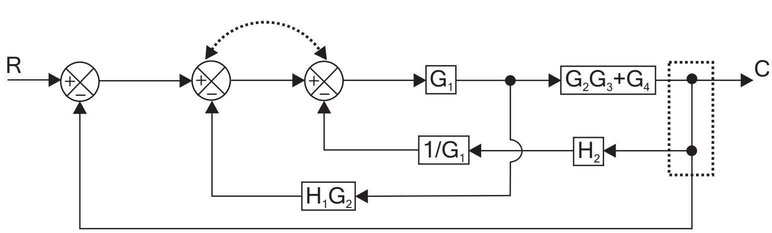
Step 2: Combining the blocks in cascade and eliminating parallel blocks



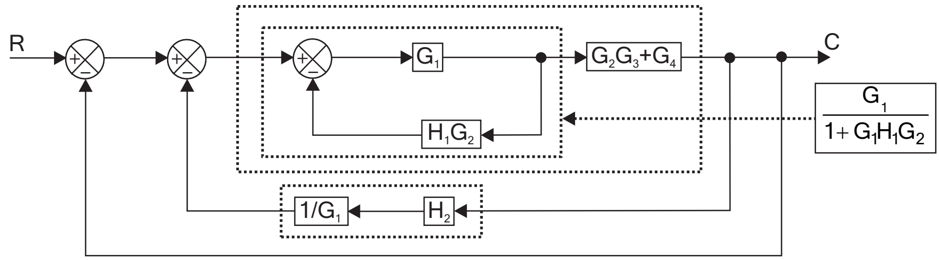
Step 3: Moving summing point before the block.



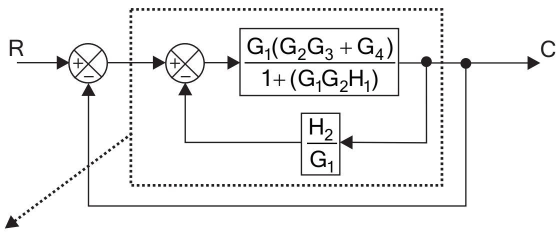
Step 4: Interchanging summing points and modifying branch points.



Step 5: Eliminating the feedback path and combining blocks in cascade

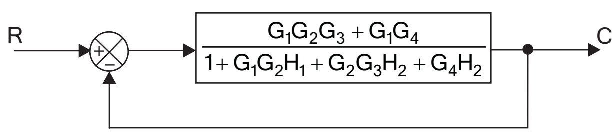


Step 6: Eliminating the feedback path



$$\frac{\dfrac{G_1(G_2G_3+G_4)}{1+G_1G_2H_1}}{1+\dfrac{G_1(G_2G_3+G_4)}{1+G_2G_3H_1}\,\dfrac{H_2}{G_1}} \Rightarrow \frac{\dfrac{G_1G_2G_3+G_1G_4}{1+G_1G_2H_1}}{\dfrac{1+G_1G_2H_1+G_2G_3H_2+G_4H_2}{1+G_1G_2H_1}} \Rightarrow \frac{G_1G_2G_3+G_1G_4}{1+G_1G_2H_1+G_2G_3H_2+G_4H_2}$$

Step 7: Eliminating the feedback path



$$\frac{C}{R}=\frac{\dfrac{G_1G_2G_3+G_1G_4}{1+G_1G_2H_1+G_2G_3H_2+G_4H_2}}{1+\dfrac{G_1G_2G_3+G_1G_4}{1+G_1G_2H_1+G_2G_3H_2+G_4H_2}}=\frac{G_1G_2G_3+G_1G_4}{1+G_1G_2H_1+G_2G_3H_2+G_4H_2+G_1G_2G_3+G_1G_4}$$

RESULT

The overall transfer function is given by,

$$\frac{C}{R}=\frac{G_1G_2G_3+G_1G_4}{1+G_1G_2H_1+G_2G_3H_2+G_4H_2+G_1G_2G_3+G_1G_4}$$

EXAMPLE 1.18

Determine the overall transfer function $\frac{C(s)}{R(s)}$ for the system shown in fig 1.

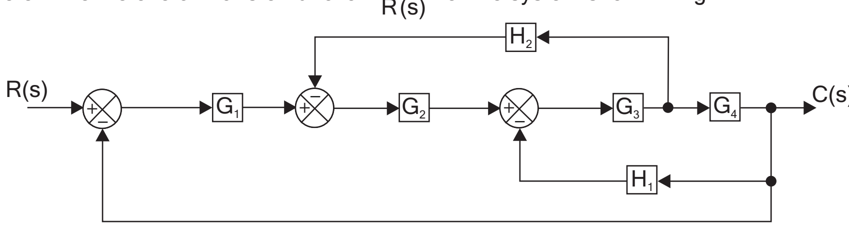
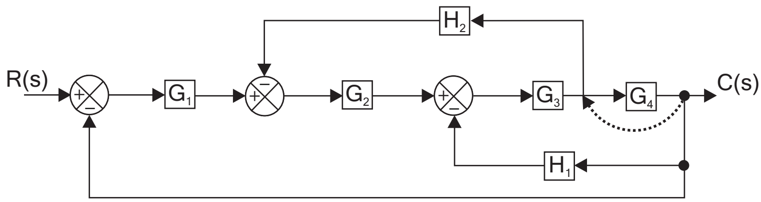


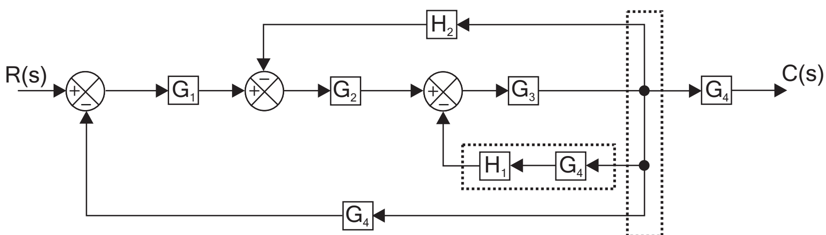
Fig 1.

SOLUTION

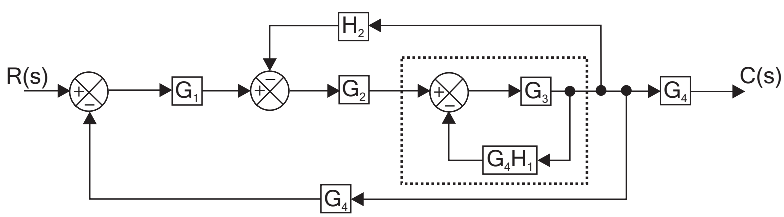
Step 1: Moving the branch point before the block



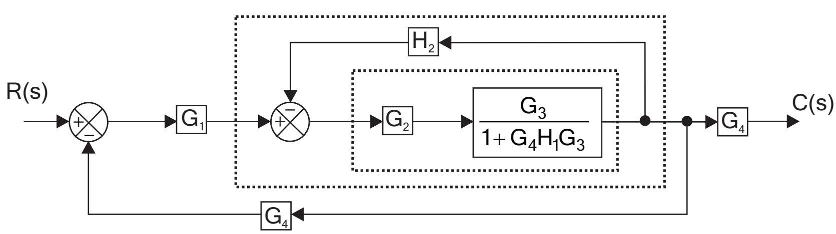
Step 2 : Combining the blocks in cascade and rearranging the branch points



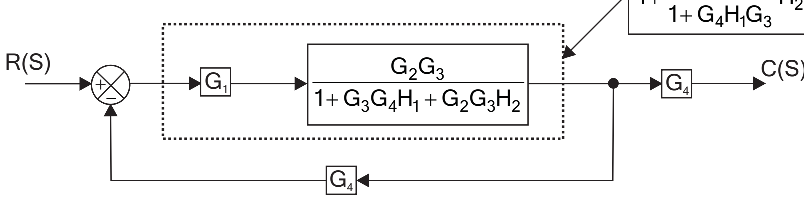
Step 3 : Eliminating the feedback path



Step 4 : Combining the blocks in cascade and eliminating feedback path

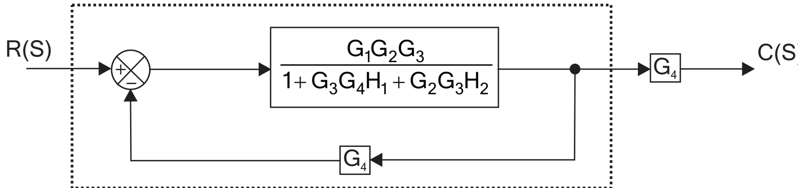


Step 5 : Combining the blocks in cascade

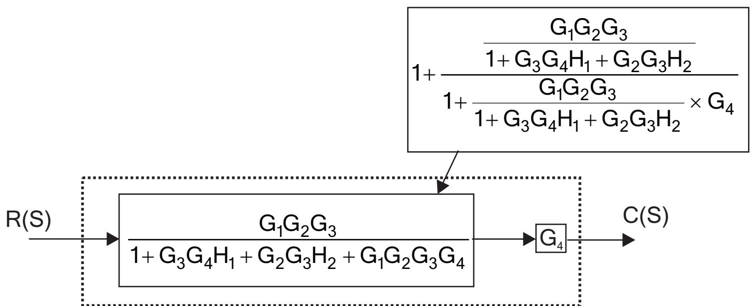


$$\frac{\dfrac{G_2G_3}{1+G_4H_1G_3}}{1+\dfrac{G_2G_3}{1+G_4H_1G_3}H_2}$$

Step 6 : Eliminating the feedback path



Step 7 : Combining the blocks in cascade



$$\frac{C(s)}{R(s)}=\frac{G_1G_2G_3G_4}{1+G_3G_4H_1+G_2G_3H_2+G_1G_2G_3G_4}$$

RESULT

The overall transfer function of the system is given by,

$$\frac{C(s)}{R(s)}=\frac{G_1G_2G_3G_4}{1+G_3G_4H_1+G_2G_3H_2+G_1G_2G_3G_4}$$

EXAMPLE 1.19

For the system represented by the block diagram shown in fig 1. Evaluate the closed loop transfer function when the input R is (i) at station-I (ii) at station-II.

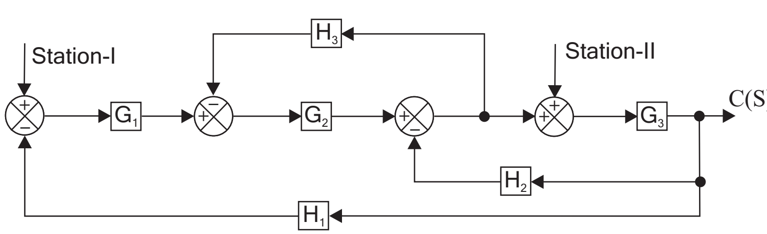


Fig 1.

SOLUTION

(i) Consider the input R is at station-I and so the input at station-II is made zero. Let the output be C_1. Since there is no input at station-II that summing point can be removed and resulting block diagram is shown in fig 2.

Step 1 : Shift the take off point of feedback H_3 beyond G_3 and rearrange the branch points

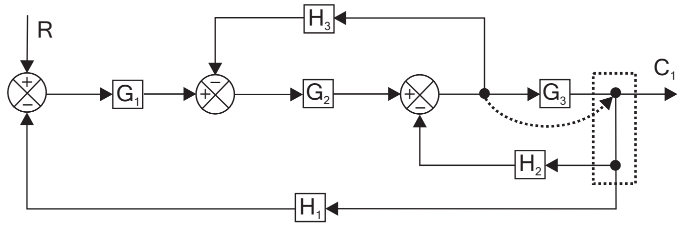
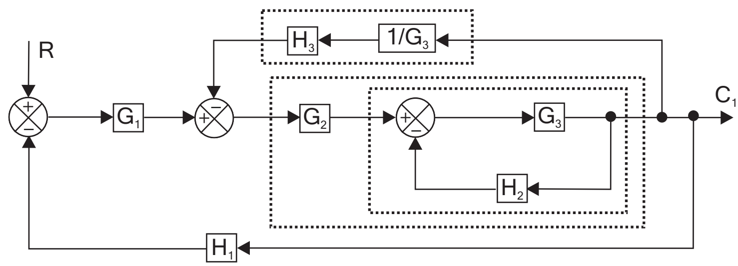
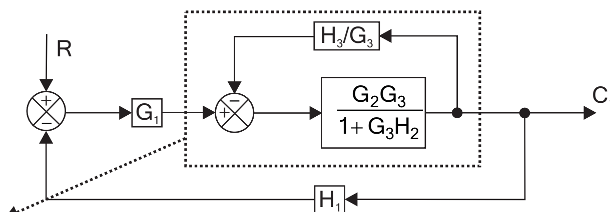


Fig 2.

Step 2 : Eliminating the feedback H_2 and combining blocks in cascade

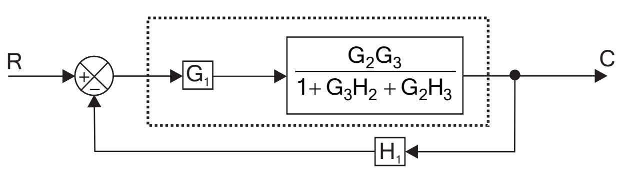


Step 3: Eliminating the feedback path

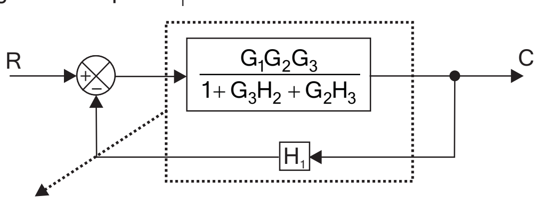


$$\frac{\frac{G_2G_3}{1+G_3H_2}}{1+\frac{G_2G_3}{1+G_3H_2}\times\frac{H_3}{G_3}} = \frac{\frac{G_2G_3}{1+G_3H_2}}{1+\frac{G_2H_3}{1+G_3H_2}} = \frac{G_2G_3}{1+G_3H_2+G_2H_3}$$

Step 4: Combining the blocks in cascade



Step 5: Eliminating feedback path H_1



$$\frac{\frac{G_1G_2G_3}{1+G_3H_2+G_2H_3}}{1+\frac{G_1G_2G_3}{1+G_3H_2+G_2H_3}\times H_1} = \frac{G_1G_2G_3}{1+G_3H_2+G_2H_3+G_1G_2G_3H_1}$$

$$\therefore \frac{C_1(s)}{R(s)} = \frac{G_1G_2G_3}{1+G_3H_2+G_2H_3+G_1G_2G_3H_1}$$

(ii) Consider the input R at station-II, the input at station-I is made zero. Let output be C_2. Since there is no input in station-I that corresponding summing point can be removed and a negative sign can be attached to the feedback path gain H_1. The resulting block diagram is shown in fig 3.

Step 1: Combining the blocks in cascade, shifting the summing point of H_2 before G_2 and rearranging the branch points.

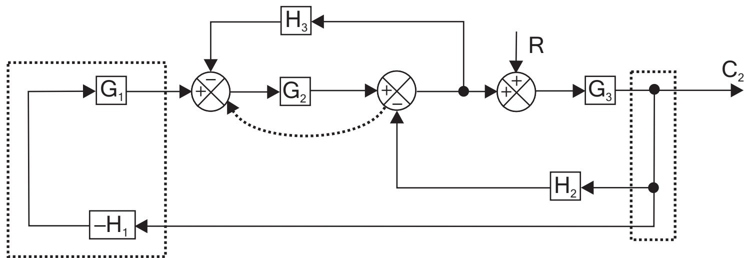
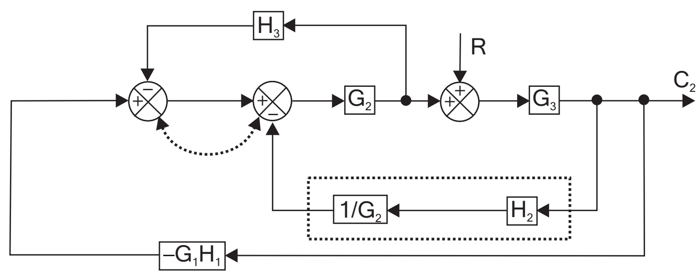
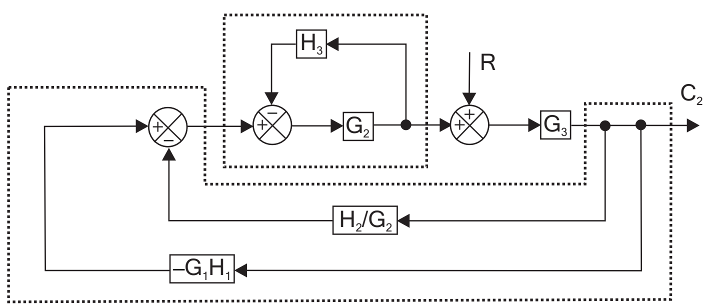


Fig 3.

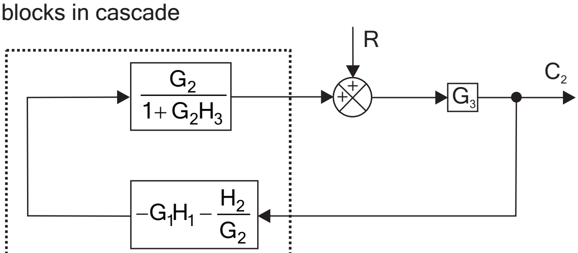
Step 2: Interchanging summing points and combining the blocks in cascade.



Step 3: Combining parallel blocks and eliminating feedback path

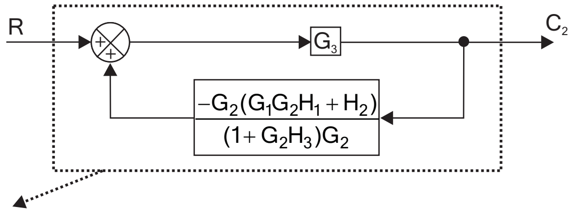


Step 4: Combining the blocks in cascade



$$\left(\frac{G_2}{1+G_2H_3}\right)\times\left(-G_1H_1-\frac{H_2}{G_2}\right)=\left(\frac{G_2}{1+G_2H_3}\right)\times\left(\frac{-G_1H_1G_2-H_2}{G_2}\right)=\frac{-G_2(G_1G_2H_1+H_2)}{(1+G_2H_3)G_2}$$

Step 5: Eliminating the feedback path



$$\frac{G_3}{1-\left(\frac{-(G_1G_2H_1+H_2)}{1+G_2H_3}\right)G_3} = \frac{G_3}{\frac{1+G_2H_3+G_3(G_1G_2H_1+H_2)}{1+G_2H_3}} = \frac{G_3(1+G_2H_3)}{1+G_2H_3+G_3(G_1G_2H_1+H_2)}$$

$$\therefore \frac{C_2}{R} = \frac{G_3(1+G_2H_3)}{1+G_2H_3+G_3(G_1G_2H_1+H_2)}$$

RESULT

The transfer function of the system with input at station-I is,

$$\frac{C_1}{R} = \frac{G_1G_2G_3}{1+G_3H_2+G_2H_3+G_1G_2G_3H_1}$$

The transfer function of the system with input at station-II is,

$$\frac{C_2}{R} = \frac{G_3(1+G_2H_3)}{1+G_2H_3+G_3(G_1G_2H_1+H_2)}$$

EXAMPLE 1.20

For the system represented by the block diagram shown in the fig 1, determine C_1/R_1 and C_2/R_1.

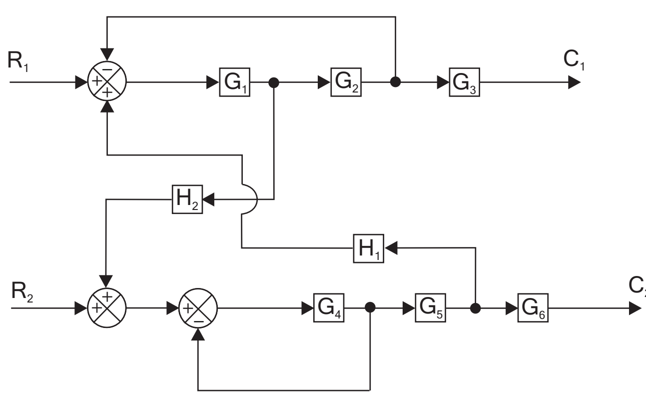


Fig 1

SOLUTION

Case (i) To find $\frac{C_1}{R_1}$

In this case set R_2 = 0 and consider only one output C_1. Hence we can remove the summing point which adds R_2 and need not consider G_6, since G_6 is on the open path. The resulting block diagram is shown in fig 2.

Step 1: Eliminating the feedback path

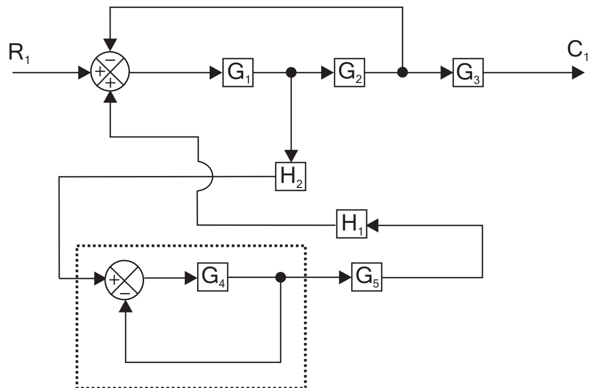
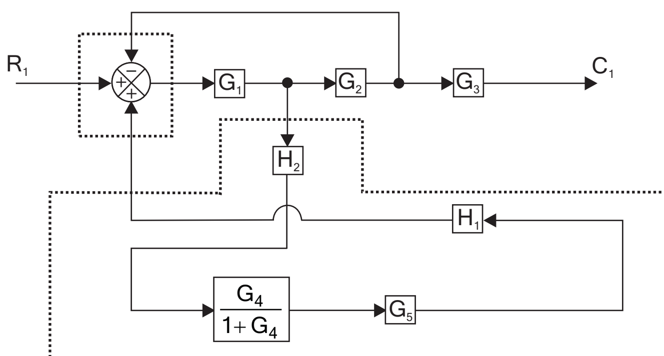
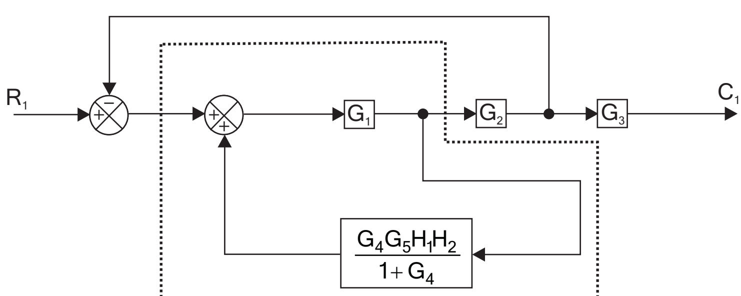


Fig 2.

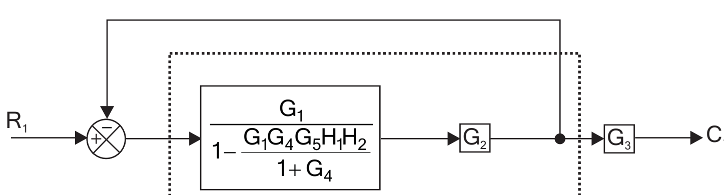
Step 2: Combining the blocks in cascade and splitting the summing point



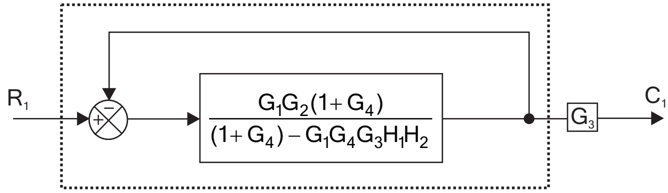
Step 3: Eliminating the feedback path

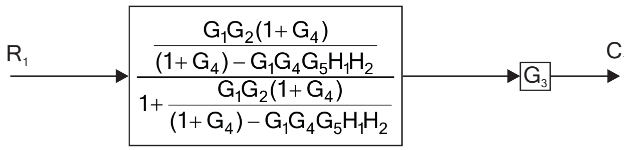


Step 4: Combining the blocks in cascade

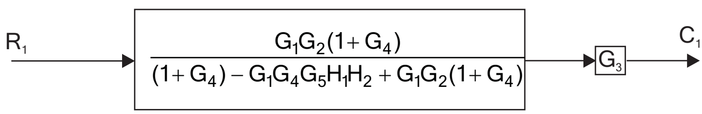


Step 5 : Eliminating the feedback path





Step 6: Combining the blocks in cascade



$$\frac{C_1}{R_1} = \frac{G_1G_2G_3(1+G_4)}{(1+G_1G_2)(1+G_4) - G_1G_4G_5H_1H_2}$$

Case 2 : To find $\frac{C_2}{R_1}$

In this case set $R_2 = 0$ and consider only one output C_2. Hence we can remove the summing point which adds R_2 and need not consider G_3, since G_3 is on the open path. The resulting block diagram is shown in fig 3.

Step 1: Eliminate the feedback path.

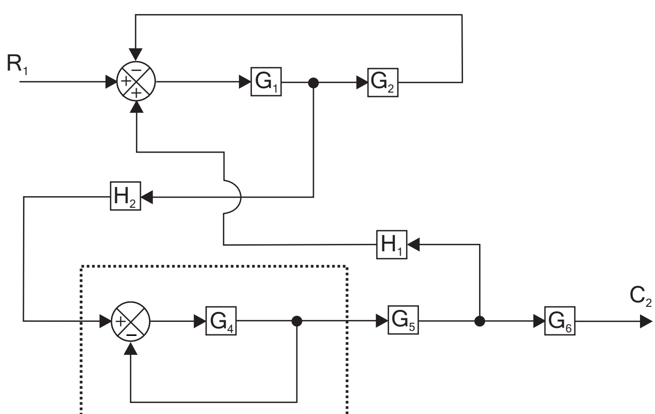
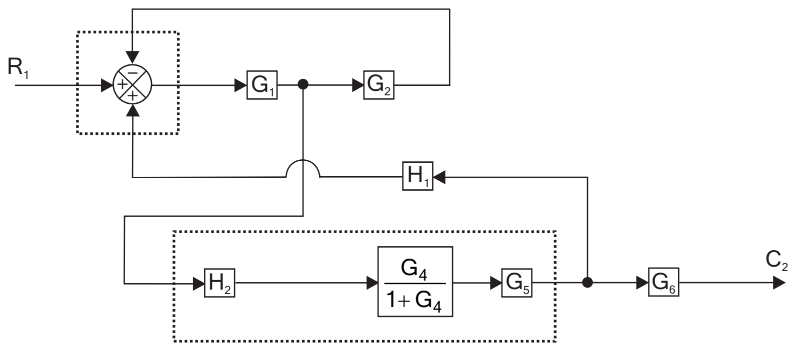
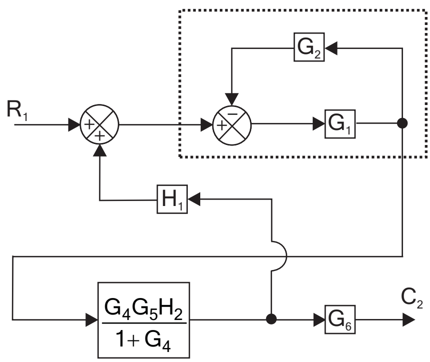


Fig 3.

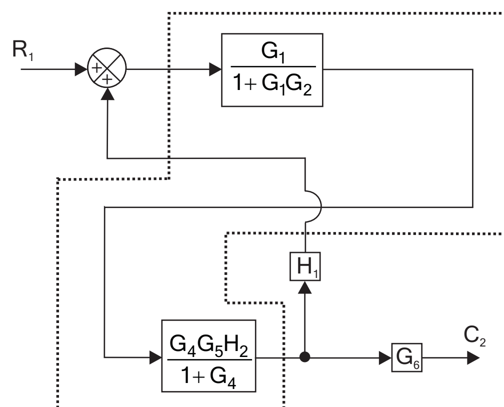
Step 2: Combining blocks in cascade and splitting the summing point



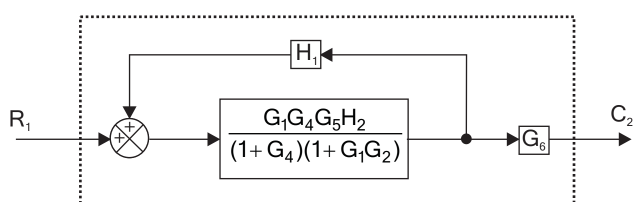
Step 3: Eliminating the feedback path

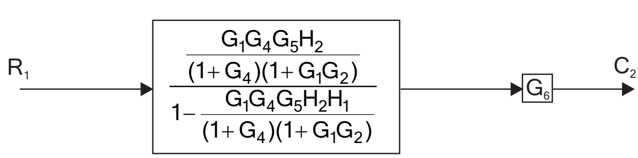


Step 4 : Combining the blocks in cascade

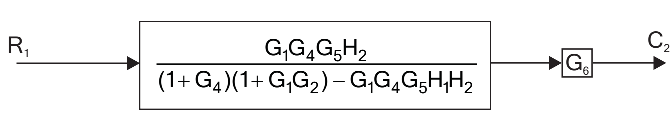


Step 5: Eliminating the feedback path





Step 6: Combining the blocks in cascade



$$\frac{C_2}{R_1} = \frac{G_1G_4G_5G_6H_2}{(1+G_4)(1+G_1G_2) - G_1G_4G_5H_1H_2}$$

RESULT

The transfer function of the system when the input and output are R_1 and C_1 is given by,

$$\frac{C_1}{R_1} = \frac{G_1G_2G_3(1+G_4)}{(1+G_1G_2)(1+G_4) - G_1G_4G_5H_1H_2}$$

The transfer function of the system when the input and output are R_1 and C_2 is given by,

$$\frac{C_2}{R_1} = \frac{G_1G_4G_5G_6H_2}{(1+G_4)(1+G_1G_2) - G_1G_4G_5H_1H_2}$$

EXAMPLE 1.21

Obtain the closed loop transfer function C(s)/R(s) of the system whose block diagram is shown in fig 1.

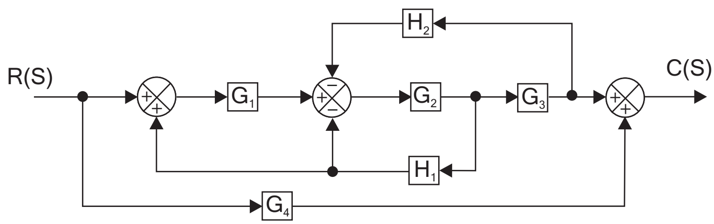
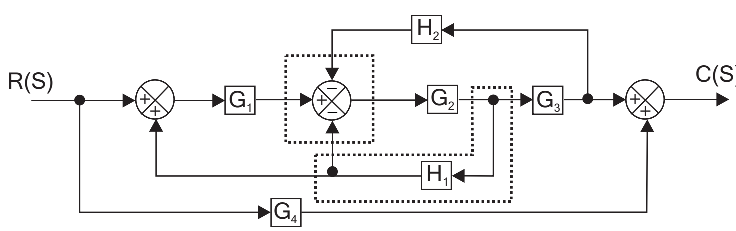


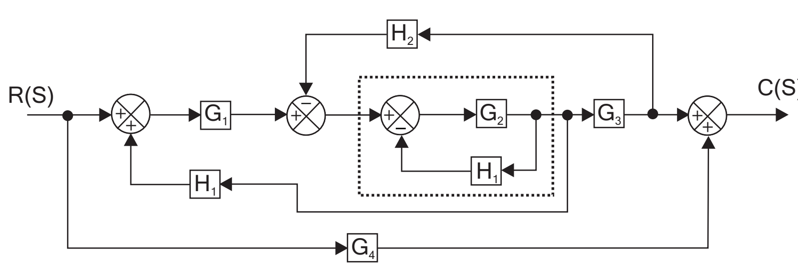
Fig 1.

SOLUTION

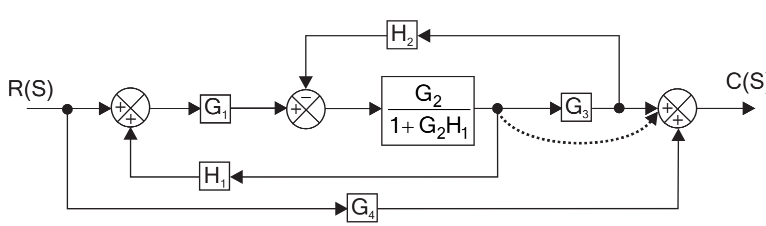
Step 1 : Splitting the summing point and rearranging the branch points



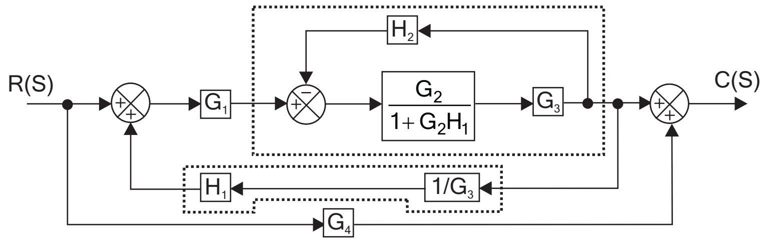
Step 2 : Eliminating the feedback path



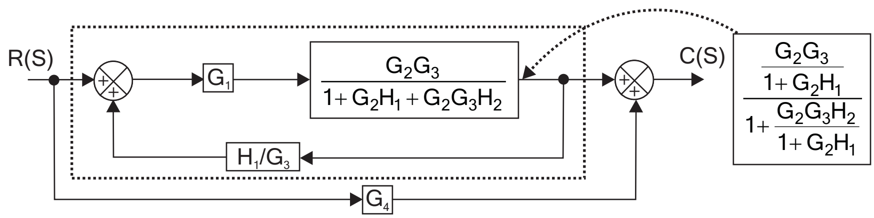
Step 3 : Shifting the branch point after the block.



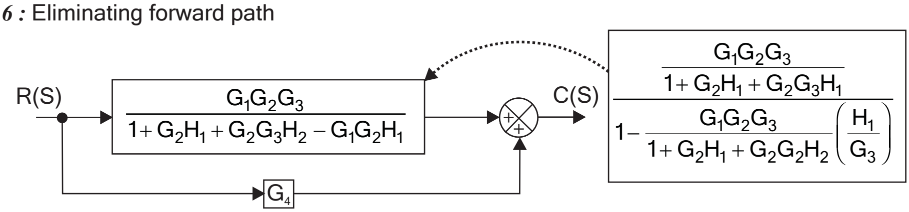
Step 4 : Combining the blocks in cascade and eliminating feedback path



Step 5 : Combining the blocks in cascade and eliminating feedback path



Step 6 : Eliminating forward path



$$\therefore \ \frac{C(s)}{R(s)} = \frac{G_1G_2G_3}{1+G_2H_1+G_2G_3H_2-G_1G_2H_1} + G_4$$

RESULT

The transfer function of the system is $\frac{C(s)}{R(s)} = \frac{G_1G_2G_3}{1+G_2H_1+G_2G_3H_2-G_1G_2H_1} + G_4$

EXAMPLE 1.22

The block diagram of a closed loop system is shown in fig 1. Using the block diagram reduction technique determine the closed loop transfer function C(s)/R(s).

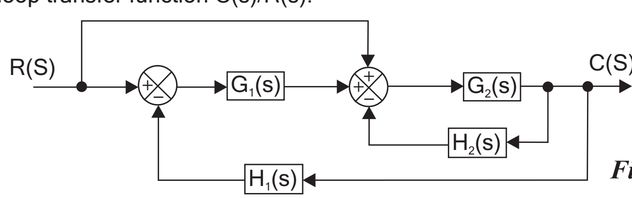
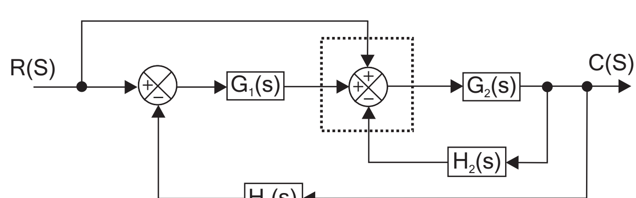


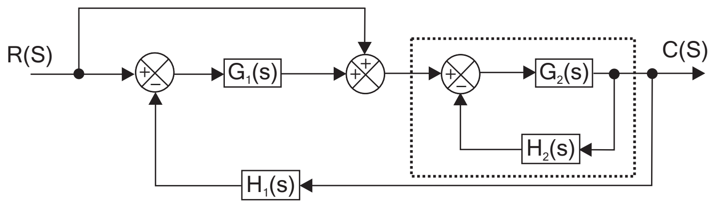
Fig 1.

SOLUTION

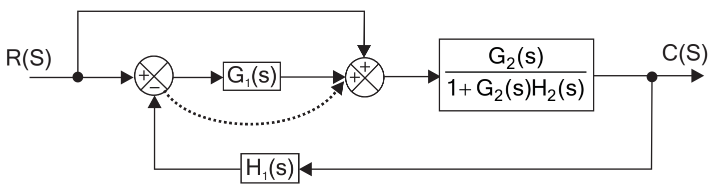
Step 1 : Splitting the summing point.



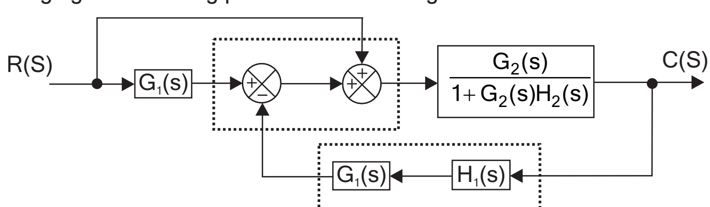
Step 2 : Eliminating the feedback path.



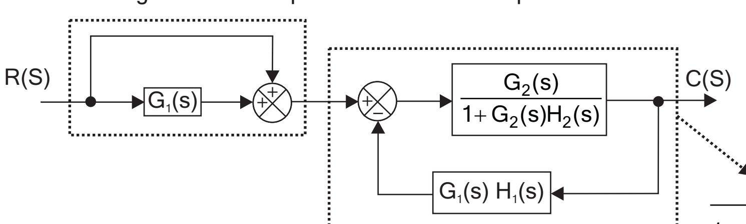
Step 3 : Moving the summing point after the block.



Step 4 : Interchanging the summing points and combining the blocks in cascade

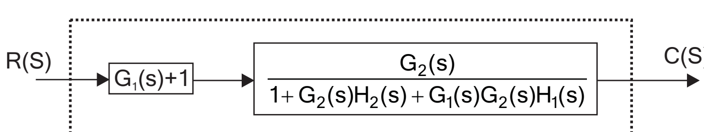


Step 5 : Eliminating the feedback path and feed forward path



$$\frac{\dfrac{G_2(s)}{1+G_2(s)H_2(s)}}{1+\dfrac{G_2(s)}{1+G_2(s)H_2(s)}G_1(s)H_1(s)}$$

Step 6 : Combining the blocks in cascade



$$\therefore \frac{C(s)}{R(s)} = \frac{G_2(s)\,[G_1(s)+1]}{1+G_2(s)\,H_2(s)+G_1(s)\,G_2(s)\,H_1(s)}$$

RESULT

The transfer function of the system is,

$$\frac{C(s)}{R(s)} = \frac{G_2(s)\,[G_1(s)+1]}{1+G_2(s)\,H_2(s)+G_1(s)\,G_2(s)\,H_1(s)}$$

EXAMPLE 1.23

Using block diagram reduction technique find the transfer function C(s)/R(s) for the system shown in fig 1.

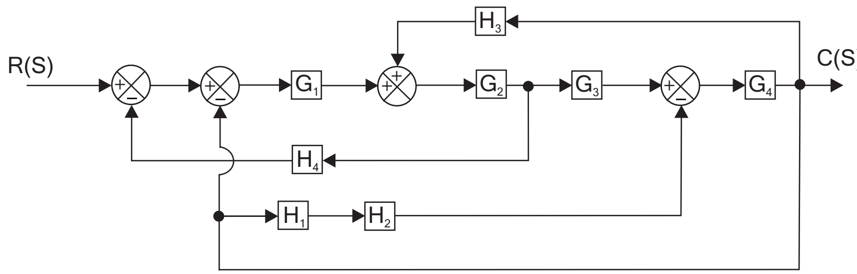
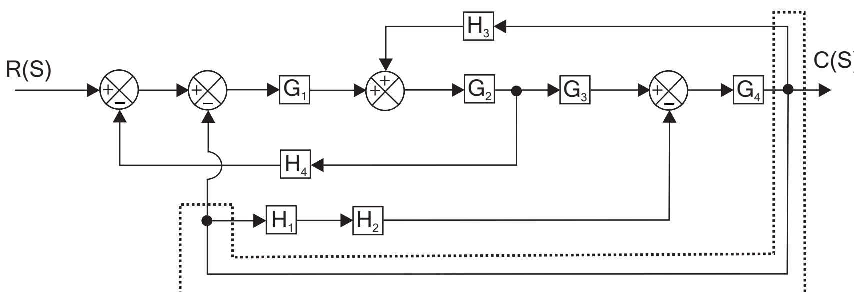


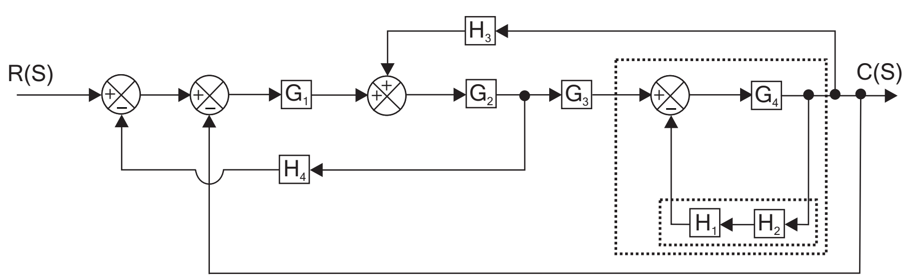
Fig 1.

SOLUTION

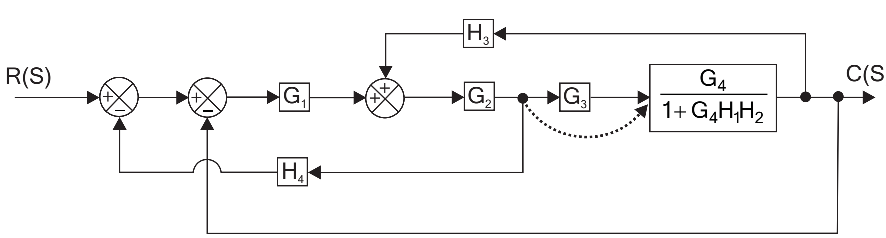
Step 1 : Rearranging the branch points



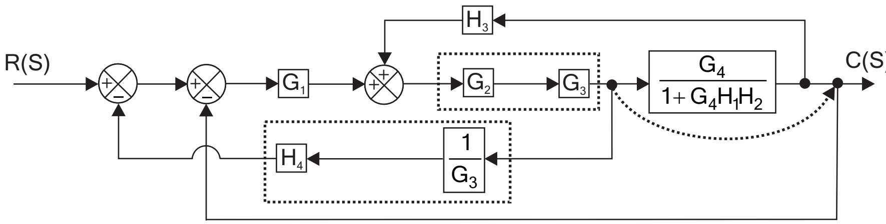
Step 2 : Combining the blocks in cascade and eliminating the feedback path.



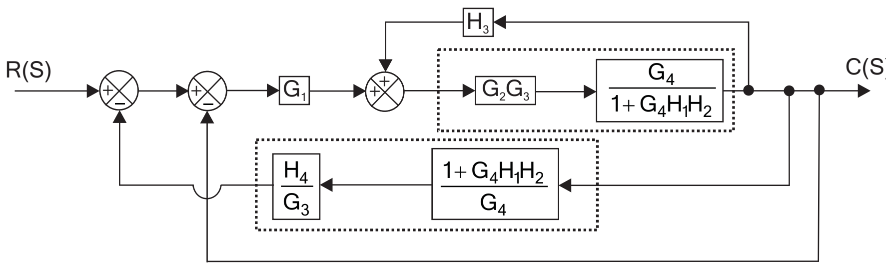
Step 3 : Moving the branch point after the block.



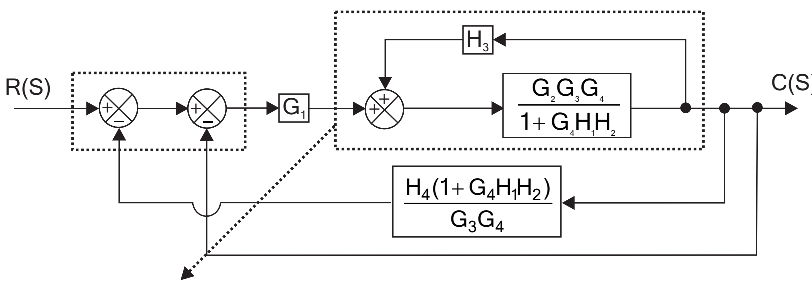
Step 4 : Moving the branch point and combining the blocks in cascade.



Step 5 : Combining the blocks in cascade

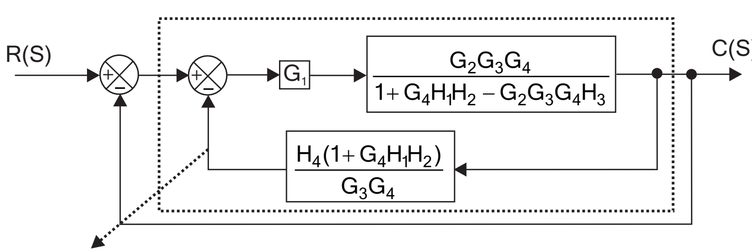


Step 6 : Eliminating feedback path and interchanging the summing points.



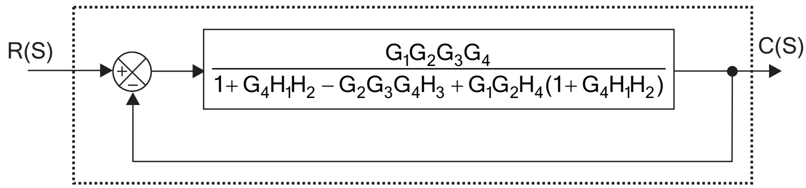
$$\frac{\dfrac{G_2G_3G_4}{1+G_4H_1H_2}}{1-\dfrac{G_2G_3G_4H_3}{1+G_4H_1H_2}} = \frac{G_2G_3G_4}{1+G_4H_1H_2-G_2G_3G_4H_3}$$

Step 7 : Combining the blocks in cascade and eliminating the feedback path



$$\frac{\dfrac{G_1G_2G_3G_4}{1+G_4H_1H_2-G_2G_3G_4H_3}}{1+\left(\dfrac{G_1G_2G_3G_4}{1+G_4H_1H_2-G_2G_3G_4H_3}\right)\left(\dfrac{H_4(1+G_4H_1H_2}{G_3G_4}\right)} = \frac{G_1G_2G_3G_4}{1+G_4H_1H_2-G_2G_3G_4H_3+G_1G_2H_4(1+G_4H_1H_2)}$$

Step 8 : Eliminating the unity feedback path.



$$\therefore \frac{C(s)}{R(s)} = \frac{\dfrac{G_1G_2G_3G_4}{1+G_4H_1H_2-G_2G_3G_4H_3+G_1G_2H_4(1+G_4H_1H_2)}}{1+\dfrac{G_1G_2G_3G_4}{1+G_4H_1H_2-G_2G_3G_4H_3+G_1G_2H_4(1+G_4H_1H_2)}}$$

$$= \frac{G_1G_2G_3G_4}{1+G_4H_1H_2-G_2G_3G_4H_3+G_1G_2H_4(1+G_4H_1H_2)+G_1G_2G_3G_4}$$

$$= \frac{G_1G_2G_3G_4}{1+H_1H_2(G_4+G_1G_2G_4H_4)+G_1G_2(H_4+G_3G_4)-G_2G_3G_4H_3}$$

RESULT

The transfer function of the system is,

$$\frac{C(s)}{R(s)} = \frac{G_1G_2G_3G_4}{1+H_1H_2(G_4+G_1G_2G_4H_4)+G_1G_2(H_4+G_3G_4)-G_2G_3G_4H_3}$$

1.8 SIGNAL FLOW GRAPH MODELS

The signal flow graph is used to represent the control system graphically and it was developed by **S.J. Mason.**

A signal flow graph is a diagram that represents a set of simultaneous linear algebraic equations. By taking Laplace transform, the time domain differential equations governing a control system can be transferred to a set of algebraic equations in s-domain. The signal flow graph of the system can be constructed using these equations.

It should be noted that the signal flow graph approach and the block diagram approach yield the same information. The advantage in signal flow graph method is that, using Mason's gain formula the overall gain of the system can be computed easily. This method is simpler than the tedious block diagram reduction techniques.

The signal flow graph depicts the flow of signals from one point of a system to another and gives the relationships among the signals. A signal flow graph consists of a network in which nodes are connected by directed branches. Each node represents a system variable and each branch connected between two nodes acts as a signal multiplier. Each branch has a gain or transmittance. When the signal pass through a branch, it gets multiplied by the gain of the branch.

In a signal flow graph, the signal flows in only one direction. The direction of signal flow is indicated by an arrow placed on the branch and the gain (multiplication factor) is indicated along the branch.

EXPLANATION OF TERMS USED IN SIGNAL FLOW GRAPH

Node : A node is a point representing a variable or signal.

Branch : A branch is directed line segment joining two nodes. The arrow on the branch indicates the direction of signal flow and the gain of a branch is the transmittance.

Transmittance : The gain acquired by the signal when it travels from one node to another is called transmittance. The transmittance can be real or complex.

Input node (Source) : It is a node that has only outgoing branches.

Output node (Sink) : It is a node that has only incoming branches.

Mixed node : It is a node that has both incoming and outgoing branches.

Path : A path is a traversal of connected branches in the direction of the branch arrows. The path should not cross a node more than once.

Open path : A open path starts at a node and ends at another node.

Closed path : Closed path starts and ends at same node.

Forward path : It is a path from an input node to an output node that does not cross any node more than once.

***Forward path* gain** : It is the product of the branch transmittances (gains) of a forward path.

Individual loop : It is a closed path starting from a node and after passing through a certain part of a graph arrives at same node without crossing any node more than once.

Loop gain : It is the product of the branch transmittances (gains) of a loop.

Non-touching Loops : If the loops does not have a common node then they are said to be non- touching loops.

PROPERTIES OF SIGNAL FLOW GRAPH

The basic properties of signal flow graph are the following :

(i) The algebraic equations which are used to construct signal flow graph must be in the form of cause and effect relationship.

(ii) Signal flow graph is applicable to linear systems only.

(iii) A node in the signal flow graph represents the variable or signal.

(iv) A node adds the signals of all incoming branches and transmits the sum to all outgoing branches.

(v) A mixed node which has both incoming and outgoing signals can be treated as an output node by adding an outgoing branch of unity transmittance.

(vi) A branch indicates functional dependence of one signal on the other.

(vii) The signals travel along branches only in the marked direction and when it travels it gets multiplied by the gain or transmittance of the branch.

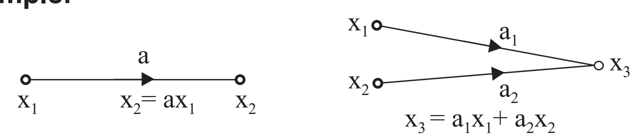
(viii) The signal flow graph of system is not unique. By rearranging the system equations different types of signal flow graphs can be drawn for a given system.

SIGNAL FLOW GRAPH ALGEBRA

Signal flow graph for a system can be reduced to obtain the transfer function of the system using the following rules. The guideline in developing the rules for signal flow graph algebra is that the signal at a node is given by sum of all incoming signals.

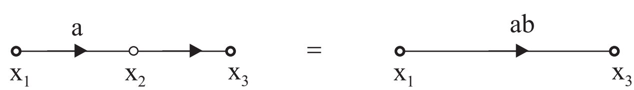
Rule 1 **:** Incoming signal to a node through a branch is given by the product of a signal at previous node and the gain of the branch.

Example:



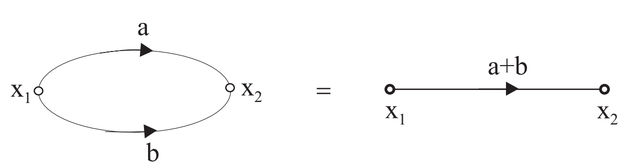
Rule 2 **:** Cascaded branches can be combined to give a single branch whose transmittance is equal to the product of individual branch transmittance.

Example:



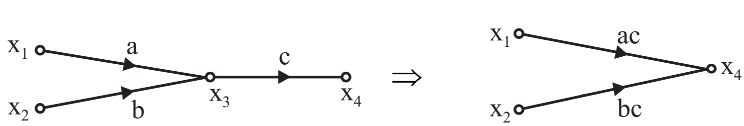
Rule 3 **:** Parallel branches may be represented by single branch whose transmittance is the sum of individual branch transmittances.

Example:



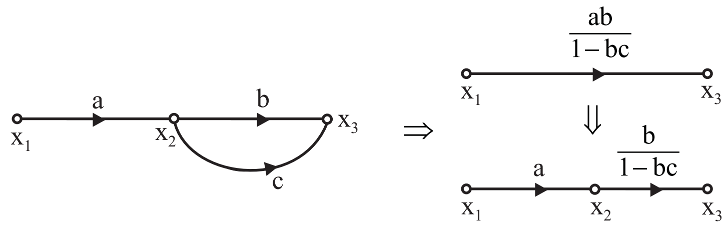
Rule 4 **:** A mixed node can be eliminated by multiplying the transmittance of outgoing branch (from the mixed node) to the transmittance of all incoming branches to the mixed node.

Example:



Rule 5 **:** A loop may be eliminated by writing equations at the input and output node and rearranging the equations to find the ratio of output to input. This ratio gives the gain of resultant branch.

Example:



Proof **:**

$x_2 = ax_1 + cx_3$; $x_3 = bx_2$

Put, $x_2 = ax_1 + cx_3$ in the equation for x_3.

$\therefore\ x_3 = b(ax_1 + cx_3) \quad \Rightarrow \quad x_3 = abx_1 + bcx_3 \quad \Rightarrow \quad x_3 - bcx_3 = abx_1 \quad \Rightarrow \quad x_3(1 - bc) = abx_1$

$$\therefore\ \frac{x_3}{x_1} = \frac{ab}{1 - bc}$$

SIGNAL FLOW GRAPH REDUCTION

The signal flow graph of a system can be reduced either by using the rules of a signal flow graph algebra or by using Mason's gain formula.

For signal flow graph reduction using the rules of signal flow graph, write equations at every node and then rearrange these equations to get the ratio of output and input (transfer function).

The signal flow graph reduction by above method will be time consuming and tedious. **S.J.Mason** has developed a simple procedure to determine the transfer function of the system represented as a signal flow graph. He has developed a formula called by his name **mason's gain formula** which can be directly used to find the transfer function of the system.

MASON'S GAIN FORMULA

The Mason's gain formula is used to determine the transfer function of the system from the signal flow graph of the system.

Let, R(s) = Input to the system

C(s) = Output of the system

Now, Transfer function of the system, $T(s) = \frac{C(s)}{R(s)}$ .....(1.34)

Mason's gain formula states the overall gain of the system [transfer function] as follows,

$$\text{Overall gain, } T = \frac{1}{\Delta}\sum_{k} P_k \Delta_k \qquad .....(1.35)$$

where, $T = T(s)$ = Transfer function of the system

P_K = Forward path gain of K^{th} forward path

K = Number of forward paths in the signal flow graph

$$\Delta = 1 - (\text{Sum of individual loop gains}) + \begin{pmatrix}\text{Sum of gain products of all possible} \\ \text{combinations of two non – touching loops}\end{pmatrix} - \begin{pmatrix}\text{Sum of gain products of all possible} \\ \text{combinations of three non – touching loops}\end{pmatrix} + \ldots\ldots$$

Δ_K = Δ for that part of the graph which is not touching K^{th} forward path

CONSTRUCTING SIGNAL FLOW GRAPH FOR CONTROL SYSTEMS

A control system can be represented diagrammatically by signal flow graph. The differential equations governing the system are used to construct the signal flow graph. The following procedure can be used to construct the signal flow graph of a system.

1. Take Laplace transform of the differential equations governing the system in order to convert them to algebraic equations in s-domain.
2. The constants and variables of the s-domain equations are identified.
3. From the working knowledge of the system, the variables are identified as input, output and intermediate variables.
4. For each variable a node is assigned in signal flow graph and constants are assigned as the gain or transmittance of the branches connecting the nodes.
5. For each equation a signal flow graph is drawn and then they are interconnected to give overall signal flow graph of the system.

PROCEDURE FOR CONVERTING BLOCK DIAGRAM TO SIGNAL FLOW GRAPH

The signal flow graph and block diagram of a system provides the same information but there is no standard procedure for reducing the block diagram to find the transfer function of the system. Also the block diagram reduction technique will be tedious and it is difficult to choose the rule to be applied for simplification. Hence it will be easier if the block diagram is converted to signal flow graph and **Mason's gain formula** is applied to find the transfer function. The following procedure can be used to convert block diagram to signal flow graph.

1. Assume nodes at input, output, at every summing point, at every branch point and in between cascaded blocks.
2. Draw the nodes separately as small circles and number the circles in the order 1, 2, 3, 4, ... etc.
3. From the block diagram find the gain between each node in the main forward path and connect all the corresponding circles by straight line and mark the gain between the nodes.
4. Draw the feed forward paths between various nodes and mark the gain of feed forward path along with sign.
5. Draw the feedback paths between various nodes and mark the gain of feedback paths along with sign.

EXAMPLE 1.24

Construct a signal flow graph for armature controlled dc motor.

SOLUTION

The differential equations governing the armature controlled dc motor are (refer section 1.3.1)

$$v_a = i_a R_a + L_a \frac{di_a}{dt} + e_b \quad ; \quad T = K_f i_a \quad ; \quad T = J\frac{d\omega}{dt} + B\omega \quad ; \quad e_b = K_b \omega \quad ; \quad \omega = d\theta/dt$$

On taking Laplace transform of above equations we get,

$$V_a(s) = I_a(s)\, R_a + L_a\, s\, I_a(s) + E_b(s) \qquad .....(1)$$

$$T(s) = K_t I_a(s) \qquad .....(2)$$

$$T(s) = J\, s\, \omega(s) + B\, \omega(s) \qquad .....(3)$$

$$E_b(s) = K_b\, \omega(s) \qquad .....(4)$$

$$\omega(s) = s\, \theta(s) \qquad .....(5)$$

The input and output variables of armature controlled dc motor are armature voltage $V_a(s)$ and angular displacement $\theta(s)$ respectively. The variables $I_a(s)$, $T(s)$, $E_b(s)$ and $\omega(s)$ are intermediate variables.

The equations (1) to (5) are rearranged & individual signal flow graph are shown in fig 1 to fig 5.

$$V_a(s) - E_b(s) = I_a(s)\,[R_a + s\,L_a]$$

$$\therefore\ I_a(s) = \frac{1}{R_a + sL_a}\,[\,V_a(s) - E_b(s)\,]$$

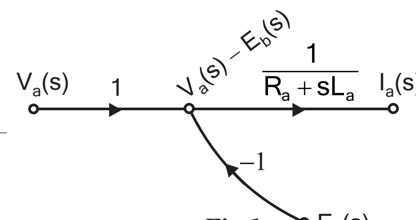


Fig 1

$$T(s) = K_t I_a(s)$$

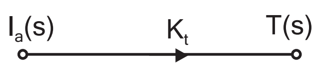


Fig 2

$$T(s) = \omega(s)\,[Js + B]$$

$$\therefore\ \omega(s) = \frac{1}{Js + B}\,T(s)$$

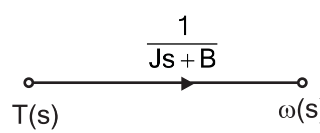


Fig 3

$$E_b(s) = K_b\, \omega(s)$$

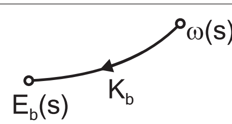


Fig 4

$$\omega(s) = s\theta(s)$$

$$\therefore\ \theta(s) = \frac{1}{s}\,\omega(s)$$

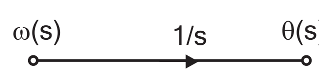


Fig 5

The overall signal flow graph of armature controlled dc motor is obtained by interconnecting the individual signal flow graphs shown in fig 1 to fig 5. The overall signal flow graph is shown in fig 6.

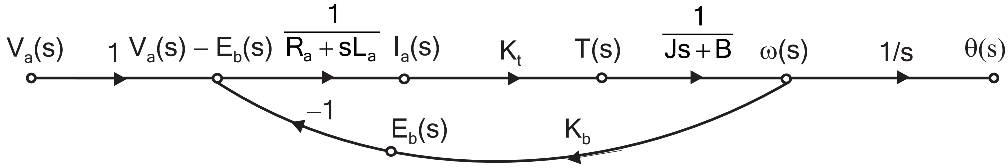


***Fig 6 :** Signal flow graph of armature controlled dc motor.*

EXAMPLE 1.25

Find the overall transfer function of the system whose signal flow graph is shown in fig 1.

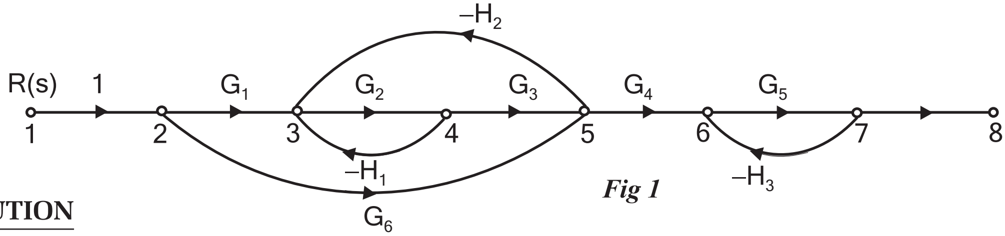


Fig 1

SOLUTION

I. Forward Path Gains

There are two forward paths. $\therefore$ K = 2

Let forward path gains be P_1 and P_2.

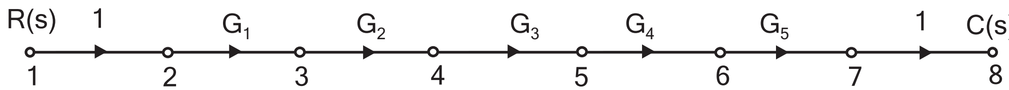


***Fig 2 :** Forward path-1.*

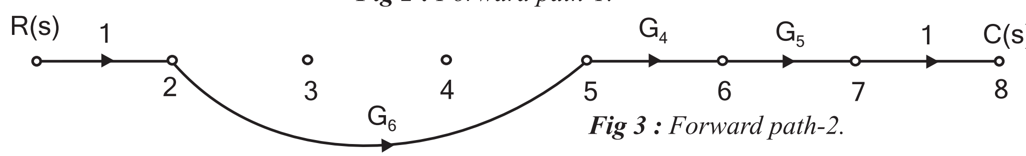


***Fig 3 :** Forward path-2.*

Gain of forward path-1, $P_1 = G_1\ G_2\ G_3\ G_4\ G_5$

Gain of forward path-2, $P_2 = G_4 G_5 G_6$

II. Individual Loop Gain

There are three individual loops. Let individual loop gains be P_{11}, P_{21} and P_{31}.

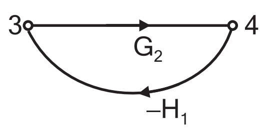


***Fig 4 :** Loop-1.*

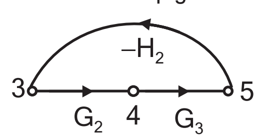


***Fig 5 :** Loop-2.*

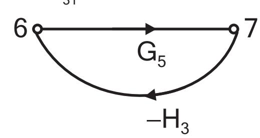


***Fig 6 :** Loop-3.*

Loop gain of individual loop-1, $P_{11} = -\ G_2H_1$

Loop gain of individual loop-2, $P_{21} = -\ G_2G_3H_2$

Loop gain of individual loop-3, $P_{31} = -\ G_5H_3$

III. Gain Products of Two Non-touching Loops

There are two combinations of two non-touching loops. Let the gain products of two non touching loops be P_{12} and P_{22}.

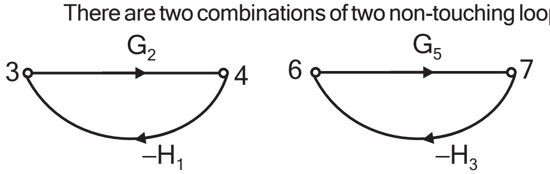


***Fig 7 :** First combination of 2 non-touching loops.*

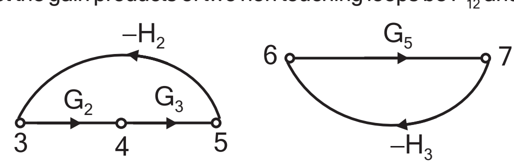


***Fig 8 :** Second combination of 2 non-touching loops.*

Gain product of first combination of two non touching loops $\Big\}$ $P_{12} = P_{11}P_{31} = (-\ G_2H_1)(-\ G_5H_3) = G_2G_5H_1H_3$

Gain product of second combination of two non touching loops $\Big\}$ $P_{22} = P_{21}P_{31} = (-\ G_2G_3H_2)(-\ G_5H_3) = G_2G_3G_5H_2H_3$

IV. Calculation of Δ and Δ_K

$$\Delta = 1 - (P_{11} + P_{21} + P_{31}) + (P_{12} + P_{22})$$
$$= 1 - (-G_2H_1 - G_2G_3H_2 - G_5H_3) + (G_2G_5H_1H_3 + G_2G_3G_5H_2H_3)$$
$$= 1 + G_2H_1 + G_2G_3H_2 + G_5H_3 + G_2G_5H_1H_3 + G_2G_3G_5H_2H_3$$

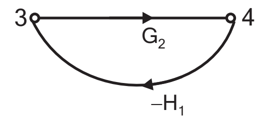


Fig. 9.

$\Delta_1 = 1$, Since there is no part of graph which is not touching with first forward path.

The part of the graph which is non touching with second forward path is shown in fig 9.

$$\Delta_2 = 1 - P_{11} = 1 - (-G_2H_1) = 1 + G_2H_1$$

V. Transfer Function, T

By Mason's gain formula the transfer function, T is given by,

$$T = \frac{1}{\Delta}\sum_K P_K\Delta_K = \frac{1}{\Delta}(P_1\Delta_1 + P_2\Delta_2) \quad \text{(Number of forward paths is 2 and so K = 2)}$$

$$= \frac{G_1G_2G_3G_4G_5 + G_4G_5G_6(1 + G_2H_1)}{1 + G_2H_1 + G_2G_3H_2 + G_5H_3 + G_2G_5H_1H_3 + G_2G_3G_5H_2H_3}$$

$$= \frac{G_1G_2G_3G_4G_5 + G_4G_5G_6 + G_2G_4G_5G_6H_1}{1 + G_2H_1 + G_2G_3H_2 + G_5H_3 + G_2G_5H_1H_3 + G_2G_3G_5H_2H_3}$$

$$= \frac{G_2G_4G_5[G_1G_3 + G_6/G_2 + G_6H_1]}{1 + G_2H_1 + G_2G_3H_2 + G_5H_3 + G_2G_5H_1H_3 + G_2G_3G_5H_2H_3}$$

EXAMPLE 1.26

Find the overall gain of the system whose signal flow graph is shown in fig 1.

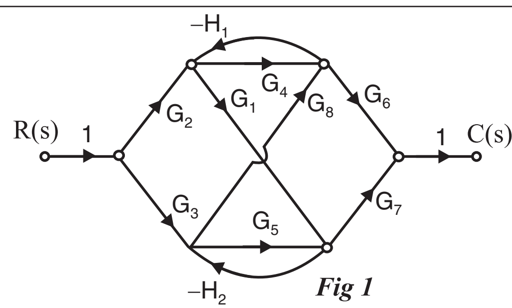


Fig 1

SOLUTION

Let us number the nodes as shown in fig 2.

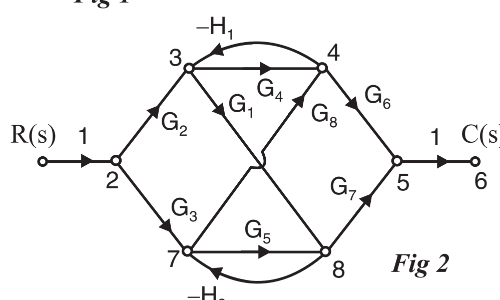


Fig 2

I. Forward Path Gains

There are six forward paths. $\therefore$ K = 6

Let the forward path gains be P_1, P_2, P_3, P_4, P_5 and P_6.

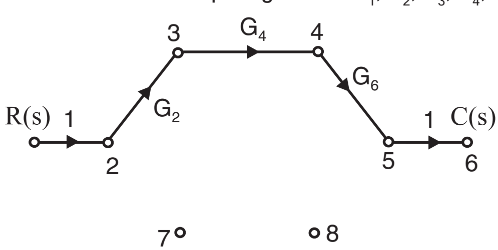


***Fig 3 :** Forward path-1.*

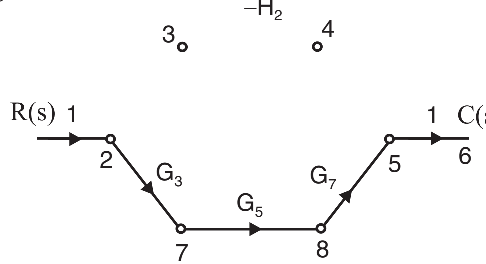


***Fig 4 :** Forward path-2.*

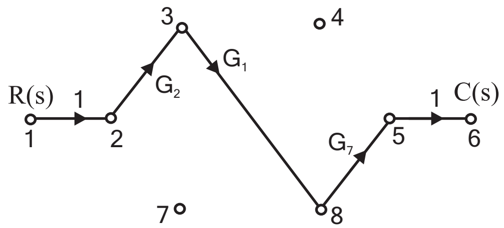


Fig 5 : Forward path-3

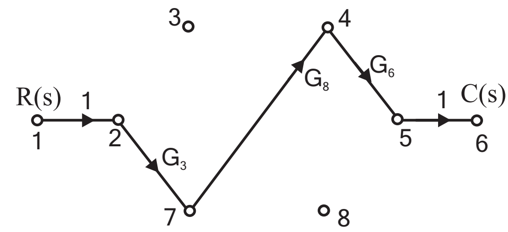


Fig 6 : Forward path-4

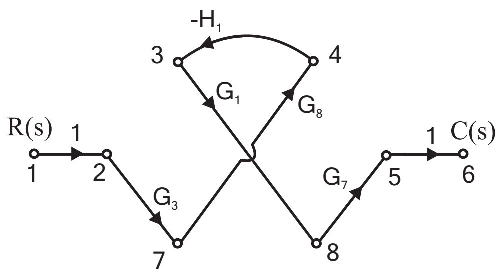


Fig 7 : Forward path-5

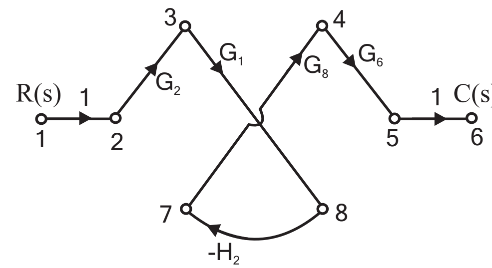


Fig 8 : Forward path-6

Gain of forward path-1, $P_1 = G_2G_4G_6$

Gain of forward path-2, $P_2 = G_3G_5G_7$

Gain of forward path-3, $P_3 = G_1G_2G_7$

Gain of forward path-4, $P_4 = G_3G_8G_6$

Gain of forward path-5, $P_5 = -G_1G_3G_7G_8H_1$

Gain of forward path-6, $P_6 = -G_1G_2G_6G_8H_2$

II. Individual Loop Gain

There are three individual loops.

Let individual loop gains be P_{11}, P_{21} and P_{31}.

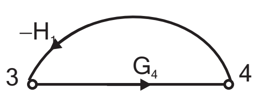


Fig 9 : Loop-1

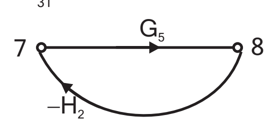


Fig 10 : Loop-2

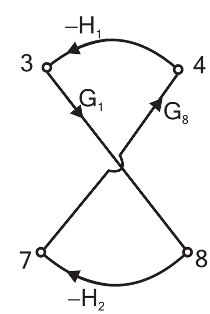


Fig 11 : Loop-3

Loop gain of individual loop-1, $P_{11} = -G_4H_1$

Loop gain of individual loop-2, $P_{21} = -G_5H_2$

Loop gain of individual loop-3, $P_{31} = G_1G_8H_1H_2$

III. Gain Products of Two Non-touching Loops

There is only one combination of two non-touching loops. Let gain product of two non-touching loops be P_{12}.

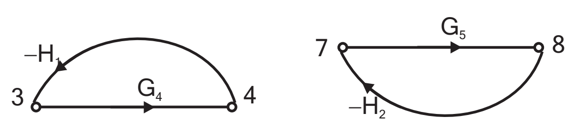


Fig 12 : Combination of 2 non-touching loops

$$\left.\begin{array}{l}\text{Gain product of first combination}\\ \text{of two non - touching loops}\end{array}\right\} P_{12} = P_{11}P_{21} = (-G_4H_1)(-G_5H_2) = G_4G_5H_1H_2$$

IV. Calculation of Δ and Δ_K

$$\Delta = 1 - (P_{11} + P_{21} + P_{31}) + P_{12} = 1 - (-G_4H_1 - G_5H_2 + G_1G_8H_1H_2) + G_4G_5H_1H_2$$

$$= 1 + G_4H_1 + G_5H_2 - G_1G_8H_1H_2 + G_4G_5H_1H_2$$

The part of the graph non-touching forward path - 1 is shown in fig 13.

$$\therefore\ \Delta_1 = 1 - (-G_5H_2) = 1 + G_5H_2$$

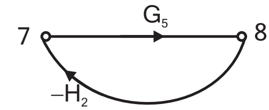


Fig 13

The part of the graph non-touching forward path -2 is shown in fig 14.

$$\therefore\ \Delta_2 = 1 - (-G_4H_1) = 1 + G_4H_1$$

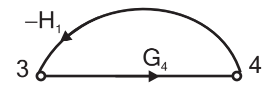


Fig 14

There is no part of the graph which is non-touching with forward paths 3, 4, 5 and 6.

$$\therefore\ \Delta_3 = \Delta_4 = \Delta_5 = \Delta_6 = 1$$

V. Transfer Function, T

By Mason's gain formula the transfer function, T is given by,

$$T = \frac{1}{\Delta}\left(\sum_K P_K \Delta_K\right) \qquad \text{(Number of forward paths is six and so K = 6)}$$

$$= \frac{1}{\Delta}(P_1\Delta_1 + P_2\Delta_2 + P_3\Delta_3 + P_4\Delta_4 + P_5\Delta_5 + P_6\Delta_6)$$

$$= \frac{G_2G_4G_6(1+G_5H_2) + G_3G_5G_7(1+G_4H_1) + G_1G_2G_7 + G_3G_6G_8 - G_1G_3G_7G_8H_1 - G_1G_2G_6G_8H_2}{1 + G_4H_1 + G_5H_2 - G_1G_8H_1H_2 + G_4G_5H_1H_2}$$

EXAMPLE 1.27

Find the overall gain C(s)/R(s) for the signal flow graph shown in fig 1.

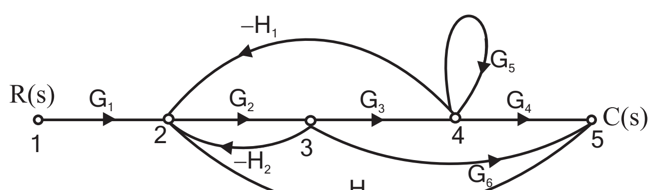


Fig 1

SOLUTION

I. Forward Path Gains

There are two forward paths. $\therefore$ K = 2. Let the forward path gains be P_1 and P_2.

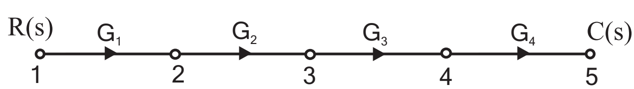


***Fig 2 :** Forward path-1*

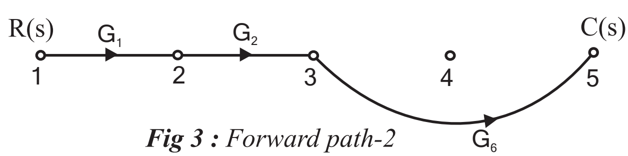


***Fig 3 :** Forward path-2*

Gain of forward path-1, $P_1 = G_1G_2G_3G_4$

Gain of forward path-2, $P_2 = G_1G_2G_6$

II. Individual Loop Gain

There are five individual loops. Let the individual loop gains be p_{11}, p_{21}, p_{31}, p_{41} and p_{51}.

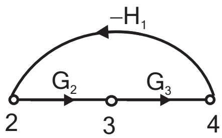


***Fig 4 :** loop-1*

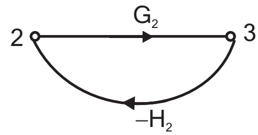


***Fig 5 :** loop-2*

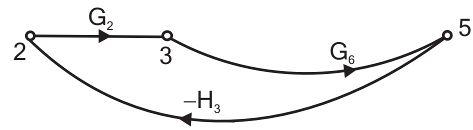


***Fig 6 :** loop-3*

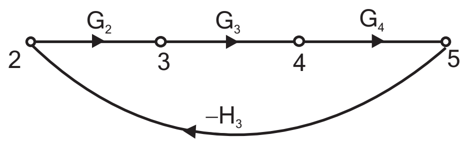


***Fig 7 :** loop-4*

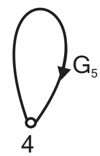


***Fig 8 :** loop-5*

Loop gain of individual loop-1, $P_{11} = -G_2G_3H_1$

Loop gain of individual loop-2, $P_{21} = -H_2G_2$

Loop gain of individual loop-3, $P_{31} = -G_2G_6H_3$

Loop gain of individual loop-4, $P_{41} = -G_2G_3G_4H_3$

Loop gain of individual loop-5, $P_{51} = G_5$

III. Gain Products of Two Non-touching Loops

There are two combinations of two non-touching loops.

Let the gain products of two non-touching loops be P_{12} and P_{22}.

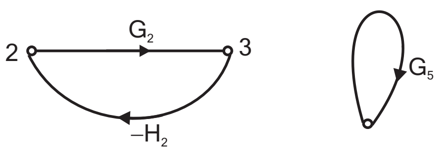


***Fig 9 :** First combination of two non-touching loops*

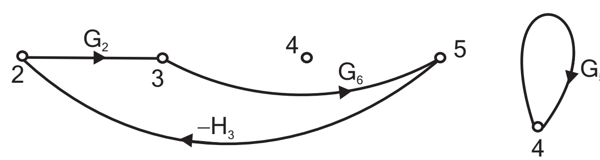


***Fig 10 :** Second combination of two non-touching loops*

Gain product of first combination of two non touching loops $\Big\}\ P_{12} = P_{21}P_{51} = (-G_2H_2)(G_5) = G_2G_5H_2$

Gain product of second combination of two non touching loops $\Big\}\ P_{22} = P_{31}P_{51} = (-G_2G_6H_3)(G_5) = -G_2G_5G_6H_3$

IV. Calculation of Δ and Δ_K

$$\Delta = 1 - (P_{11} + P_{21} + P_{31} + P_{41} + P_{51}) + (P_{12} + P_{22})$$

$$= 1 - (-G_2G_3H_1 - H_2G_2 - G_2G_3G_4H_3 + G_5 - G_2G_6H_3) + (-G_2H_2G_5 - G_2G_5G_6H_3)$$

Since there is no part of graph which is not touching forward path-1, $\Delta_1 = 1$.

The part of graph which is not touching forward path-2 is shown in fig 11.

$$\therefore \Delta_2 = 1 - G_5$$

Fig 11

V. Transfer Function, T

By Mason's gain formula the transfer function, T is given by,

$$T = \frac{1}{\Delta}\sum_K P_K\Delta_K \quad \text{(Number of forward path is 2 and so K = 2)}$$

$$= \frac{1}{\Delta}[P_1\Delta_1 + P_2\Delta_2] = \frac{1}{\Delta}[G_1G_2G_3G_4 \times 1 + G_1G_2G_6(1 - G_5)]$$

$$= \frac{G_1G_2G_3G_4 + G_1G_2G_6 - G_1G_2G_5G_6}{1 + G_2G_3H_1 + H_2G_2 + G_2G_3G_4H_3 - G_5 + G_2G_6H_3 - G_2H_2G_5 - G_2G_5G_6H_3}$$

EXAMPLE 1.28

Find the overall gain C(s)/R(s) for the signal flow graph shown in fig 1.

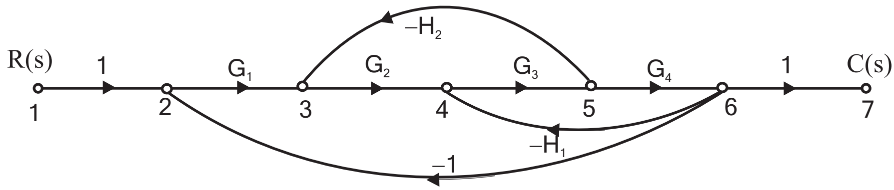


Fig 1

SOLUTION

I. Forward Path Gains

There is only one forward path. $\therefore$ K = 1.

Let the forward path gain be P_1.

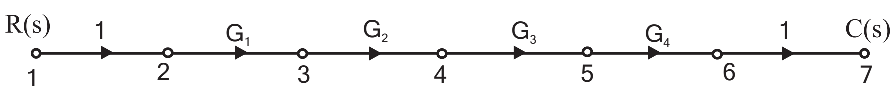


***Fig 2 :** Forward path-1*

Gain of forward path-1, $P_1 = G_1G_2G_3G_4$

II. Individual Loop Gain

There are three individual loops. Let the loop gains be P_{11}, P_{21}, P_{31}.

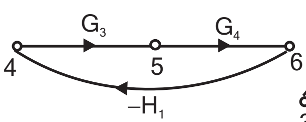


***Fig 3 :** loop-1*

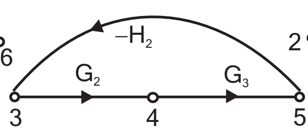


***Fig 4 :** loop-2*

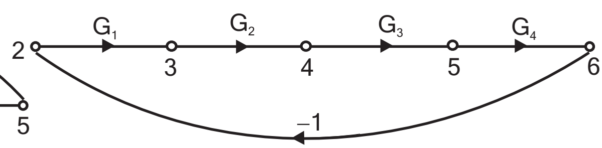


***Fig 5 :** loop-3*

Loop gain of individual loop-1, $P_{11} = -G_3G_4H_1$

Loop gain of individual loop-2, $P_{21} = -G_2G_3H_2$

Loop gain of individual loop-3, $P_{31} = -G_1G_2G_3G_4$

III. Gain Products of Two Non-touching Loops

There are no possible combinations of two non-touching loops, three non-touching loops, etc.

IV. Calculation of Δ and Δ_K

$$\Delta = 1 - (P_{11} + P_{21} + P_{31})$$
$$= 1 - (-G_3G_4H_1 - G_2G_3H_2 - G_1G_2G_3G_4)$$
$$= 1 + G_3G_4H_1 + G_2G_3H_2 + G_1G_2G_3G_4$$

Since no part of the graph is non-touching with forward path-1, $\Delta_1 = 1$.

V. Transfer Function, T

By Mason's gain formula the transfer function, T is given by,

$$T = \frac{C(s)}{R(s)} = \frac{1}{\Delta}\sum_K P_K \Delta_K = \frac{1}{\Delta} P_1 \Delta_1 \text{(Number of forward path is 1 and so K = 1)}$$

$$= \frac{G_1G_2G_3G_4}{1 + G_3G_4H_1 + G_2G_3H_2 + G_1G_2G_3G_4}$$

EXAMPLE 1.29

The signal flow graph for a feedback control system is shown in fig 1. Determine the closed loop transfer function C(s)/R(s).

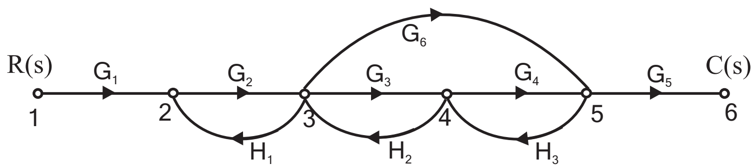


Fig 1

SOLUTION

I. Forward Path Gains

There are two forward paths. $\therefore$ K = 2.

Let forward path gains be P_1 and P_2.

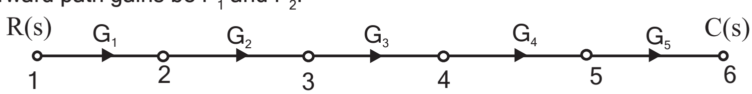


***Fig 2 :** Forward path-1*

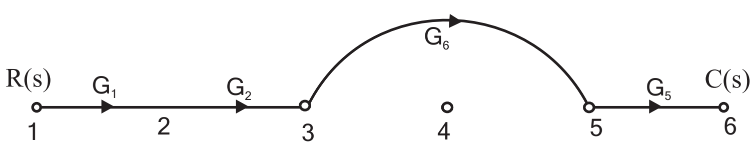


***Fig 3 :** Forward path-2*

Gain of forward path-1, $P_1 = G_1G_2G_3G_4G_5$

Gain of forward path-2, $P_2 = G_1G_2G_6G_5$

II. Individual Loop Gain

There are four individual loops. Let individual loop gains be P_{11}, P_{21}, P_{31} and P_{41}.

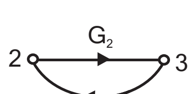


***Fig 4 :** loop-1*

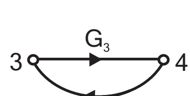


***Fig 5 :** loop-2*

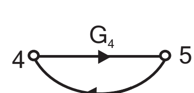


***Fig 6 :** loop-3*

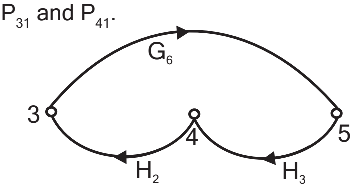


***Fig 7 :** loop-4*

Loop gain of individual loop-1, $P_{11} = G_2H_1$

Loop gain of individual loop-2, $P_{21} = G_3H_2$

Loop gain of individual loop-3, $P_{31} = G_4H_3$

Loop gain of individual loop-4, $P_{41} = G_6H_2H_3$

III. Gain Products of Two Non-touching Loops

There is only one combination of two non-touching loops. Let the gain products of two non-touching loops be P_{12}.

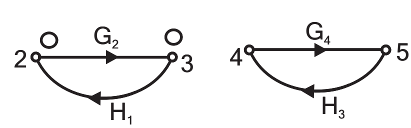


***Fig 8 :** First combination of two non touching loops*

Gain product of first combination of two non - touching loops $\left.\right\}$ $P_{12} = (G_2H_1)(G_4H_3)$

$$= G_2G_4H_1H_3$$

IV. Calculation of Δ and Δ_K

$$\Delta = 1 - (P_{11} + P_{21} + P_{31} + P_{41}) + P_{12}$$

$$= 1 - (G_2H_1 + G_3H_2 + G_4H_3 + G_6H_2H_3) + G_2G_4H_1H_3$$

$$= 1 - G_2H_1 - G_3H_2 - G_4H_3 - G_6H_2H_3 + G_2G_4H_1H_3$$

Since there is no part of graph which is non-touching with forward path-1 and 2, $\Delta_1 = \Delta_2 = 1$

V. Transfer Function, T

By Mason's gain formula the transfer function, T is given by,

$$T = \frac{1}{\Delta}\sum_K P_K\Delta_K = \frac{1}{\Delta}(P_1\Delta_1 + P_2\Delta_2) \quad \text{(Number of forward paths is two and so K = 2)}$$

$$= \frac{G_1G_2G_3G_4G_5 + G_1G_2G_5G_6}{1 - G_2H_1 - G_3H_2 - G_4H_3 - G_6H_2H_3 + G_2G_4H_1H_3}$$

EXAMPLE 1.30

Convert the given block diagram to signal flow graph and determine C(s)/R(s).

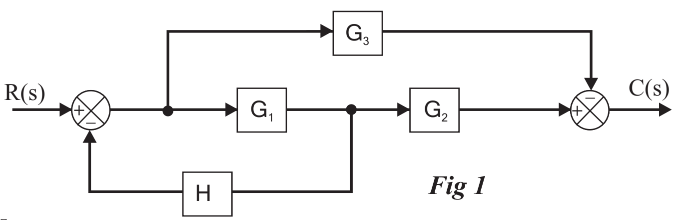


Fig 1

SOLUTION

The nodes are assigned at input, output, at every summing point & branch point as shown in fig 2.

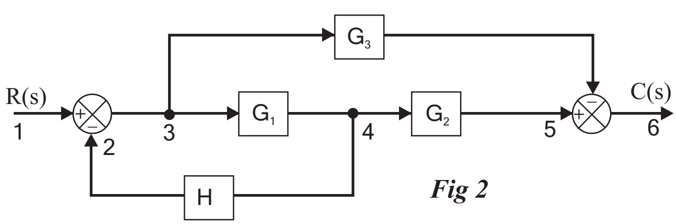


Fig 2

The signal flow graph of the above system is shown in fig 3.

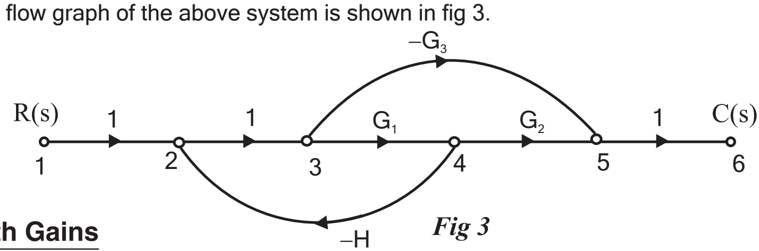


Fig 3

I. Forward Path Gains

There are two forward paths. $\therefore$ K = 2

Let the forward path gains be P_1 and P_2.

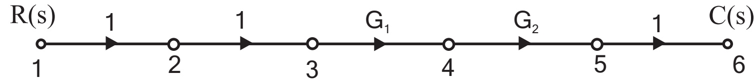


Fig 4 : Forward path-1

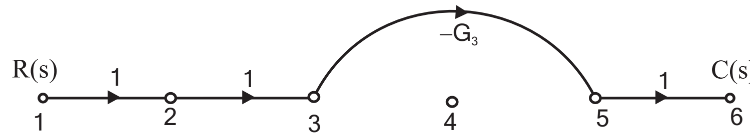


Fig 5 : Forward path-2

Gain of forward path-1, $P_1 = G_1G_2$

Gain of forward path-2, $P_2 = -G_3$

II. Individual Loop Gain

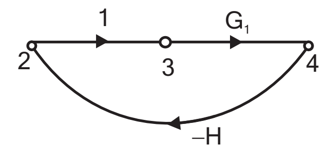


Fig 6 : loop-1

There is only one individual loop. Let the individual loop gain be P_{11}.

Loop gain of individual loop-I, $P_{11} = -G_1H$.

III. Gain Products of Two Non-touching Loops

There are no combinations of non-touching loops.

IV. Calculation of Δ and Δ_K

$$\Delta = 1 - [P_{11}] = 1 + G_1H$$

Since there are no part of the graph which is non-touching with forward path-1 and 2,

$$\Delta_1 = \Delta_2 = 1$$

V. Transfer Function, T

By Mason's gain formula the transfer function, T is given by,

$$T = \frac{1}{\Delta}\sum_K P_K \Delta_K = \frac{1}{\Delta}[P_1\Delta_1 + P_2\Delta_2] = \frac{G_1G_2 - G_3}{1 + G_1H}$$

EXAMPLE 1.31

Convert the block diagram to signal flow graph and determine the transfer function using Mason's gain formula.

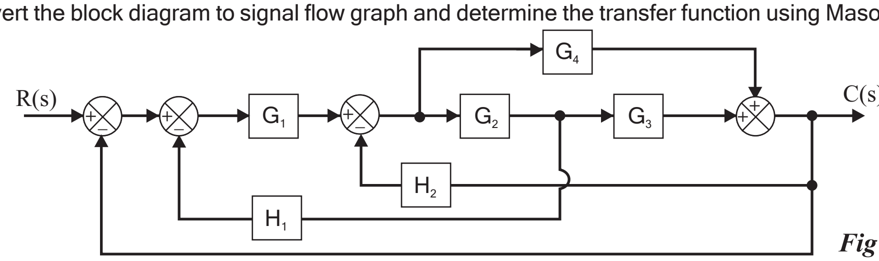


Fig 1

SOLUTION

The nodes are assigned at input, ouput, at every summing point & branch point as shown in fig 2.

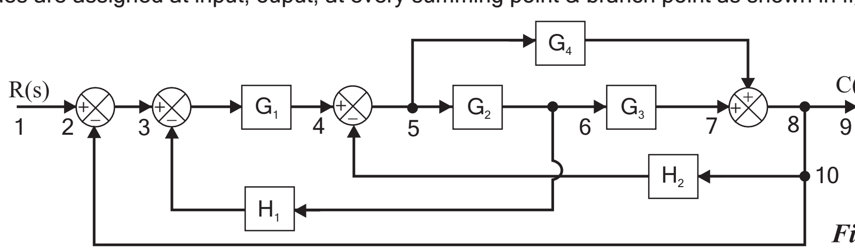


Fig 2

The signal flow graph for the above block diagram is shown in fig 3.

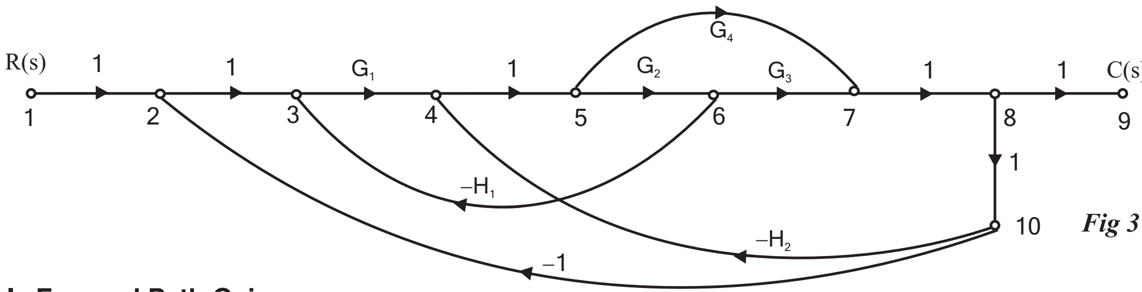


Fig 3

I. Forward Path Gains

There are two forward paths. $\therefore$ K=2.

Let the gain of the forward paths be P_1 and P_2.

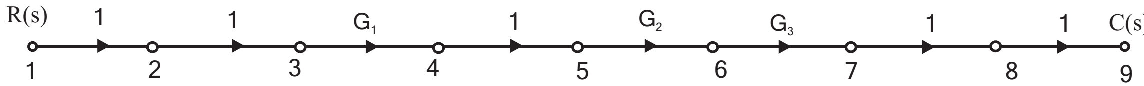


***Fig 4** : Forward path-1*

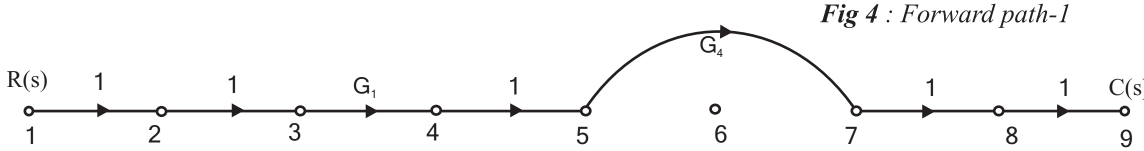


***Fig 5** : Forward path-2*

Gain of forward path-1, $P_1 = G_1G_2G_3$

Gain of forward path-2, $P_2 = G_1G_4$

II. Individual Loop Gain

There are five individual loops. Let the individual loop gain be P_{11}, P_{21}, P_{31}, P_{41} and P_{51}.

Loop gain of individual loop-1, $P_{11} = - G_1G_2G_3$

Loop gain of individual loop-2, $P_{21} = - G_2G_1H_1$

Loop gain of individual loop-3, $P_{31} = - G_2G_3H_2$

Loop gain of individual loop-4, $P_{41} = - G_1G_4$

Loop gain of individual loop-5, $P_{51} = - G_4H_2$

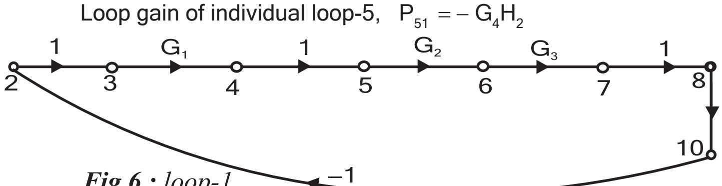


***Fig 6 :** loop-1.*

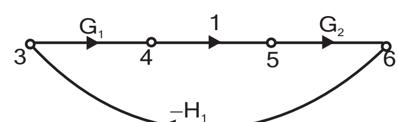


***Fig 7 :** loop-2.*

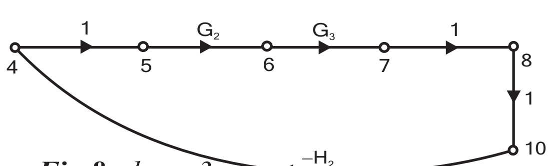


***Fig 8 :** loop-3.*

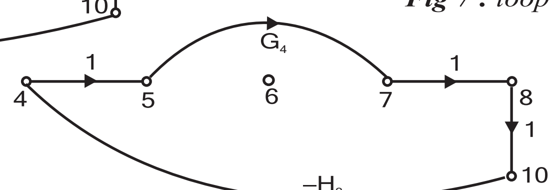


***Fig 10 :** loop-5.*

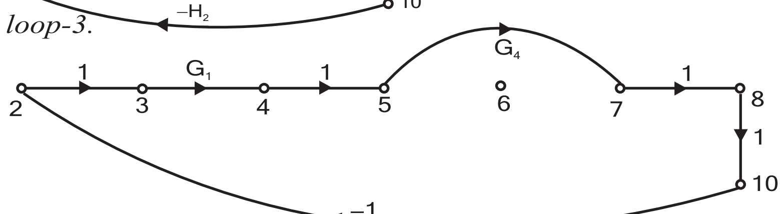


***Fig 9 :** loop-4.*

III. Gain Products of Two Non-touching Loops

There are no possible combinations of two non-touching loops, three non-touching loops, etc.,.

IV. Calculation of Δ and Δ_K

$$\Delta = 1 - [P_{11} + P_{21} + P_{31} + P_{41} + P_{51}] = 1 + G_1G_2G_3 + G_1G_2H_1 + G_2G_3H_2 + G_1G_4 + G_4H_2$$

Since no part of graph is non touching with forward paths-1 and 2, $\Delta_1 = \Delta_2 = 1$.

V. Transfer Function, T

By Mason's gain formula the transfer function, T is given by,

$$T = \frac{1}{\Delta}\sum_k P_K\Delta_K = \frac{1}{\Delta}[P_1\Delta_1 + P_2\Delta_2]$$

$$= \frac{G_1G_2G_3 + G_1G_4}{1 + G_1G_2G_3 + G_1G_2H_1 + G_2G_3H_2 + G_1G_4 + G_4H_2}$$

EXAMPLE 1.32

Convert the block diagram to signal flow graph and determine the transfer function using Mason's gain formula.

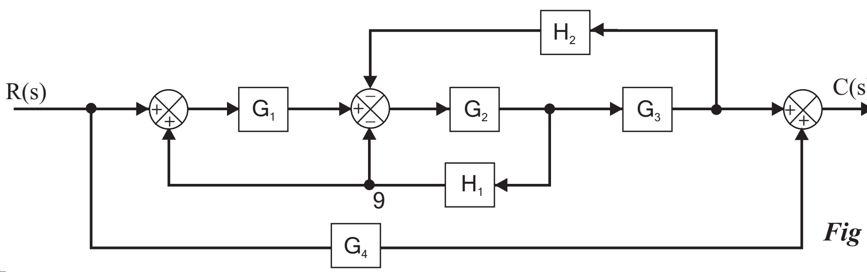


Fig 1

SOLUTION

The nodes are assigned at input, output, at every summing point & branch point as shown in fig 2.

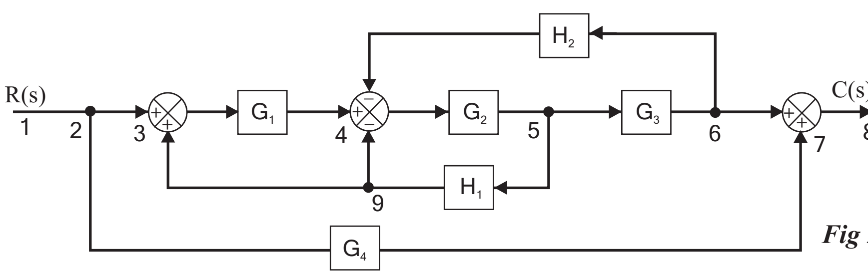


Fig 2

The signal flow graph for the above block diagram is shown in fig 3.

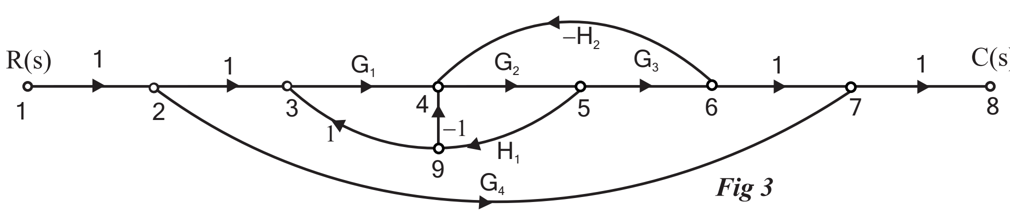


Fig 3

Forward Path Gains

There are two forward path, $\therefore$ K=2.

Let the forward path gains be P_1 and P_2.

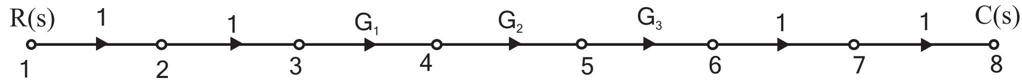


Fig 4 : *Forward path-1.*

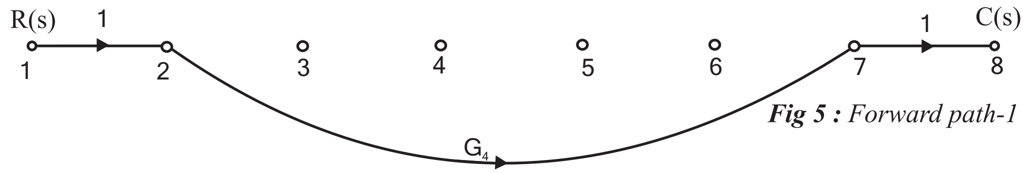


Fig 5 : *Forward path-1*

Gain of forward path-1, $P_1 = G_1G_2G_3$

Gain of forward path-2, $P_2 = G_4$

II. Individual Loop Gain

There are three individual loops with gains P_{11},P_{21} and P_{31}.

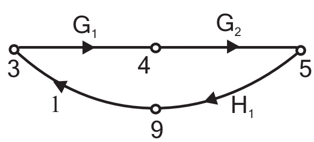


Fig 6 : *loop-1.*

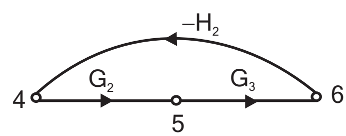


Fig 7 : *loop-2.*

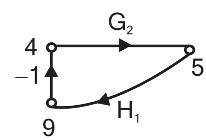


Fig 8 : *loop-3.*

Gain of individual loop-1, $P_{11} = G_1G_2H_1$

Gain of individual loop-2, $P_{21} = -G_2G_3H_2$

Gain of individual loop-3, $P_{31} = -G_2H_1$

III. Gain Products of Two Non-touching Loops

There are no possible combinations of two-non touching loops, three non-touching loops, etc.,.

IV. Calculation of Δ and Δ_K

$$\Delta = 1 - [P_{11} + P_{21} + P_{31}] = 1 - G_1G_2H_1 + G_2G_3H_2 + G_2H_1$$

Since no part of graph touches forward path-1, $\Delta_1 = 1$.

The part of graph non touching forward path-2 is shown in fig 9.

$$\therefore \Delta_2 = 1 - [G_1G_2H_1 - G_2G_3H_2 - G_2H_1]$$

$$= 1 - G_1G_2H_1 + G_2G_3H_2 + G_2H_1$$

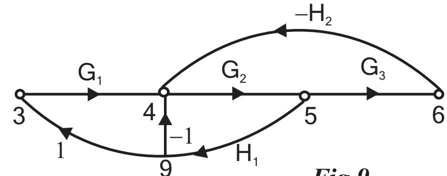


Fig 9

V. Transfer Function, T

By Mason's gain formula the transfer function, T is given by,

$$T = \frac{1}{\Delta}\sum_K P_K \Delta_K = \frac{1}{\Delta}[P_1\Delta_1 + P_2\Delta_2] \quad \text{(Number of forward paths is 2 and so K = 2)}$$

$$= \frac{1}{\Delta}[G_1G_2G_3 + G_4(1 - G_1G_2H_1 + G_2G_3H_2 + G_2H_1)]$$

$$= \frac{1}{\Delta}[G_1G_2G_3 + G_4 - G_1G_2G_4H_1 + G_2G_3G_4H_2 + G_2G_4H_1]$$

$$= \frac{G_1G_2G_3 + G_4 - G_1G_2G_4H_1 + G_2G_3G_4H_2 + G_2G_4H_1}{1 - G_1G_2H_1 + G_2G_3H_2 + G_2H_1}$$

EXAMPLE 1.33

Draw a signal flow graph and evaluate the closed loop transfer function of a system whose block diagram is shown in fig 1.

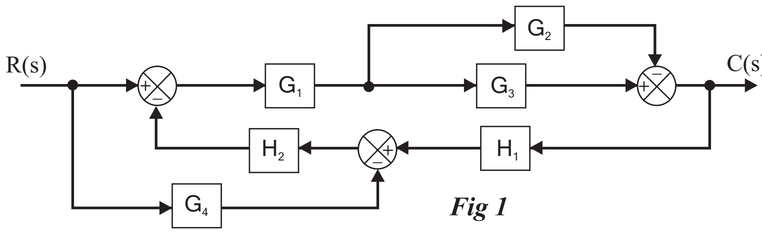


Fig 1

SOLUTION

The nodes are assigned at input, output, at every summing point & branch point as shown in fig 2.

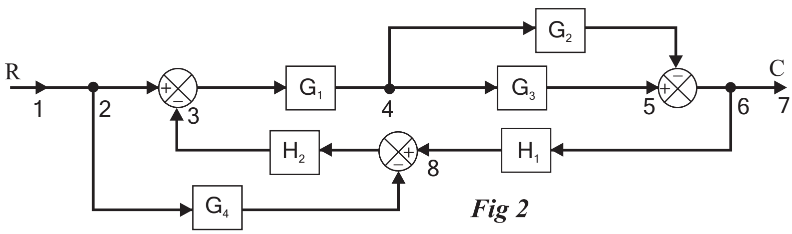
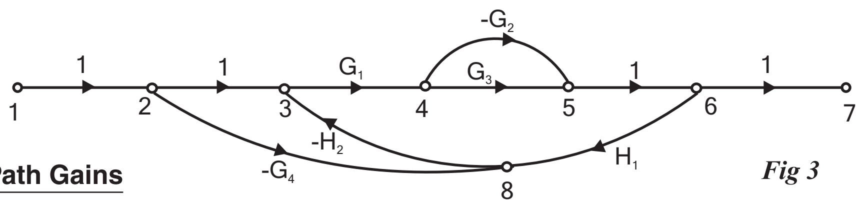


Fig 2

The signal flow graph for the block diagram of fig 2, is shown in fig 3.



I. Forward Path Gains

There are four forward paths, ∴ K = 4

Let the forward path gains be P_1, P_2, P_3 and P_4.

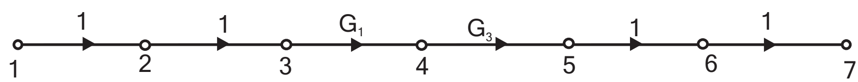


***Fig 4 :** Forward path-1.*

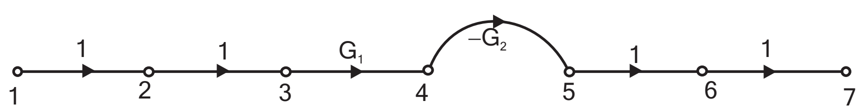
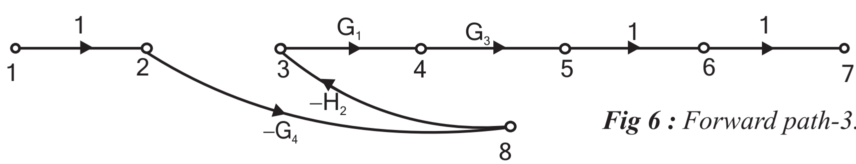


***Fig 5 :** Forward path-2.*



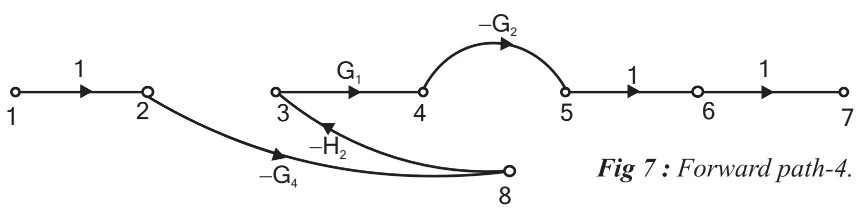


***Fig 7 :** Forward path-4.*

Gain of forward path-1, $P_1 = G_1G_3$
Gain of forward path-2, $P_2 = -G_1G_2$
Gain of forward path-3, $P_3 = G_1G_3G_4H_2$
Gain of forward path-4, $P_4 = -G_1G_2G_4H_2$

II. Individual Loop Gain

There are two individual loops, let individual loop gains be P_{11} and P_{21}.

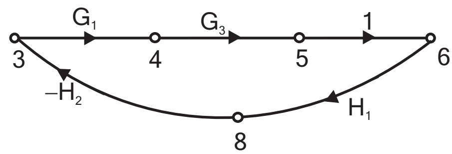


***Fig 8 :** loop-1*

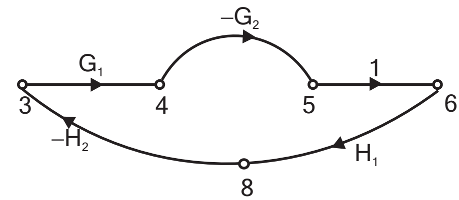


***Fig 9 :** loop-2*

Loop gain of individual loop-1, $P_{11} = -G_1G_3H_1H_2$

Loop gain of individual loop-2, $P_{21} = G_1G_2H_1H_2$

III. Gain Products of Two Non-touching Loops

There are no possible combinations of two non-touching loops, three non-touching loops, etc.,.

IV. Calculation of Δ and Δ_K

$$\Delta = 1 - [\text{ sum of individual loop gain }] = 1 - (P_{11} + P_{21})$$

$$= 1 - [-G_1G_3H_1H_2 + G_1G_2H_1H_2] = 1 + G_1G_3H_1H_2 - G_1G_2H_1H_2$$

Since no part of graph is non touching with the forward paths, $\Delta_1 = \Delta_2 = \Delta_3 = \Delta_4 = 1$.

V. Transfer Function, T

By Mason's gain formula the transfer function, T is given by,

$$T = \frac{1}{\Delta}\sum_K P_K \Delta_K = \frac{P_1 + P_2 + P_3 + P_4}{\Delta} \quad \text{(Number of forward paths is 4 and so K = 4)}$$

$$= \frac{G_1G_3 - G_1G_2 + G_1G_3G_4H_2 - G_1G_2G_4H_2}{1 + G_1G_3H_1H_2 - G_1G_2H_1H_2}$$

$$= \frac{G_1(G_3 - G_2) + G_1G_4H_2(G_3 - G_2)}{1 + G_1H_1H_2(G_3 - G_2)} = \frac{G_1(G_3 - G_2)(1 + G_4H_2)}{1 + G_1H_1H_2(G_3 - G_2)}$$

1.9 AUTOMATIC CONTROL SYSTEM

The basic block diagram of an automatic control system are Error detector, Amplifier and Controller, Actuator (Power actuator), Plant and Sensor or Feedback system. The block diagram of an automatic control system is shown in fig 1.30.

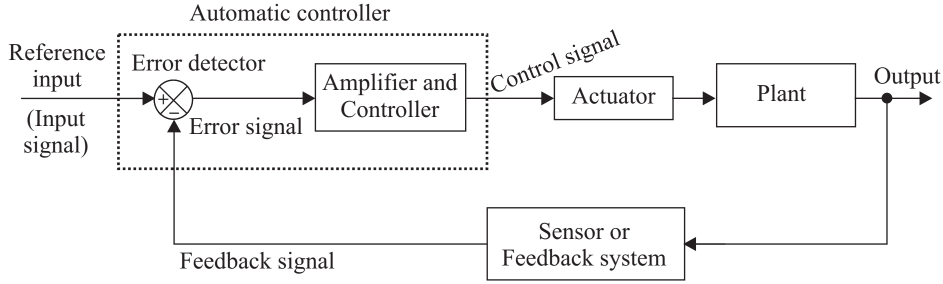


***Fig 1.30:** Block diagram of automatic control system.*

The plant is the open loop system whose output is automatically controlled by closed loop system. The combined unit of error detector, amplifier and controller is called ***automatic controller***, because without this unit the system becomes open loop system.

In automatic control systems the reference input will be an input signal proportional to desired output. The feedback signal is a signal proportional to current output of the system. The error detector compares the reference input and feedback signal and if there is a difference it produces an error signal. An amplifier can be used to amplify the error signal and the controller modifies the error signal for better control action.

The actuator amplifies the controller output and converts to the required form of energy that is acceptable for the plant. Depending on the input to the plant, the output will change. This process continues as long as there is a difference between reference input and feedback signal. If the difference is zero, then there is no error signal and the output settles at the desired value.

The function of error detector is to compare the reference input with feedback signal, to produce an error signal if there is a difference between them. The error signal is used to correct the output if there is a deviation from the desired value. Examples of error detector are potentiometer, LVDT (Linearly Variable Differential Transformer), Synchros, etc.,.

Generally, the error signal will be a weak signal and so it has to be amplified and then modified for better control action. In most of the system the controller itself amplifies the error signal and integrates or differentiates to produce a control signal (i.e., modified error signal). The different types of controllers are P,PI, PD and PID controllers.

The controllers employed may be electrical, electronic, hydraulic or pneumatic depending on the nature of error signal. If the error signal is electrical then the controller may be electrical or electronic and they are designed using R-C circuit or Operational amplifiers. If the error signal is mechanical then the controller may be hydraulic or pneumatic and they are designed using hydraulic servomotors or pneumatic flapper valves.

The actuator is a power amplifying device that produces the input to the plant according to the control signal. The actuator may be a pneumatic motor/valve, hydraulic motor or electric motor. Examples of electric motors employed as actuator are DC servomotor, AC servomotor and stepper motor.

The feedback system samples the output to produce a feedback signal which is proportional to current output. Also the feedback system should convert the output variable into another suitable variable such as displacement, pressure or voltage, so that it can be used to compare with the reference input. Usually the feedback system consists of sensor and associated circuit/devices. Transducers, Tachogenerators, etc., are used as feedback systems.

Many transducers like thermocouples, photo electric cells produce dc voltages proportional to the quantity to be measured. If this signal is to actuate an ac system, then this dc signal has to be converted to an ac signal before it is applied to ac systems. The device which transfers the information available in a dc signal to ac signal is called a modulator and the convertion process is called **modulation.** In modulation the control signal is superimposed on a high frequency carrier. Certain control system components like ac tachogenerators produces a modulated output signal. Hence the information is obtained by demodulation. The device which is used to extract the information available on a high frequency carrier is called demodulator and the process is called **demodulation**. In demodulation the control signal is extracted from the carrier signal.

Sometimes power transmitters like transformers, levers and gear trains are employed in control system. The function of transformer is to alter the voltage and current level of the power being transmitted. The fuction of lever is to alter the force and that of gear train is to alter the torque of the power being transmitted.

1.9.1 DC SERVO SYSTEM

Servo Systems are automatic position control systems. In the servo systems if the nature of control signals is DC then the servo system is called DC servo system. In servo systems, the desired position is maintained by servo motors, and so in DC servo systems, DC servo motor is employed for position control.

The block diagram of DC servo system is shown in Fig. 1.31. The DC servo system consists of DC servo motor, DC potentiometer as error detector, DC error amplifier and DC power amplifier. The desired position is set through DC potentiometer and compared with actual position maintained by the DC servo motor. The DC amplifiers will amplify the error signals to appropriate level and apply to DC servo motor for error correction.

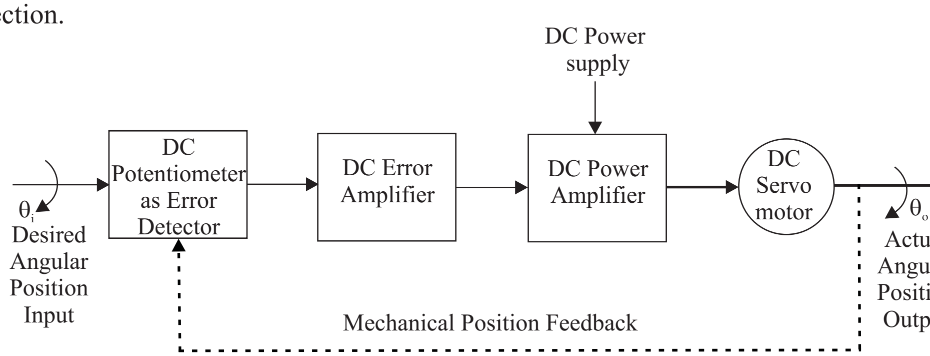


Fig. 1.31: *Block diagram of DC Servo system*

1.9.2 AC SERVO SYSTEM

Servo Systems are automatic position control systems. In the servo systems if the nature of control signals is AC then the servo system is called AC servo system. In servo systems, the desired position is maintained by servo motors, and so in AC servo systems, AC servo motor is employed for position control.

The block diagram of AC servo system is shown in Fig. 1.32. The AC servo system consists of AC servo motor, AC potentiometer/Synchro as error detector, AC error amplifier and AC power amplifier. The desired position is set through AC potentiometer/Synchro and compared with actual position maintained by the AC servo motor. The AC amplifiers will amplify the error signals to appropriate level and apply to AC servo motor for error correction.

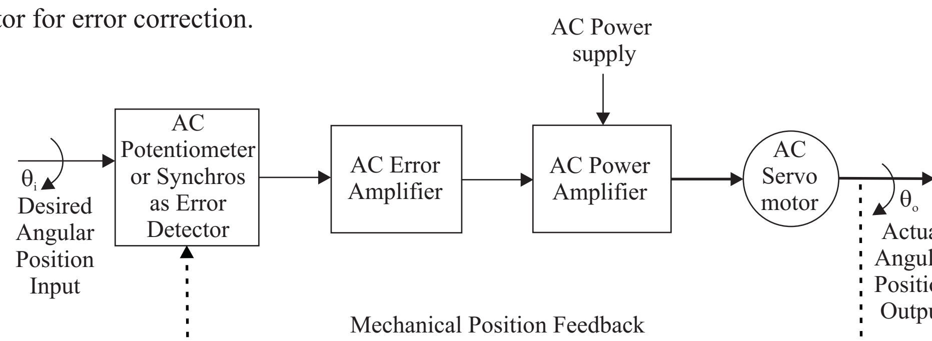


Fig. 1.32: *Block diagram of AC Servo system*

1.10 COMPONENTS OF CONTROL SYSTEM

1.10.1 POTENTIOMETER

A potentiometer is a device that can be used to convert a linear or angular displacement into a voltage. A potentiometer is a variable resistance whose value varies according to the angular/linear displacement of the wiper contact (movable contact).

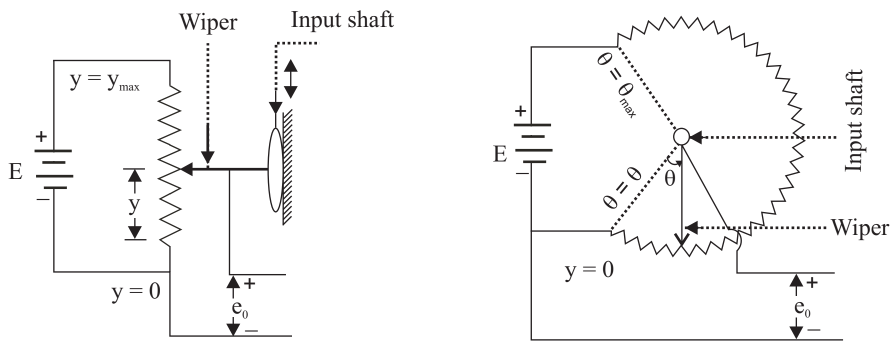


Fig 1.33a : *Linear displacement potentiometer.* ***Fig 1.33 :*** *Angular displacement potentiometer.*

Fig 1.33 : *Potentiometers.*

The resistance element can be constructed by winding resistance wire on a former or by depositing a conducting material on a plastic base. The potentiometer has an input shaft to which a wiper is attached. The displacement is applied to the input shaft. When the shaft moves, the wiper contact slides over the resistance material.

The potentiometer is excited by a dc or ac voltage. The output voltage is measured at wiper contact with respect to reference. The linear & angular displacement potentiometer are shown in fig 1.33.

LINEAR DISPLACEMENT POTENTIOMETER

y = Displacement of the wiper contact from reference ($y = 0$).

y_{max} = Maximum displacement of wiper contact.

E = Excitation voltage of potentiometer.

e_o = Output voltage.

If $y = 0$, then $e_o = 0$, and if $y = y_{max}$, then $e_o = E$

$\therefore$ For a displacement y,

$$\text{Output voltage, } e_o = \frac{E}{y_{max}} y = K_p y \qquad .....(1.36)$$

$$\text{where, } K_p = \frac{E}{y_{max}} = \text{Sensitivity of potentiometer in Volts/mm}$$

ANGULAR DISPLACEMENT POTENTIOMETER

θ = Angular displacement of wiper arm from reference ($\theta = 0$).

θ_{max} = Maximum displacement of wiper arm.

E = Excitation voltage of potentiometer.

e_o = Output voltage.

If $\theta = 0$, then $e_0 = 0$ and if $\theta = \theta_{max}$, then $e_o = E$

$\therefore$ For a displacement θ,

Output voltage, $e_o = \dfrac{E}{\theta_{max}}\theta = K_p\theta$ .....(1.37)

where, $K_p = \dfrac{E}{\theta_{max}}$ = Sensitivity of potentiometer in Volts/deg

***Note :** K_p is also called gain or gain constant of potentiometer.*

APPLICATIONS OF POTENTIOMETERS

Potentiometers can be used either to convert a mechanical motion to proportional voltage or as an error signal. A single potentiometer excited by dc or ac voltage is used to produce an output voltage proportional to displacement of the input shaft.

When potentiometers are used as error detector, two identical potentiometers are required as shown in fig 1.34. Both the potentiometer are excited by the same source and at same potential. Hence, if the wiper arm of both the potentiometers are in the same position then the voltage between two wiper arms is zero.

The position of one wiper arm is kept as reference input. The displacement to be compared is applied to the wiper arm of another potentiometer. Hence the output voltage which is measured between two wiper arms is proportional to the difference between the displacement of both the wiper arms.

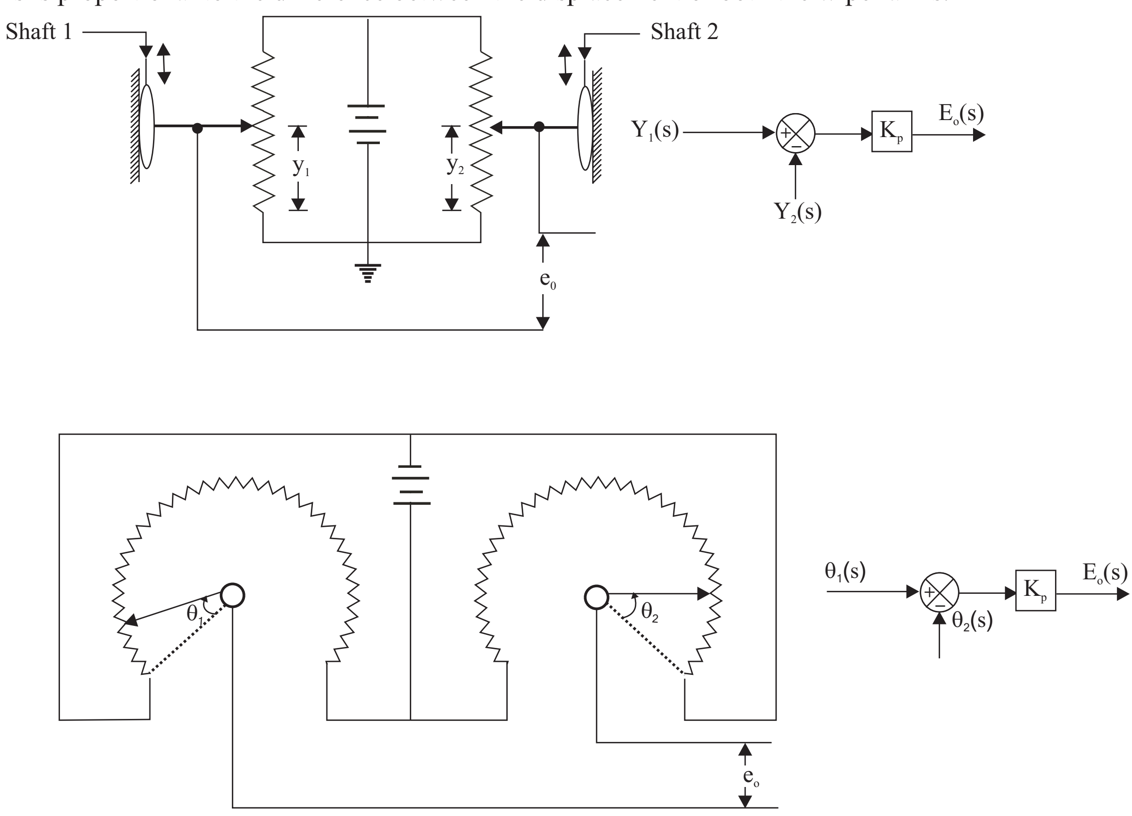


***Fig 1.34 :** Potentiometers as error detectors.*

CHARACTERISTICS OF POTENTIOMETER

1. The ideal characteristics of a potentiometer is linear variation of resistance with displacement. This is best realised by having very large radius, more number of turns and high resistance elements.
2. The device which measures the output voltage of potentiometer should have high input impedance to avoid loading error. If necessary an isolation amplifier with high input impedance may be used.
3. When the wiper slides over resistance it makes simultaneous contact with adjacent turns to avoid discontinuity in output. Consequently the output is in the form of staircase steps. Hence we define a term called ***resolution*** which specifies the output voltage per step. The resolution of a potentiometer is defined as the ratio of number of steps to total number of turns. The resolution of potentiometer is an important factor in the determination of minimum value of output voltage.

SPECIFICATIONS OF POTENTIOMETER

The specifications of potentiometers used in control system are the following,

1. Turns per unit length is in the range of 6 to 30 turns per mm.
2. Torque required for wiper movement is in the range of 1×10^{-3} Kg-m to 1×10^{-2} Kg-m.
3. The total resistance of the potentiometer is in the range of 25 ohms to 1 mega-ohms.
4. Power rating is 1 to 10 watts.
5. Heat dissipation is 1/2 watts per cm^2.
6. Excitation voltage is 4 to 20 volts.
7. Voltage gradient is 0.01 to 0.05 volt per degree.

AC POTENTIOMETER

In potentiometers excited by ac supply the output will be a modulated voltage. The carrier is the excitation voltage. The envelope of the carrier is modulated by the movement of the wiper arm. Hence the information is available in the envelope of the carrier. The ac potentiometer will have inductive effect in addition to resistance which leads to difficulty in balancing the potentiometers used as error detectors.

1.10.2 SERVOMOTOR

The motors that are used in automatic control systems are called ***Servomotors***. When the objective of the system is to control the position of an object then the system is called ***Servomechanism***. The servomotors are used to convert an electrical signal (control voltage) applied to them into an angular displacement of the shaft. They can either operate in a continuous duty or step duty depending on construction.

There are variety of servomotors available for control system applications. The suitability of a motor for a particular application depends on the characteristics of the system, the purpose of the system and its operating conditions.

In general, a servomotor should have the following feature.

1. Linear relationship between the speed and electric control signal.
2. Steady state stability.
3. Wide range of speed control.
4. Linearity of mechanical characteristics throughout the entire speed range.

5. Low mechanical and electrical inertia.
6. Fast response.

Depending on the supply required to run the motor, they are broadly classified as DC servomotors and AC servomotors. The DC motors are expensive than AC motors. But, the DC servomotors have linear characteristics and so it is easier to control.

The advantages of DC servomotors are the following :

1. Higher output than from a 50 Hz motor of same size.
2. Linearity of characteristics are achieved easily.
3. Easier speed control from zero speed to full speed in both directions.
4. High torque to inertia ratio that gives them quick response to control signals.
5. DC servomotors have light weight, low inertia and low inductance armature that can respond quickly to commands for a change in position or speed.
6. Low electrical time constants(0.1 to 6ms) and low mechanical time constants(2.3 to 40ms).
7. DC motors are capable of delivering over 3 times their rated torque for a short time but AC motors will start at 2 to 2.5 times their rated torque.

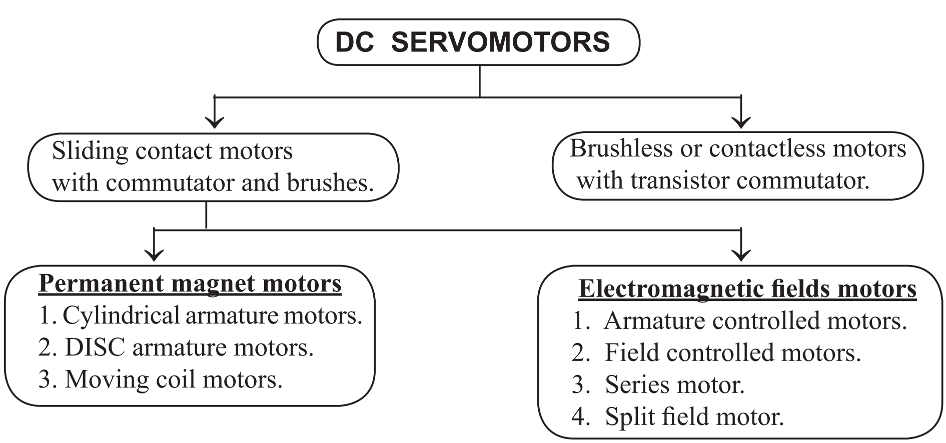
The DC servomotors are generally used for large power applications such as in machine tools and robotics.

Advantages of AC motors are lower cost, higher efficiency and less maintenance since there is no commutator and brushes. The disadvantage of AC motor is that the characteristics are quite non-linear and this motors are more difficult to control especially for positioning applications (servomechanisms).

The AC motor are best suited for low power applications such as instrument servo (eg. Control of pen in X-Y recorders) and computer related equipment (eg., Disk drives, Tape drives, Printers, etc.,). The three phase induction motors with pulse width modulated power amplifier are currently gaining popularity in high power control application.

1.10.3 DC SERVOMOTOR

DC servomotors are broadly classified as shown below.



PERMANENT MAGNET DC MOTORS

In this type of motors, the field winding is replaced by permanent magnets to produce the required magnetic field. Permanent magnet motor are economical for power ratings upto a few KW. The following are some of the advantages of permanent-magnet motors.

1. A simpler, more reliable motor because the field power supply is not required.
2. Higher efficiency due to the absence of field losses.
3. Field flux is less affected by temperature rise.
4. Less heating, making it possible to totally enclose the motor.
5. No possibility of over speeding due to loss of field.
6. A more linear torque Vs speed curve.
7. Higher power output at the same dimensions and temperature limitations.

The disadvantages of permanent magnet motors are that the magnets deteriorate with time and demagnetised by large current transients. These drawbacks are eliminated by high grade magnetic materials such as ceramic magnets and rare earth magnets (samarium cobalt). But the cost of these materials are very high.

In permanent magnet motors, the armature is placed in rotor and permanent magnet poles are fixed to the stator. The rotor employs special type of constructions to reduce the weight and so the inertia of the rotating system. The special type of constructions are cylindrical armature with small diameter and longer axial length, disc armature and hollow armature (moving coil).

ELECTRO-MAGNETIC FIELD MOTORS

These motors are economical for higher power ratings, generally above 1KW. This type of servomotors are similar to conventional dc motors constructionally. But has the following special features.

1. The number of slots and commutator segments is large to improve commutation.
2. Compoles and compensating windings are provided to eliminate sparking.
3. The diameter to length ratio is kept low to reduce inertia.
4. Oversize shafts are employed to withstand the high torque stress.
5. Eddy currents are reduced by complete lamination of the magnetic circuit and by using low-loss steel.

In this type of motor, the torque and speed may be controlled by varying the armature current and/or the field current. Generally, one of these is varied to control the torque while the other is held constant. In armature controlled mode of operation,the field current is held constant and the armature current is varied to control the torque. In the field controlled mode, the armature current is maintained constant and field current is varied to control the torque.

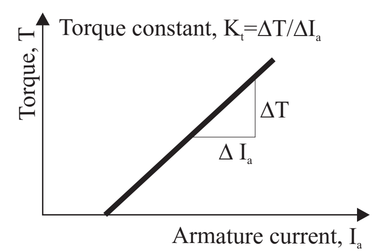


Fig 1.35a : *I_a Vs T.*

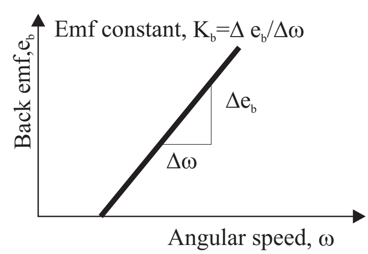


Fig 1.35b : *ω Vs E_b.*

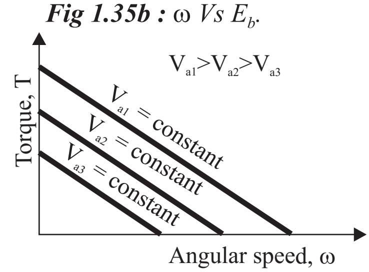


Fig 1.35c : *ωVs T.*

Fig 1.35 : *Characteristics of armature controlled dc servomotor.*

ARMATURE CONTROLLED DC SERVOMOTOR

It is a DC shunt motor designed to satisfy the requirement of a servomotor. The field is excited by a constant DC supply. If the field current is constant then speed is directly proportional to armature voltage and torque is directly proportional to armature current. Hence the torque and speed can be controlled by armature voltage. Reversible operation is possible by reversing the armature voltage.

In small motors, the armature voltage is controlled by a variable resistance. But in large motors in order to reduce power loss, armature voltage is controlled by thyristors. The steady-state operating characteristics of an armature controlled DC servomotor are illustrated in fig 1.35.

Note : *For transfer function of armature controlled DC motor, refer section-1.3.1.*

FIELD CONTROLLED DC SERVOMOTORS

It is a DC shunt motor designed to satisfy the requirement of a servomotor. In this motor, the armature is supplied with a constant current or voltage. When armature voltage is constant the torque is directly proportional to field flux. Since the field current is proportional to flux, the torque of the motor is controlled by controlling the field current. Reversible operation is possible by reversing the field current. The response of field controlled motor is however slowed by field inductance.

Note : *For the transfer function of field controlled DC motor refer section-1.3.2.*

1.10.4 AC SERVOMOTOR

An Ac servomotor is basically a two-phase induction motor except for certain special design features. A two-phase servomotor differs in the following two ways from a normal induction motor.

1. The rotor of the servomotor is built with high resistance, so that its X/R (Inductive reactance/Resistance) ratio is small which results in linear speed-torque characteristics. (But conventional induction motors will have high value of X/R which results in high efficiency and non-linear speed-torque characteristics). The speed-torque characteristics of normal induction motor (curve-a) and ac servomotor(curve-b) are shown in fig 1.36.
2. The excitation voltage applied to two stator windings should have a phase difference of 90º.

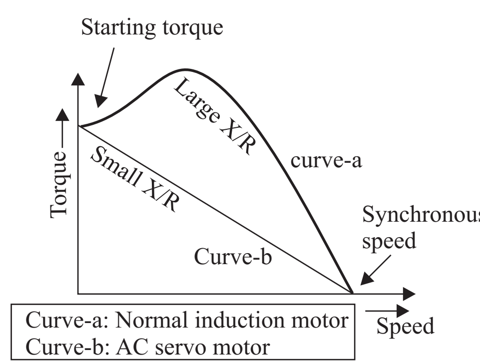


Fig 1.36 : *Speed-Torque characteristics of induction motor and ac servomotor.*

CONSTRUCTION OF AC SERVOMOTOR

The ac servomotor is basically a two phase induction motor with some special design features. The stator consists of two pole-pairs (A-B and C-D) mounted on the inner periphery of the stator, such that their axes are at an angle of 90º in space. Each pole-pair carries a winding. One winding is called reference winding and the other is called control winding. The exciting current in the winding should have a phase displacement of 90º. The supply used to drive the motor is single phase and so a phase advancing capacitor is connected to one of the phase to produce a phase difference of 90º. The simple constructional features of ac servomotor is shown in fig 1.37.

The rotor construction is usually squirrel cage or drag-cup type. The squirrel cage rotor is made of laminations. The rotor bars are placed on the slots and short circuited at both ends by end rings. The diameter of the rotor is kept small in order to reduce inertia and to obtain good accelerating characteristics.

The Drag-cup construction is employed for very low inertia applications. In this type of construction, the rotor will be in the form of hollow cylinder made of aluminium. The aluminium cylinder itself acts as short circuited rotor conductors, (Electrically both the types of rotors are identical).

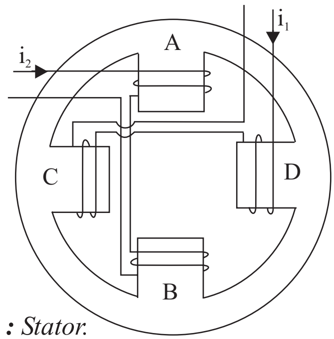


Fig 1.37a : *Stator.*

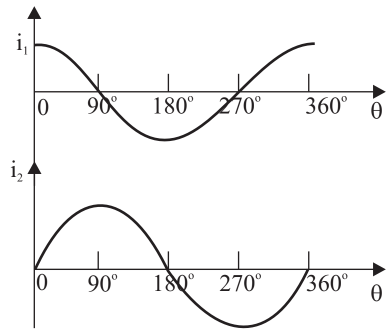


Fig 1.37b : *Exciting currents.*

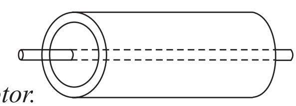


Fig 1.37c : *Rotor.*

Fig 1.37 : *Simplified constructional features of 2-phase ac servomotor.*

WORKING PRINCIPLE OF AC SERVOMOTOR

Working of servomotor as ordinary induction motor

The stator windings are excited by voltages of equal rms magnitude and 90° phase difference. This results in exciting currents i_1 and i_2 that are phase displaced by 90° and have equal rms values. These currents give rise to a rotating magnetic field of constant magnitude. The direction of rotation depends on the phase relationship of the two currents (or voltages). The exciting currents shown in fig 1.37b produces a clockwise rotating magnetic field, which results in clockwise rotation of the rotor. (A phase shift of 180° in i_1 will produce an anticlockwise rotating magnetic field, which results in anticlockwise rotation of rotor).

The rotating magnetic field sweeps over the rotor conductors. The rotor conductors experience a change in flux and so voltages are induced in rotor conductors. This voltage circulates current in the short circuited rotor conductors and the currents create rotor flux.

Due to the interaction of stator and rotor flux, a mechanical force (or torque) is developed on the rotor and so the rotor starts moving in the same direction as that of rotating magnetic field.

Working of ac servomotor in control systems

The symbolic representation of an ac servomotor as a control system component is shown in fig 1.38. The reference winding is excited by a constant voltage source with a frequency in the range 50 to 1000Hz. By using frequencies of 400 Hz or higher, the system can be made less susceptible to low frequency noise. Due to this feature, ac devices are extensively used in aircraft and missile control system in which the noise and disturbance often create problems.

The control winding is excited by the modulated control signal and this voltage is of variable magnitude and polarity. The control signal of the servo loop (or the system) dictates the magnitude and polarity of this voltage.

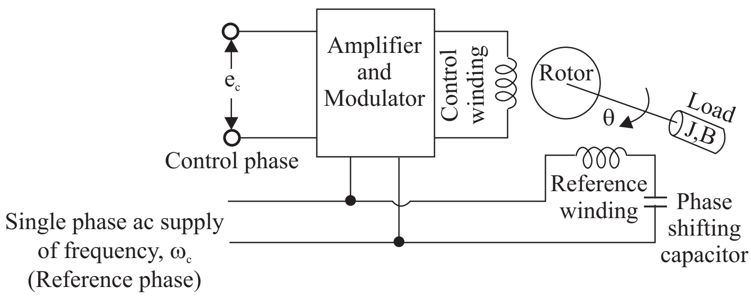


Fig 1.38 : *Symbolic representation of an ac servomotor.*

Usually the control signals will be low frequency signals, in the range of 0 to 20Hz. For production of rotating magnetic field, the control-phase voltage must be of the same frequency as the reference-phase voltage and in addition the two voltages must be in time quadrature. Hence the control signal is modulated by a carrier whose frequency is same as that of reference voltage and then applied to control winding. The ac supply itself is used as carrier signal for modulation process. The 90° phase difference between the control-phase and reference-phase voltages is obtained by the insertion of a capacitor in reference winding.

Let, e_c = Control signal

e_{car} = $E \cos \omega_c t$ = Carrier signal

e_{cm} = Modulated control signal.

The waveforms of a typical control signal, carrier signal and modulated control signal are shown in fig 1.39. The type of modulation is amplitude modulation and so the information is available on the envelope of the modulated signal. In fig 1.39 it can be observed that the envelope of the modulated wave is identical to control signal.

The polarity of e_c dictates the phase of e_{cm} with respect to that of carrier. If e_c is positive, then e_{cm} and e_{car} have the same phase,otherwise they have 180º phase difference.

$$\therefore\ e_{cm} = |E + e_c| \cos \omega_c t \qquad \text{for } e_c > 0$$

$$= |E + e_c| \cos(\omega_c t + \pi) \qquad \text{for } e_c < 0 \qquad .....(1.38)$$

This means that, a reversal in phase of e_{cm} occurs whenever the signal e_c crosses the zero-magnitude axis. This reversal in phase causes a reversal in the direction of rotation of the magnetic field and hence a reversal in the direction of rotation of the motor shaft.

> ***Note:*** *The control signal is modulated in order to match the frequency to that of reference signal. In the modulated wave the information is stored in the envelope of* e_{cm}*, but not in* e_{cm}*. Hence, we should consider* e_c *as the input and the envelope of* e_{cm} *as the output of the modulator. Therefore the transfer function of the modulator is equal to 1, because the envelope of* e_{cm} *is identical to* e_c*.*

The speed-torque curves of a typical ac servomotor plotted for fixed reference phase voltage E $\cos\omega_c t$ and different values of constant input voltages $e_c \leq E$ are shown in fig 1.40a. All these curves have negative slope. Note that the curve for $e_c = 0$ goes through the origin, this means that when the control-phase voltage becomes zero, the motor develop a decelerating torque and so the motor stops. The curves show a large torque at zero speed. This is a requirement for a servomotor in order to provide rapid acceleration.

The speed-torque curves of ac servomotor are nonlinear except in the low speed region. In order to derive a transfer function for the motor,some linearizing approximations are necessary. A servomotor

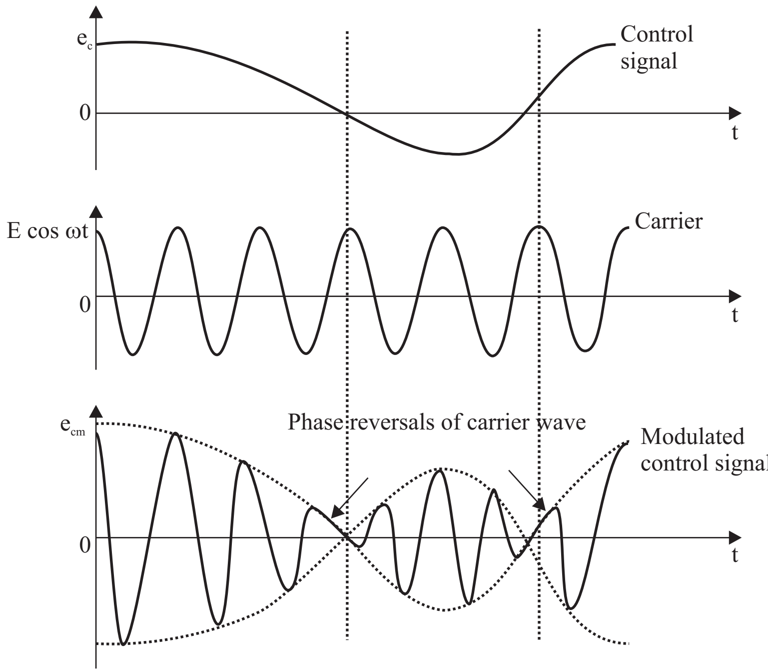


Fig 1.39 : *Waveforms of control signal, carrier and modulated control signal.*

seldom operates at high speeds, therefore the linear portions of speed-torque curves can be extended out to the high speed region as shown in fig 1.40a, by use of dashed lines. But even with this approximation, the resultant curves are still not parallel to each other. This means that for constant speeds, except near-zero speed, the torque does not vary linearly with respect to input voltage e_c. The curves in fig 1.40b illustrates this effect.

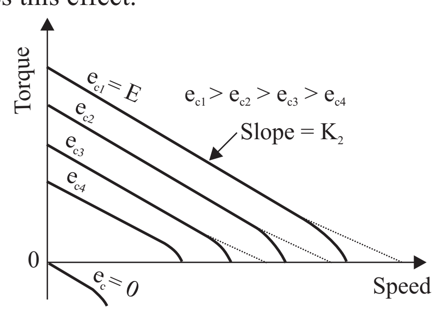


Fig 1.40a : *Speed-torque curves of an ac servomotor.*

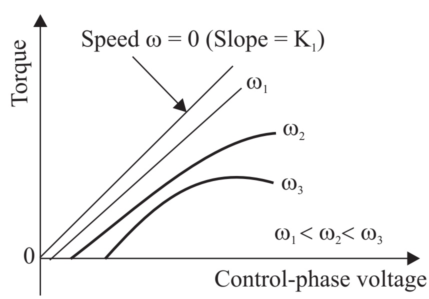


Fig 1.40b : *Control voltage Vs Torque curves of an ac servomotor.*

Fig 1.40 : *Characteristics of ac servomotor.*

TRANSFER FUNCTION OF AC SERVOMOTOR

Let, T_m = Torque developed by servomotor.

θ = Angular displacement of rotor.

$\omega = \frac{d\theta}{dt}$ = Angular speed.

T_l = Torque required by the load.

J = Moment of inertia of load and the rotor.

B = Viscous-frictional coefficient of load and the rotor.

K_1 = Slope of control-phase voltage Vs Torque characteristic.

K_2 = Slope of speed-torque characteristic.

With reference to fig 1.40, we can say that for speeds near zero, all the curves are straight lines parallel to the characteristic at rated input voltage (e_c= E) and are equally spaced for equal increments of the input voltage. Under this assumption, the torque developed by the motor is represented by equation (1.39) given below:

$$\text{Torque developed by motor, } T_m = K_1 e_c - K_2 \frac{d\theta}{dt} \quad .....(1.39)$$

The rotating part of motor and the load can be modelled by the equation (1.40) given below:

$$\text{Load torque, } T_l = J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} \quad .....(1.40)$$

At equilibruim the motor torque is equal to load torque.

$$\therefore\ J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} = K_1 e_c - K_2\frac{d\theta}{dt} \quad .....(1.41)$$

On taking Laplace transform of equation (1.39) with zero initial conditions we get,

$$J\,s^2\theta(s) + B\,s\theta(s) = K_1\,E_c(s) - K_2\,s\theta(s)$$

$$[J\,s^2 + Bs + K_2\,s]\theta(s) = K_1\,E_c(s)$$

$\mathcal{L}\{\theta\} = \theta(s)$; $\mathcal{L}\left\{\frac{d^n\theta}{dt^n}\right\} = s^n\,\theta(s)$
$\mathcal{L}\{e_c\} = E_c(s)$

$$\therefore\ \frac{\theta(s)}{E_c(s)} = \frac{K_1}{s(Js + B + K_2)} = \frac{K_1/(B+K_2)}{s\left(\frac{J}{B+K_2}s + 1\right)} = \frac{K_m}{s(\tau_m s + 1)} \quad .....(1.42)$$

$$\text{where, } K_m = \frac{K_1}{B+K_2} = \text{Motor gain constant} \quad .....(1.43)$$

$$\tau_m = \frac{J}{B+K_2} = \text{Motor time constant} \quad .....(1.44)$$

The equation (1.42) is the transfer function of ac servomotor.

> ***Note :*** *The modulation process for running the ac servomotor is not necessary if the control signal in the system is an ac signal of frequency equal to that of the reference phase supply. The transfer function of motor given by equation (1.42) is applicable in these situations also.*

1.10.5 SYNCHROS

The term synchro is a generic name for a family of inductive devices which works on the principle of a rotating transformer (Induction motor). The trade names for synchros are Selsyn, Autosyn and Telesyn. Basically they are electro-mechanical devices or electromagnetic transducers which produces an output voltage depending upon angular position of the rotor.

A synchro system is formed by interconnection of the devices called the synchro transmitter and the synchro control transformer. They are also called ***Synchro pair***. The synchro pair measures and compares two angular displacements and its output voltage is approximately linear with angular difference of the axis of both the shafts. They can be used in the following two ways,

1. To control the angular position of load from a remote place/long distance.
2. For automatic correction of changes due to disturbance in the angular position of the load.

SYNCHRO TRANSMITTER

Construction

The constructional features, electrical circuit and a schematic symbol of synchro transmitter are shown in fig 1.41. The two major parts of synchro transmitter are stator and rotor. The stator is identical to the stator of three phase alternator. It is made of laminated silicon steel and slotted on the inner periphery to accommodate a balanced three phase winding. The stator winding is concentric type with the axis of three coils 120º apart. The stator winding is star connected (Y-connection).

The rotor is of dumb bell construction with a single winding. The ends of rotor winding are terminated on two slip rings. A single phase ac excitation voltage is applied to rotor through slip rings.

Working principle

When the rotor is excited by ac voltage, the rotor current flows, and a magnetic field is produced. The rotor magnetic field induces an emf in the stator coils by transformer action. The effective voltage induced in any stator coil depends upon the angular position of the coil's axis with respect to rotor axis.

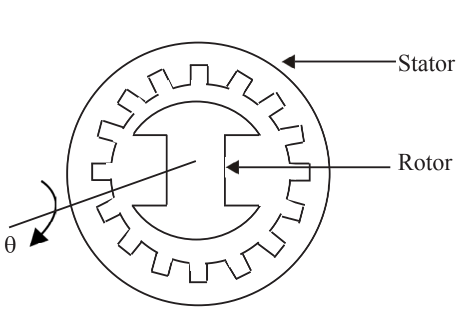


Fig 1.41a : *Constructional features.*

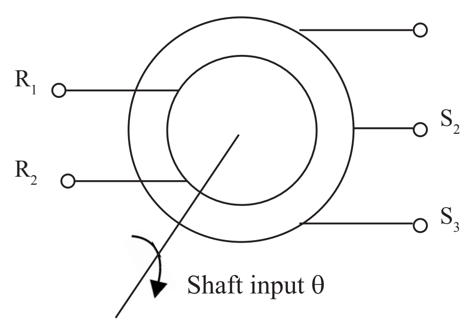


Fig 1.41b : *Schematic symbol of a synchro transmitter.*

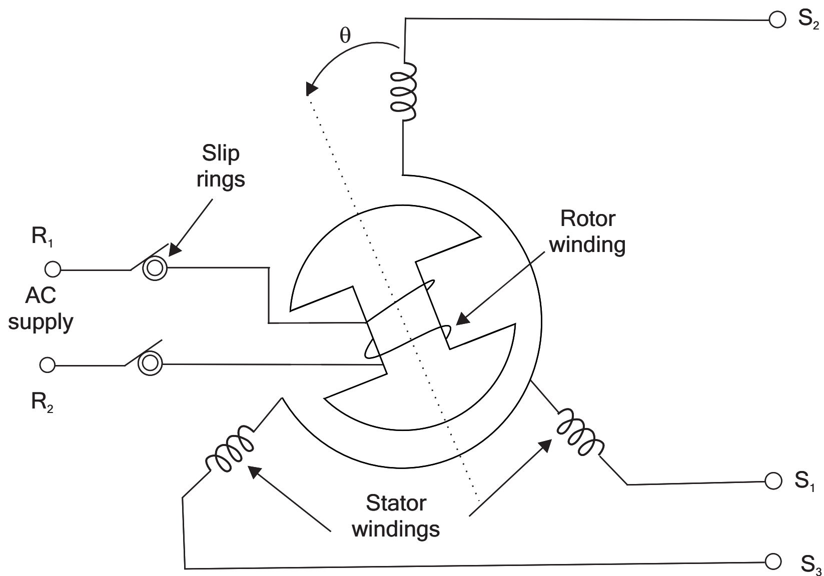


Fig 1.41c : *Electrical circuit.*
Fig 1.41 : *Synchro transmitter.*

Let, e_r = Instantaneous value of ac voltage applied to rotor.

e_{S1}, e_{S2}, e_{S3} = Instantaneous value of emf induced in stator coils S1,S2, S3 with respect to neutral respectively.

E_r = Maximum value of rotor excitation voltage.

ω = Angular frequency of rotor excitation voltage.

K_t = Turns ratio of stator and rotor windings.

K_c = Coupling coefficient.

θ = Angular displacement of rotor with respect to reference.

Let, the instantaneous value of rotor excitation voltage, $e_r = E_r \sin \omega t$ .....(1.45)

Let the rotor rotates in anticlockwise direction. When the rotor rotates by an angle,θ emfs are induced in stator coils. The frequency of induced emf is same as that of rotor frequency. The magnitude of induced emfs are proportional to the turns ratio and coupling coefficient. The turns ratio, K_t is a constant, but coupling coefficient, K_c is a function of rotor angular position.

$\therefore$ Induced emf in stator coil $= K_t K_c E_r \sin \omega t$ .....(1.46)

Let e_{S2} be reference vector. With reference to fig 1.41, when $\theta = 0$, the flux linkage of coil S_2 is maximum and when $\theta = 90^o$, the flux linkage of coil S_2 is zero. Hence the flux linkage of coil S_2 is function of cosθ (i.e., $K_c = K_1 \cos\theta$ for coil S_2). The flux linkage of coil s_3 will be maximum after a rotation of 120º in anticlockwise direction and that of S_1 after a rotation of 240^o.

$\therefore$ Coupling coefficient, K_c for coil-S_2 = $K_1 \cos\theta$

Coupling coefficient, K_c for coil-S_3 = $K_1 \cos(\theta - 120^o)$

Coupling coefficient, K_c for coil-S_1 = $K_1 \cos(\theta - 240^o)$

Hence the emfs of stator coils with respect to neutral can be expressed as follows.

$$e_{S2} = K_t K_1 \cos\theta\, E_r \sin\omega t = K\, E_r \cos\theta\, \sin\omega t \qquad .....(1.47)$$

$$e_{S3} = K_t K_1 \cos(\theta - 120^o)\, E_r \sin\omega t = K\, E_r \cos(\theta - 120^o) \sin\omega t \qquad .....(1.48)$$

$$e_{S1} = K_t K_1 \cos(\theta - 240^o)\, E_r \sin\omega t = K\, E_r \cos(\theta - 240^o) \sin\omega t \qquad .....(1.49)$$

With reference to fig 1.42 by kirchoff's voltage law the coil-to-coil emf can be expressed as,

$$e_{S1S2} = e_{S1} - e_{S2} = \sqrt{3}\, K\, E_r \sin(\theta + 240^o) \sin\omega t \qquad .....(1.50)$$

$$e_{S2S3} = e_{S2} - e_{S3} = \sqrt{3}\, K\, E_r \sin(\theta + 120^o) \sin\omega t \qquad .....(1.51)$$

$$e_{S3S1} = e_{S3} - e_{S1} = \sqrt{3}\, K\, E_r \sin\theta \sin\omega t \qquad .....(1.52)$$

$$\begin{aligned} e_{S1S2} = e_{S1} - e_{S2} &= K\, E_r \cos(\theta - 240^o) \sin\omega t - K\, E_r \cos\theta \sin\omega t \\ &= K\, E_r \left[\cos\theta \cos 240^o + \sin\theta \sin 240^o - \cos\theta\right] \sin\omega t \\ &= K\, E_r \left[\cos\theta(-0.5) + \sin\theta\left(-\frac{\sqrt{3}}{2}\right) - \cos\theta\right] \sin\omega t \\ &= \sqrt{3}\, K\, E_r \left[\sin\theta\left(-\frac{1}{2}\right) + \cos\theta\left(-\frac{\sqrt{3}}{2}\right)\right] \sin\omega t \\ &= \sqrt{3}\, K\, E_r \left[\sin\theta \cos 240^o + \cos\theta \sin 240^o\right] \sin\omega t \\ &= \sqrt{3}\, K\, E_r \sin(\theta + 240^o) \sin\omega t \end{aligned}$$

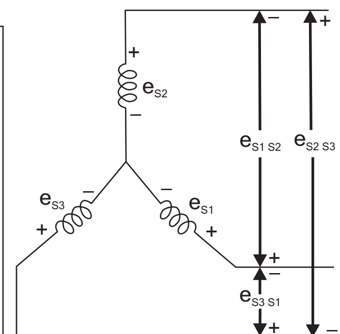


Fig 1.42 : *Induced emf in stator coils.*

$$\begin{aligned} e_{S2S3} = e_{S2} - e_{S3} &= K\, E_r \cos\theta \sin\omega t - K\, E_r \cos(\theta - 120^o) \sin\omega t \\ &= K\, E_r \left[\cos\theta - \cos\theta \cos 120^o - \sin\theta \sin 120^o\right] \sin\omega t \\ &= K\, E_r \left[\cos\theta - \cos\theta(-0.5) - \sin\theta\left(\frac{\sqrt{3}}{2}\right)\right] \sin\omega t = \sqrt{3}\, K\, E_r \left[\sin\theta\left(-\frac{1}{2}\right) + \cos\theta\left(\frac{\sqrt{3}}{2}\right)\right] \sin\omega t \\ &= \sqrt{3}\, K\, E_r \left[\sin\theta \cos 120^o + \cos\theta \sin 120^o\right] \sin\omega t = \sqrt{3}\, K\, E_r \sin(\theta + 120^o) \sin\omega t \end{aligned}$$

$$\begin{aligned} e_{S3S1} = e_{S3} - e_{S1} &= K\, E_r \cos(\theta - 120^o) \sin\omega t - K\, E_r \cos(\theta - 240^o) \sin\omega t \\ &= K\, E_r \left[\cos\theta \cos 120^o + \sin\theta \sin 120^o - \cos\theta \cos 240^o - \sin\theta \sin 240^o\right] \sin\omega t \\ &= K\, E_r \left[\cos(-0.5) + \sin\theta\left(\frac{\sqrt{3}}{2}\right) - \cos\theta(-0.5) - \sin\theta\left(-\frac{\sqrt{3}}{2}\right)\right] \sin\omega t = \sqrt{3}\, K\, E_r \sin\theta \sin\omega t \end{aligned}$$

When $\theta = 0$, from equation 1.47 we can say that maximum emf is induced in coil S_2. But from equation (1.52) it is observed that the coil-to-coil voltage e_{S3S1} is zero. This position of the rotor is defined as the electrical zero of the transmitter. The electrical zero position is used as reference for specifying the angular position of the rotor.

The input to the synchro transmitter is the angular position of its rotor shaft and the output is a set of three stator coil-to-coil voltages. By measuring and identifying the set of voltages at the stator terminals, it is possible to identify the angular position of the rotor. [A device called ***synchro/digital converter*** is available to measure the stator voltages and to calculate the angular measure and then display the direction and angle of rotation of the rotor].

SYNCHRO CONTROL TRANSFORMER

Construction

The constructional features of synchro control transformer is similar to that of synchro transmitter, except the shape of rotor. The rotor of the control transformer is made cylindrical so that the air gap is practically uniform. This feature of the control transformer minimizes the changes in the rotor impedance with the rotation of the shaft. The constructional features, electrical circuit and a schematic symbol of control transformer are shown in fig 1.43.

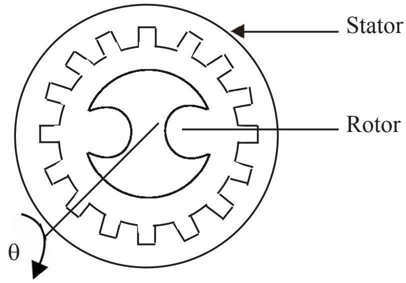


Fig 1.43a : *Constructional features.*

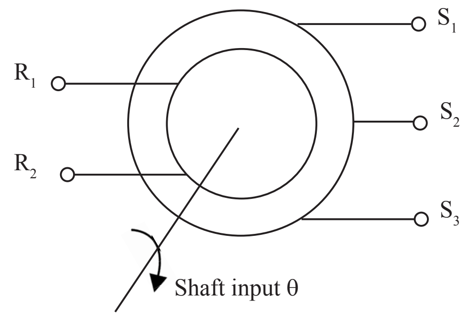


Fig 1.43b : *Schematic symbol of a synchro control transformer.*

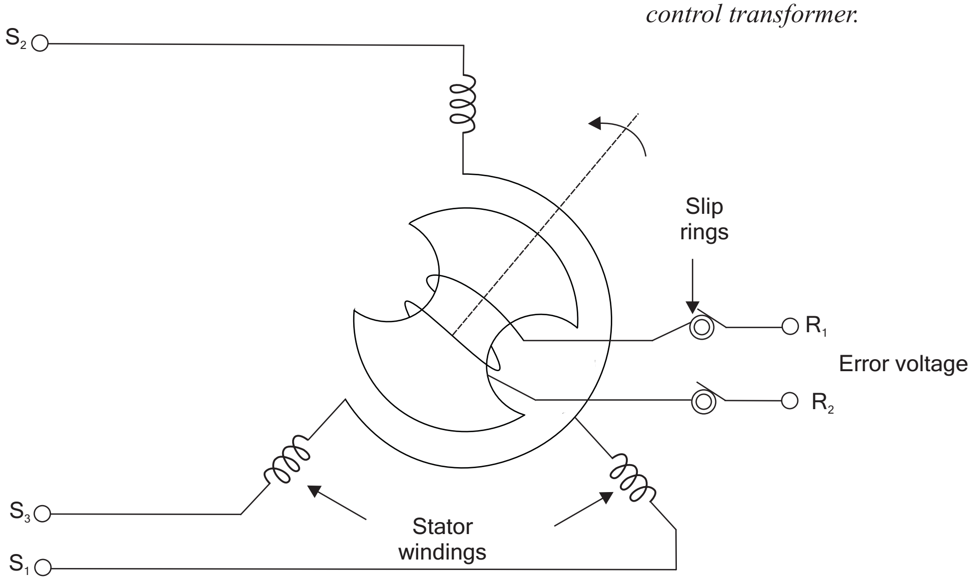


Fig 1.43c : *Electrical circuit.*

Fig 1.43 : *Synchro control transformer.*

Working

The generated emf of the synchro transmitter is applied as input to the stator coils of control transformer. The rotor shaft is connected to the load whose position has to be maintained at the desired value. Depending on the current position of the rotor and the applied emf on the stator, an emf is induced on the rotor winding. This emf can be measured and used to drive a motor so that the position of the load is corrected.

SYNCHRO AS ERROR DETECTOR

The synchro error detector is formed by interconnection of a synchro transmitter and synchro control transformer. In this arrangement, the stator leads of the transmitter are directly connected to the stator leads of the control transformer. The angular position of the transmitter-rotor is the reference input (or the input corresponding to the desired output) and the rotor is excited by ac supply with frequency, ω.

The control transformer rotor is connected to a servo motor and to the shaft of the load, whose position is the desired output. The induced emf (error voltage) available across the rotor slip rings of control transformer is measured by a signal conditioning circuit. The output of signal conditioning circuit is used to drive motor so that desired load position is achieved. A simple schematic diagram of synchros as error detector is shown in fig 1.44.

Initially the shafts of transmitter and control transformer are assumed to be in aligned position. In this position the transmitter rotor will be in electrical zero position and the control transformer rotor will be in null position and the angular separation of both rotor axis in aligned position is 90°. The null position of a control transformer in a servo system is defined as position of its rotor for which the output voltage on the rotor winding is zero with the transmitter in its electrical zero position.

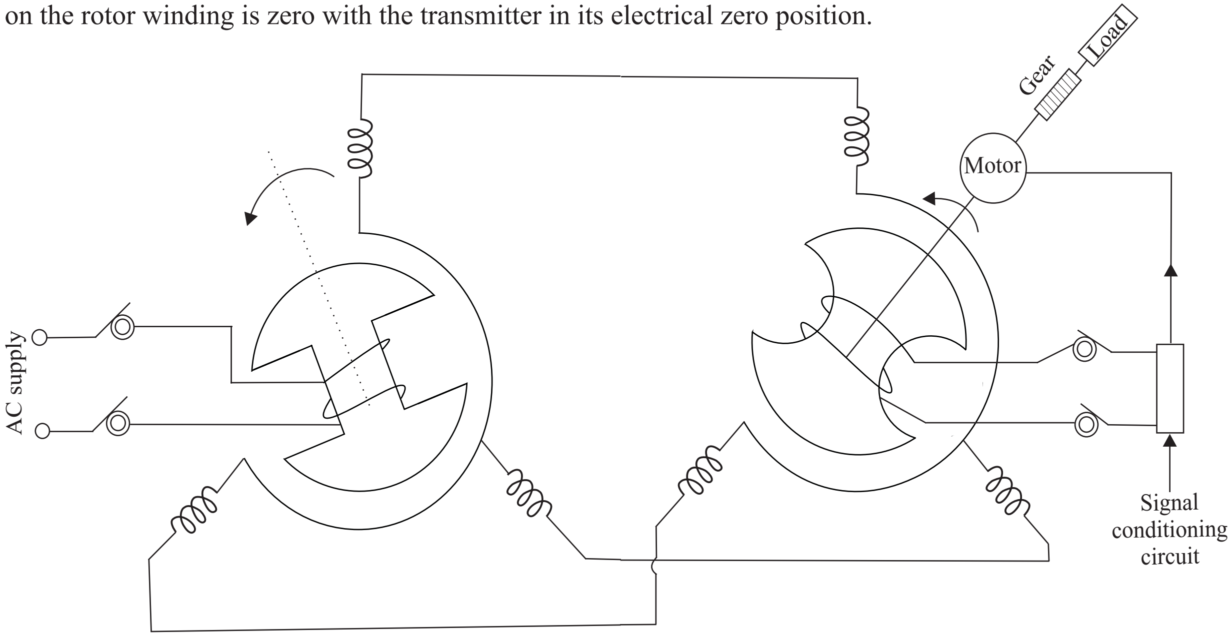


Fig 1.44 : *Servo system using synchro error detector.*

When, the transmitter rotor is excited, the rotor flux is set-up and emfs are induced in stator coils. These induced emfs are impressed on the stator coils of control transformer. The currents in the stator coils set up flux in control transformer. Due to the similarity in the magnetic construction, the flux patterns produced in the two synchros will be the same if all losses are neglected. The flux patterns are shown in fig 1.45.

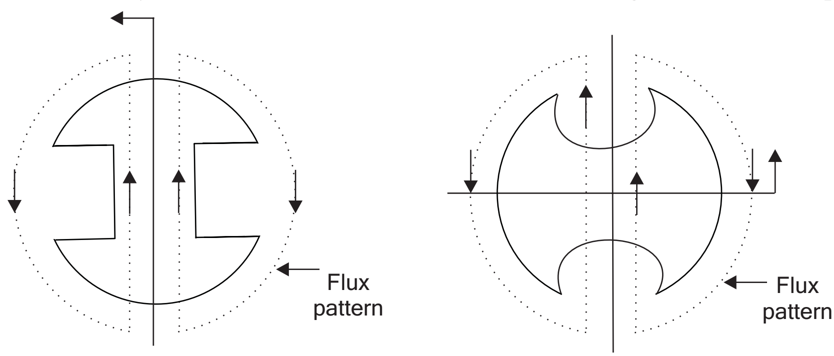


Fig 1.45 : Rotor positions and flux patterns.

Let the rotor of the transmitter rotate through an angle θ from its electrical zero position. Now the rotor of the control transformer will rotate in the same direction through an angle α from its null position.

The net angular separation of the two rotors is equal to $(90 - \theta + \alpha)$ and the voltage induced in the control transformer rotor is proportional to the cosine of this angle. The error voltage is amplified and used to drive a servo motor. The motor drives the shaft of the synchro control transformer until it comes to a newaligned position at which the error voltage is zero.

$\therefore$ Voltage across slip rings of control transformer (modulated error voltage) $\left.\right\} e_m = K' E_r \cos(90 - \theta + \alpha)\sin\omega t$

$$= K' E_r \cos(90 - (\theta - \alpha))\sin\omega t$$

$$= K' E_r \sin(\theta - \alpha)\sin\omega t$$

where K' is a propotional constant

Let, $\phi(t) = \theta - \alpha$ .....(1.53)

For small values of $\phi(t)$, $\sin(\theta - \alpha) = \sin\phi(t) \approx \phi(t)$

$$\therefore e_m = K' E_r \phi(t)\sin\omega t \qquad .....(1.54)$$

From the equation (1.53) we can say that the output voltage of the synchro error detector is a modulated signal with carrier frequency, ω (which is same as supply frequency of the transmitter rotor). The magnitude of the modulated carrier wave is proportional to $\phi(t)$ and the phase reversals of the modulated wave depend on the sign of $\phi(t)$. The signal conditioning circuit demodulates the voltage available across slip rings and develops a demodulated and amplified error voltage to drive the motor.

The demodulated error voltage, $e = K_s\phi(t)$ .....(1.55)

where K_s = Sensitivity of synchro error detector in Volts/deg.

On taking Laplace transform of equation (1.54) We get,

$$E(s) = K_s\phi(s) \qquad \therefore \frac{E(s)}{\phi(s)} = K_s$$

The equation (1.55) is the transfer function of the Synchro error detector.

> ***Note :*** *If the motor employed is an ac servomotor then the signal conditioning circuit will not include a demodulator.*

1.11 MULTIVARIABLE CONTROL SYSTEMS

Control systems with single input and single output are called SISO (Single-Input-Single-Output) systems. SISO systems will have a single variable to be controlled. The input is the set point or desired value of the variable and output is actual value of the variable maintained by the system. Examples of SISO systems are speed control of a motor, temperature control of a heating oven and angular position control of a servo motor.

When a control system has two or more variables to be controlled then it is called a multivariable control system. In multivariable control systems for each control variable there will be a reference input and an output which is the actual value of the variable maintained by the system. The multivariable control systems are also called MIMO (Multi-Input-Multi-Output) systems.

Controlling the supply voltage and speed of the motor is an example of multivariable control system with 2-inputs and 2-outputs. Controlling the temperature, pressure and liquid flow rate of a process control plant is an example of multivariable control system with 3-inputs and 3-outputs.

In multivariable control systems the variables may be interacting or non-interacting. The interacting variables are also called coupled variables and non-interacting variables are also called decoupled variables. When the variables are decoupled, controlling the variables is straight forward by designing a suitable independent controller for each variable.

When the variables are coupled, then there are two approaches in controlling the variables. In one approach, the variables are decoupled by designing a decoupling controller and then the variables are controlled by designing a suitable independent controller for each variable. In another approach a single controller is designed by considering the interactions between variables.

The transfer function is defined between one input and one output. Therefore, in MIMO systems, if all the variables are interacting or coupled, then there will be a transfer function between each input and output.

Consider a multivariable control system with m-inputs and m-outputs.

Let, $U_1(s), U_2(s), U_3(s), \ldots\ldots, U_m(s)$ be m-inputs.

Let, $Y_1(s), Y_2(s), Y_3(s), \ldots\ldots, Y_m(s)$ be m-outputs.

Now, $G_{ij}(s)$ = Transfer function between output $Y_i(s)$ and input $U_j(s)$.

Therefore, the transfer function between all inputs and outputs of a multivariable control system when all the variables are interacting can be expressed in the matrix form as shown below.

$$\begin{bmatrix} Y_1(s) \\ Y_2(s) \\ Y_3(s) \\ \vdots \\ Y_m(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) & G_{13}(s) \ldots\ldots & G_{1m}(s) \\ G_{21}(s) & G_{22}(s) & G_{23}(s) \ldots\ldots & G_{2m}(s) \\ G_{31}(s) & G_{32}(s) & G_{33}(s) \ldots\ldots & G_{3m}(s) \\ \vdots & \vdots & \vdots & \vdots \\ G_{m1}(s) & G_{m2}(s) & G_{m3}(s) \ldots\ldots & G_{mm}(s) \end{bmatrix} \begin{bmatrix} U_1(s) \\ U_2(s) \\ U_3(s) \\ \vdots \\ U_m(s) \end{bmatrix}$$

From the above matrix representation, when m=3, we get the following equations.

$$Y_1(s) = G_{11}(s)\, U_1(s) + G_{12}(s)\, U_2(s) + G_{13}(s)\, U_3(s)$$

$$Y_2(s) = G_{21}(s)\, U_1(s) + G_{22}(s)\, U_2(s) + G_{23}(s)\, U_3(s)$$

$$Y_3(s) = G_{31}(s)\, U_1(s) + G_{32}(s)\, U_2(s) + G_{33}(s)\, U_3(s)$$

Using the above equations, the open loop block diagram of 3-input and 3-output interacting multivariable control system can be drawn as shown in Fig 1.46. The closed loop control for interacting multivariable control system is quite complicated.

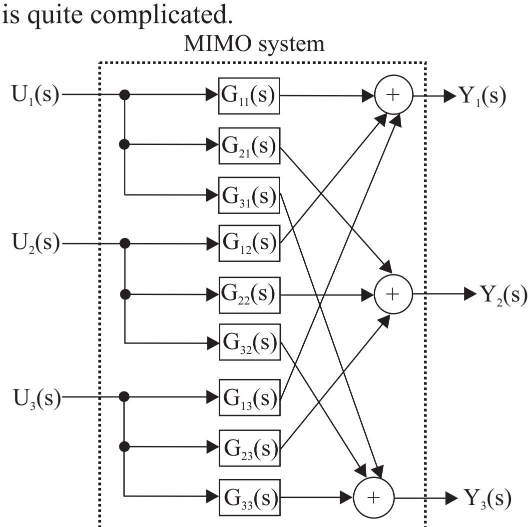


Fig 1.46: *Block diagram of interacting multivariable open loop control system*

When the variables are non-interacting, $G_{ij}(s) = 0$ for all values of i and j. Therefore, the transfer function matrix will be a diagonal matrix. Therefore, the matrix representation of non-interacting multivariable control system will be as shown below.

$$\begin{bmatrix} Y_1(s) \\ Y_2(s) \\ Y_3(s) \\ \vdots \\ Y_m(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & 0 & 0 & \ldots\ldots & 0 \\ 0 & G_{22}(s) & 0 & \ldots\ldots & 0 \\ 0 & 0 & G_{33}(s) & \ldots\ldots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \ldots\ldots & G_{mm}(s) \end{bmatrix} \begin{bmatrix} U_1(s) \\ U_2(s) \\ U_3(s) \\ \vdots \\ U_m(s) \end{bmatrix}$$

From the above matrix representation,when m=3, we get the following equations.

$$Y_1(s) = G_{11}(s)\, U_1(s)$$

$$Y_2(s) = G_{22}(s)\, U_2(s)$$

$$Y_3(s) = G_{33}(s)\, U_3(s)$$

Using the above equations, the open loop block diagram of 3-input and 3-output non-interacting multivariable control system can be drawn as shown in Fig 1.47. Here, the MIMO system is considered as three independent SISO systems.

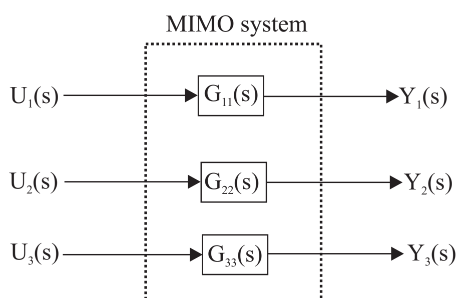


Fig 1.47: *Block diagram of non-interacting multivariable open loop control system*

When the variables are non-interacting, separate controllers can be designed for closed loop control. Therefore the closed loop block diagram of 3-input and 3-output non-interacting multivariable control system can be drawn as shown in Fig 1.48, where $G_{c1}(s)$, $G_{c2}(s)$ and $G_{c3}(s)$ are separate controllers to control the three variables of the multivariable control system.

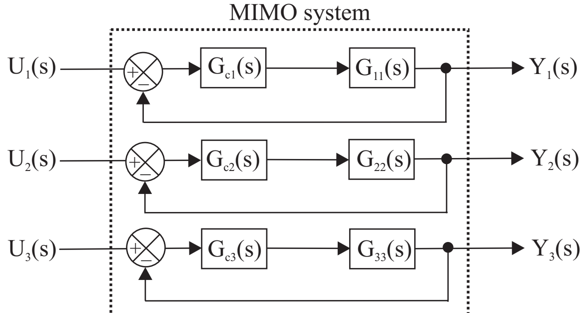


Fig 1.48: *Block diagram of non-interacting multivariable closed loop control system*

1.12 SHORT-ANSWER QUESTIONS

Q1.1 What is system?

When a number of elements or components are connected in a sequence to perform a specific function, the group thus formed is called a system.

Q1.2 What is control system?

A system consists of a number of components connected together to perform a specific function. In a system when the output quantity is controlled by varying the input quantity, then the system is called control system. The output quantity is called controlled variable or response and input quantity is called command signal or excitation.

Q1.3 What are the two major type of control systems?

The two major type of control systems are open loop and closed loop systems.

Q1.4 Define open loop system.

The control system in which the output quantity has no effect upon the input quantity are called open loop control system. This means that the output is not fedback to the input for correction.

Q1.5 Define closed loop system.

The control systems in which the output has an effect upon the input quantity in order to maintain the desired output value are called closed loop control systems.

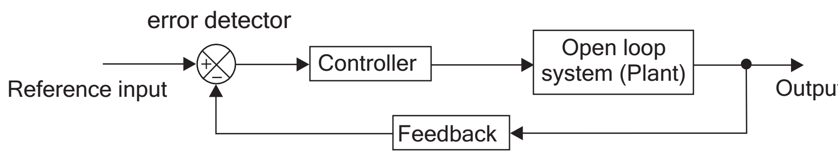
Q1.6 What is feedback? What type of feedback is employed in control system?

The feedback is a control action in which the output is sampled and a proportional signal is given to input for automatic correction of any changes in desired output.

Negative feedback is employed in control system.

Q1.7 What are the components of feedback control system?

The components of feedback control system are plant, feedback path elements, error detector and controller.



Q1.8 Why negative feedback is invariably preferred in a closed loop system?

The negative feedback results in better stability in steady state and rejects any disturbance signals. It also has low sensitivity to parameter variations. Hence negative feedback is preferred in closed loop systems.

Q1.9 What are the characteristics of negative feedback?

The characteristics of negative feedback are as follows :

(i) accuracy in tracking steady state value.

(ii) rejection of disturbance signals.

(iii) low sensitivity to parameter variations.

(iv) reduction in gain at the expense of better stability.

Q1.10. What is the effect of positive feedback on stability?

The positive feedback increases the error signal and drives the output to instability. But sometimes the positive feedback is used in minor loops in control systems to amplify certain internal signals or parameters.

Q1.11. ***Distinguish between open loop and closed loop system.***

Open loop	Closed loop
1. Inaccurate & unreliable.	1. Accurate & reliable.
2. Simple and economical.	2. Complex and costly.
3. Changes in output due to external disturbances are not corrected automatically.	3. Changes in output due to external disturbances are corrected automatically.
4. They are generally stable.	4. Great efforts are needed to design a stable system.

Q1.12 ***What is servomechanism?***

The servomechanism is a feedback control system in which the output is mechanical position (or time derivatives of position e.g. velocity and acceleration).

Q1.13 ***State the principle of homogenity (or) State the principle of superposition.***

The principle of superposition and homogenity states that if the system has responses $c_1(t)$ and $c_2(t)$ for the inputs $r_1(t)$ and $r_2(t)$ respectively then the system response to the linear combination of these input $a_1r_1(t) + a_2r_2(t)$ is given by linear combination of the individual outputs $a_1c_1(t) + a_2c_2(t)$, where a_1 and a_2 are constants.

Q1.14 ***Define linear system.***

A system is said to be linear, if it obeys the principle of superposition and homogenity, which states that the response of a system to a weighed sum of signals is equal to the corresponding weighed sum of the responses of the system to each of the individual input signals. The concept of linear system is diagrammatically shown below.

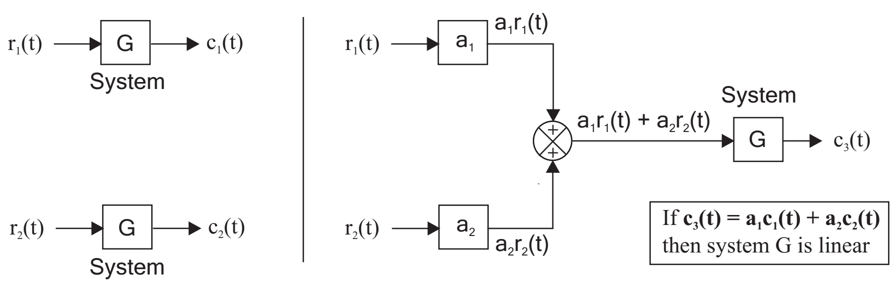


Fig Q1.14 : *Principle of linearity and superposition.*

Q1.15 ***What is time invariant system?***

A system is said to be time invariant if its input-output characteristics do not change with time. A linear time invariant system can be represented by constant coefficient differential equations. (In linear time varying systems the coefficients of the differential equation governing the system are function of time).

Q1.16 ***Define transfer function.***

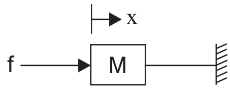
The transfer function of a system is defined as the ratio of Laplace transform of output to Laplace transform of input with zero initial conditions. (It is also defined as the Laplace transform of the impulse response of system with zero initial conditions).

Q1.17 ***What are the basic elements used for modelling mechanical translational system?***

The model of mechanical translational system can be obtained by using three basic elements mass, spring and dashpot.

Q1.18 ***Write the force balance equation of ideal mass element.***

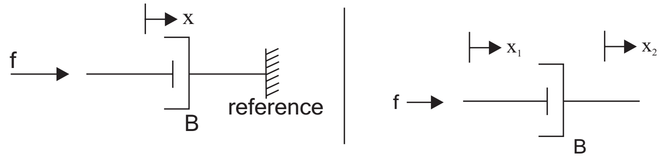
Let a force f be applied to an ideal mass M. The mass will offer an opposing force, f_m which is proportional to acceleration.



$$\therefore\ f = f_m = M\frac{d^2x}{dt^2}$$

Q1.19 Write the force balance equation of ideal dashpot.

Let a force f be applied to an ideal dashpot, with viscous frictional coefficient B. The dashpot will offer an opposing force, f_b which is proportional to velocity.



$$f = f_b = B\frac{dx}{dt} \qquad f = f_b = B\frac{d}{dt}(x_1 - x_2)$$

Q1.20 Write the force balance equation of ideal spring.

Let a force f be applied to an ideal spring with spring constant K. The spring will offer an opposing force, f_k which is proportional to displacement.

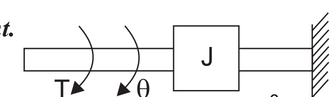
$$f = f_k = Kx \qquad f = f_k = K(x_1 - x_2)$$

Q1.21 What are the basic elements used for modelling mechanical rotational system?

The model of mechanical rotational system can be obtained using three basic elements mass with moment of inertia, J, dash-pot with rotational frictional coefficient, B and torsional spring with stiffness, K.

Q1.22 Write the torque balance equation of an ideal rotational mass element.

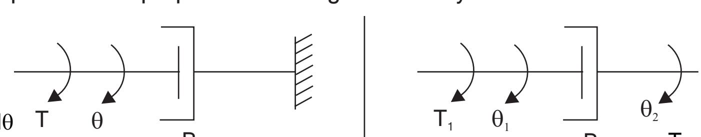
Let a torque T be applied to an ideal mass with moment of inertia, J. The mass will offer an opposing torque T_j which is proportional to angular acceleration.



$$T = T_j = J\frac{d^2\theta}{dt^2}$$

Q1.23 Write the torque balance equation of an ideal rotational dash-pot.

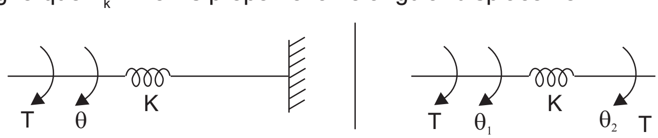
Let a torque T be applied to a rotational dash-pot with frictional coefficient B. The dashpot will offer an opposing torque which is proportional to angular velocity.



$$T = T_b = B\frac{d\theta}{dt} \qquad T = T_b = B\frac{d}{dt}(\theta_1 - \theta_2)$$

Q1.24 Write the torque balance equation of ideal rotational spring.

Let a torque T be applied to an ideal rotational spring with spring constant K. The spring will offer an opposing torque T_k which is proportional to angular displacement.



$$T_k = K\theta \qquad T = T_k = K(\theta_1 - \theta_2)$$

Q1.25 Name the two types of electrical analogous for mechanical system.

The two types of analogies for the mechanical system are force-voltage and force-current analogy.

Q1.26 ***Write the analogous electrical elements in force-voltage analogy for the elements of mechanical translational system.***

Force, f	→ Voltage, e	Frictional coefficient , B	→ Resistance, R
Velocity, v	→ Current, i	Stiffness, K	→ Inverse of capacitance, 1/C
Displacement, x	→ Charge, q	Newton's second law, $\Sigma f = 0$	→ Kirchoff 's voltage law, $\Sigma v = 0$
Mass, M	→ Inductance, L		

Q1.27 ***Write the analogous electrical elements in force-current analogy for the elements of mechanical translational system.***

Force, f	→ Current, i	Frictional coefficient, B	→ Conductance, G =1/ R
Velocity, v	→ Voltage, v	Stiffness, K	→ Inverse of Inductance, 1/L
Displacement, x	→ Flux, ϕ	Newton's second law, $\Sigma f = 0$	→ Kirchoff's current law, $\Sigma i = 0$
Mass, M	→ Capacitance, C		

Q1.28 ***Write the analogous electrical elements in torque-voltage analogy for the elements of mechanical rotational system.***

Torque, T	→Voltage, e	Stiffness of spring, K	→ Inverse of capacitance, 1/C
Angular velocity, ω	→Current, i	Frictional coefficient, B	→ Resistance, R
Moment of inertia, J	→Inductance, L	Newton's second law, $\Sigma T = 0$	→ Kirchoff 's voltage law, $\Sigma v = 0$.
Angular displacement, θ	→ Charge, q		

Q1.29 ***Write the analogous electrical elements in torque-current analogy for the elements of mechanical rotational system.***

Torque, T	→ Current, i	Frictional coefficient , B	→ Conductance, G = 1/R
Angular velocity, ω	→ Voltage, v	Stiffness of spring, K	→ Inverse of inductance, 1/L
Angular displacement, θ	→ Flux, ϕ	Newton's second law, $\Sigma T = 0$	→Kirchoff 's current law, $\Sigma i = 0$
Moment of inertia, J	→ Capacitance, C		

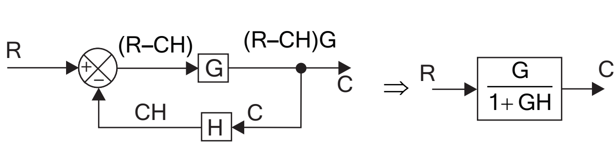
Q1.30 ***What is block diagram? What are the basic components of block diagram?***

A block diagram of a system is a pictorial representation of the functions performed by each component of the system and shows the flow of signals. The basic elements of block diagram are block, branch point and summing point.

Q1.31 ***What is the basis for framing the rules of block diagram reduction technique?***

The rules for block diagram reduction technique are framed such that any modification made on the diagram does not alter the input output relation.

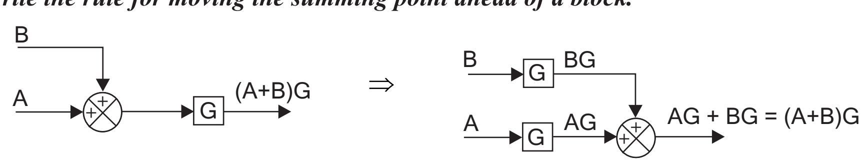
Q1.32 ***Write the rule for eliminating negative feedback loop.***



Proof

$$C = (R - CH)\,G$$
$$C = RG - CHG$$
$$C + CHG = RG$$
$$C(1 + HG) = RG$$
$$\frac{C}{R} = \frac{G}{1+GH}$$

Q1.33 ***Write the rule for moving the summing point ahead of a block.***



Q1.34 What is a signal flow graph?

A signal flow graph is a diagram that represents a set of simultaneous linear algebraic equations. By taking Laplace transform, the time domain differential equations governing a control system can be transferred to a set of algebraic equations in s-domain. The signal flow graph of the system can be constructed using these equations.

Q1.35 What is transmittance?

The transmittance is the gain acquired by the signal when it travels from one node to another node in signal flow graph.

Q1.36 What is sink and source?

Source is the input node in the signal flow graph and it has only outgoing branches. Sink is a output node in the signal flow graph and it has only incoming branches.

Q1.37 Define non-touching loop.

The loops are said to be non-touching if they do not have common nodes.

Q1.38 What are the basic properties of signal flow graph?

The basic properties of signal flow graph are,

(i) Signal flow graph is applicable to linear systems.

(ii) It consists of nodes and branches. A node is a point representing a variable or signal. A branch indicates functional dependence of one signal on the other.

(iii) A node adds the signals of all incoming branches and transmits this sum to all outgoing branches.

(iv) Signals travel along branches only in the marked direction and when it travels it gets multiplied by the gain or transmittance of the branch.

(v) The algebraic equations must be in the form of cause and effect relationship.

Q1.39 Write the Mason's gain formula.

Mason's gain formula states that the overall gain of the system [transfer function] as follows,

$$\text{Overall gain, } T = \frac{1}{\Delta}\sum_{K} P_K \Delta_K$$

T = T(s) = Transfer function of the system

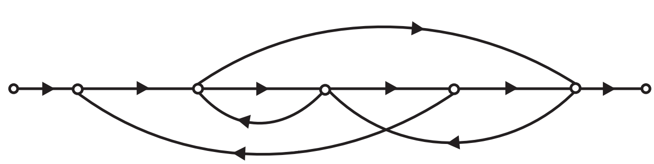
K = Number of forward paths in the signal flow graph

P_K = Forward path gain of K^{th} forward path

$$\Delta = 1 - \begin{bmatrix}\text{sum of individual} \\ \text{loop gains}\end{bmatrix} + \begin{bmatrix}\text{sum of gain products of all possible} \\ \text{combinations of two non-touching loops}\end{bmatrix}$$
$$- \begin{bmatrix}\text{sum of gain products of all possible} \\ \text{combinations of three non-touching loops}\end{bmatrix} + \ldots\ldots$$

$\Delta_K = \Delta$ for that part of the graph which is not touching K^{th} forward path

Q1.40 For the given signal flow graph, identify the number of forward path and number of individual loop.



Number of forward paths = 2
Number of individual loops = 4

Q1.41 What are the basic components of an automatic control system ?

The basic components of an automatic control system are,

1. Error detector
2. Amplifier and controller
3. Actuator (Power actuator)
4. Plant
5. Sensor or feedback system

Q1.42 What is automatic controller ?

The combined unit of error detector, amplifier and controller is called automatic controller.

Q1.43 What is a Potentiometer?

A potentiometer is a device that can be used to convert linear or angular displacement into a voltage. Basically it is a variable resistance whose value varies according to the angular or linear displacement of the wiper contact.

Q1.44 What are the differences between AC and DC potentiometers?

1. The output of AC potentiometer is a modulated voltage and so it has to be demodulated to get the error or control signal. But the output of DC potentiometer need not be demodulated.
2. The AC potentiometer will have inductive effects. But the DC potentiometer will not have any inductive effects.

Q1.45 What are the applications of Potentiometer?

The potentiometers are used to convert a linear or angular displacement into a proportional electrical signal. It is also used as error detector in which it produces an output voltage which is proportional to the difference between two linear or angular displacements.

Q1.46 A 10KΩ potentiometer whose center point is grounded at the two fixed ends are excited by +10V and –10V. The potentiometer has a total angular motion of 350º. What is the gain constant of potentiometer.

$$\text{Gain constant, } K_p = \frac{\text{Total excitation voltage}}{\text{Total angular motion}} = \frac{10-(-10)}{350^\circ \times \pi/180} = \frac{20}{350^\circ \times \pi/180} = 3.27 \text{ V/rad}$$

Q1.47 Determine the number of turns of wire needed to provide a potentiometer with the resolution of 0.05%..

$$\%\text{resolution} = \frac{100}{\text{number of turns}} \quad ; \quad \therefore\ 0.05 = \frac{100}{N} \quad ; \quad N = \frac{100}{0.05} = 2000 \text{ turns}$$

Q1.48 A helical 5 turn pot has a resistance of 10KΩ and 9000 winding turns. If the measured resistance at its midpoint setting is 5050Ω, then what is the linearity?

Deviation from nominal at midpoint = 5050 – 5000 = 50

$$\text{Linearity} = \frac{\text{Deviation from nominal}}{\text{Total resistance}} \times 100 = \frac{50}{10000} \times 100 = 0.5\%$$

Q1.49 What is Synchro?

A synchro is a device used to convert an angular motion to an electrical signal or viceversa. It works on the principle of a rotating transformer (induction motor).

Q1.50 What is synchro pair?

A synchro pair is a system formed by interconnection of the devices : synchro transmitter and synchro control transformer. A synchro pair is used to either transmit an angular motion from one place to another or employed to produce an error voltage proportional to the difference between two angular motions.

Q1.51 What are the differences between synchro transmitter and control transformer?

1. Rotor of synchro transmitter is of dumb bell shape. But rotor of control transformer is cylindrical.
2. The rotor winding of synchro transmitter is excited by an AC voltage. In control transformer, the induced emf in the rotor is used as an output signal (error signal).

Q1.52 What is electrical zero of a synchro?

The electrical zero of a synchro transmitter is a position of rotor at which one of the coil to coil voltage is zero. Any angular motion of the rotor is measured with respect to the electrical zero position of the rotor.

For the arrangement shown in fig Q1.52, the coil S_2 will have maximum emf induced in it and the coil to coil voltage e_{S3S1} will be zero and the rotor is in electrical zero position.

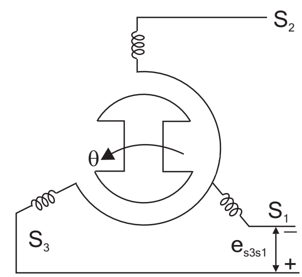


Fig Q1.52 : *Electrical zero position of synchro transmitter.*

Q1.53 What is Null position in Synchro?

The Null position of a synchro control transformer in a servo system is defined as, the position of its rotor for which the output voltage on the rotor winding is zero, with the transmitter in its electrical zero position.

Q1.54 What is aligned position of a synchro pair?

In the aligned position of a synchro pair, the transmitter rotor will be in electrical zero position and the control transformer rotor will be in null position. The angular separation of both rotor axis in aligned position is 90°. The error signal is zero in the aligned position.

Q1.55 What are the applications of Synchro?

The synchros are used in positional control systems (servomechanism) as error detector and to convert angular displacements to proportional electrical signals. It is also used in control systems to transmit angular motions from one place to another.

Q1.56 What are the trade names of Synchros?

The trade names for synchros are Selsyn, Autosyn and Telesyn.

Q1.57 What is Servomotor?

The motors used in automatic control system or in servomechanism are called Servomotors. They are used to convert electrial signal to angular motion.

Q1.58 What are the characteristic of servomotors?

1. Linear relationship between the speed and electric control signal.
2. Steady-state stability.
3. Wide range of speed control.
4. Linearity of mechanical characteristic throughout the entire speed range.
5. Low mechanical and electrical inertia.
6. Fast response.

Q1.59 compare the AC and DC sevomotors?

DC servomotor	AC servomotor
1. Higher power output.	1. Relatively lesser power output than a DC servomotor of same size.
2. Characteristics are linear.	2. Characteristics are non-linear.
3. Fast response due to low electrical and mechanical time constant.	3. The response is relatively slower than DC servomotors due to higher values of time constants.
4. Suitable for large power applications.	4. Suitable for low power applications.

Q1.60 What are the advantages of permanent magnet DC servomotors?

1. A simpler, more reliable motor because the field power supply is not required.
2. Higher efficiency due to the absence of field losses.
3. Field flux is less affected by temperature rise.
4. Less heating, making it possible to totally enclose the motor.
5. No possibility of over speeding due to loss of field.
6. A more linear torque Vs speed curve.
7. Higher power output at the same dimensions and temperature limitations.

Q1.61 What are the special features of DC servomotors ?

1. The number of slots and commutator segments is large to improve commutation.
2. Compoles and compensating windings are provided to eliminate sparking.
3. The diameter to length ratio is kept low to reduce inertia.
4. Oversize shafts are employed to withstand the high torque stress.
5. Eddy currents are reduced by complete lamination of magnetic circuit and by using low-loss steel.

Q1.62 What is the difference between ac servomotor and two phase induction motor?

1. The ac servomotor has low value of X/R to achieve linear speed-torque characteristics. But conventional induction motor will have large values of X/R for higher efficiency.
2. The ac servomotor has low inertia rotor. The inertia of the rotor is reduced by reducing the diameter or by drag-cup construction.

Q1.63 What are the different types of rotor that are used in ac servomotor?

The types of rotors of ac servomotor are squirrel-cage rotor and drag-cup rotor.

Q1.64 Write the differential equation governing the ac servomotor.

The differential equation governing the ac servomotor is, $T_m = K_1 e_c - K_2 \frac{d\theta}{dt}$

where,
T_m = Torque developed by motor.
e_c = Control signal.
θ = Angular displacement of rotor.
K_1 = Slope of Control-phase voltage Vs Torque characteristics.
K_2 = Slope of Speed Vs Torque characteristics.

1.13 EXERCISES

E1.1 For the mechanical system shown in fig E1.1derive the transfer function. Also draw the force-voltage and force-current analogous circuits.

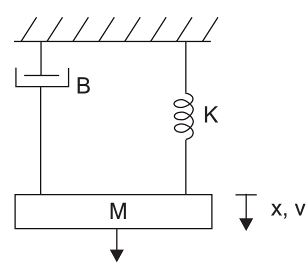


Fig E1.1

E1.2 For the mechanical system shown in fig E1.2 draw the force-voltage and force-current analogous circuits.

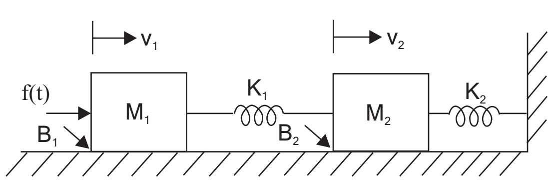


Fig E1.2

E1.3 Write the differential equations governing the mechanical system shown in fig E1.3(a) & (b). Also draw the force-voltage and force-current analogous circuit.

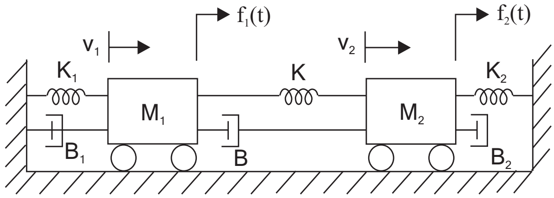


Fig E1.3(a)

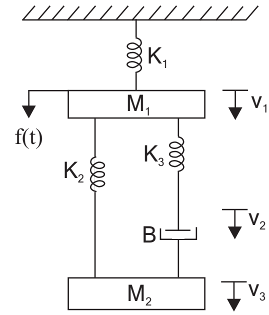


Fig E1.3(b)

E1.4 Consider the mechanical translational system shown in fig E1.4, Draw(a) force-voltage and (b) force-current analogous circuits.

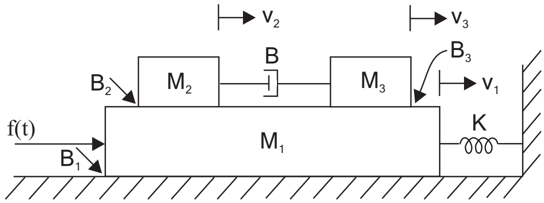


Fig E1.4

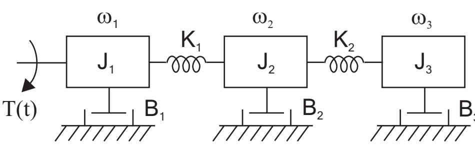


Fig E1.5

E1.5 Write the differential equations governing the rotational mechanical system shown in fig E1.5. Also draw the torque-voltage and torque-current analogous circuits.

E1.6 In an electrical circuit the elements resistance, capacitance and inductance are connected in parallel across the voltage source E as shown in fig E1.6, Draw(a) Translation mechnical analogous system (b) Rotational mechanical analogous system.

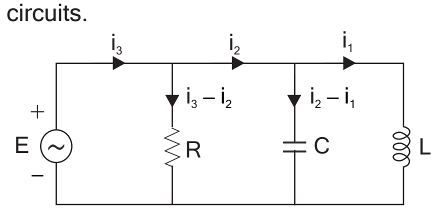


Fig E1.6

E1.7 Consider the block diagram shown in fig E.1.7(a), (b) (c) & (d). Using the block diagram reduction technique, find C/R.

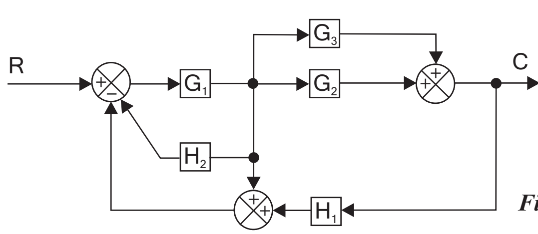


Fig E1.7(a)

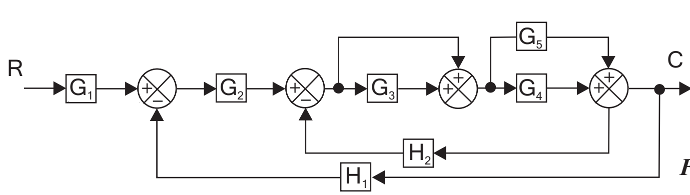


Fig E1.7(b)

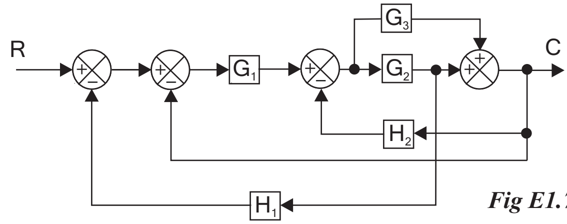


Fig E1.7(c)

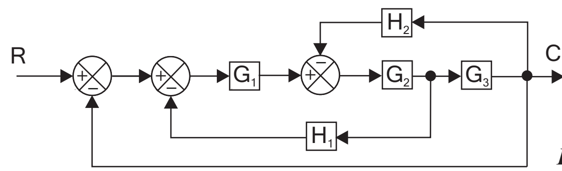


Fig E1.7(d)

E1.8 Convert the block diagram shown in fig E1.8 to signal flow graph and find the transfer function of the system.

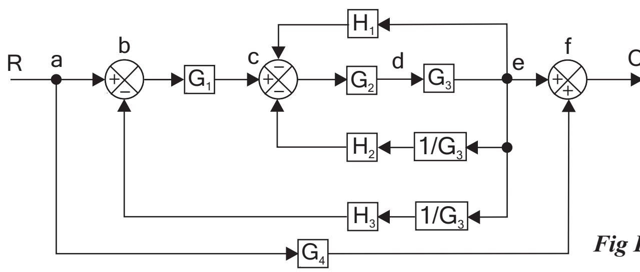


Fig E1.8

E1.9 Consider the system shown in fig E1.9(a), (b), (c) & (d). obtain the transfer function using Mason's gain formula.

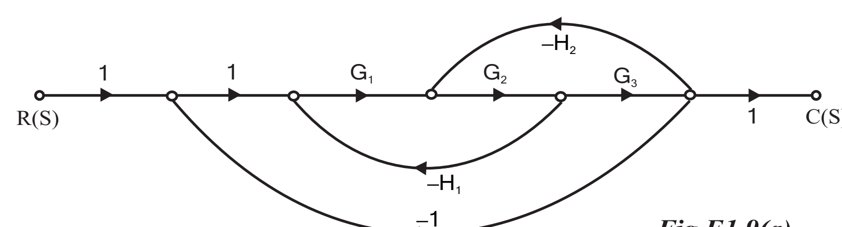


Fig E1.9(a)

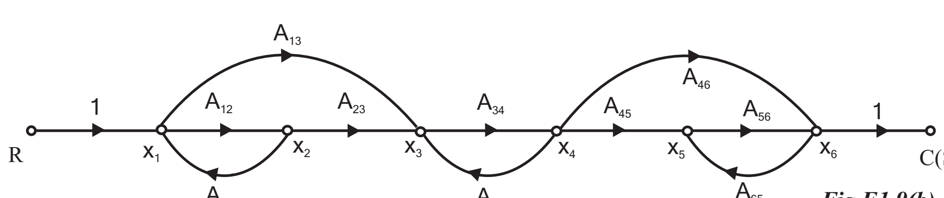


Fig E1.9(b)

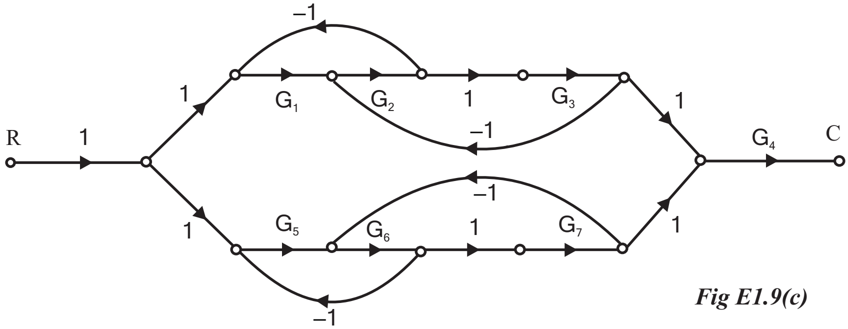


Fig E1.9(c)

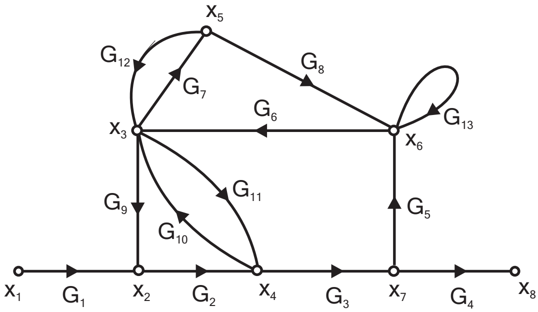


Fig E1.9(d)

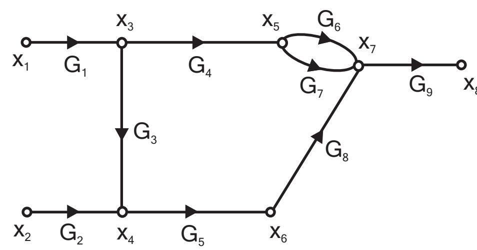


Fig E1.10

E1.10 Consider the signal flow graph shown in fig E.1.10 obtain $\frac{x_8}{x_1}$ and $\frac{x_8}{x_2}$

E1.11 Find the transfer functions of the networks shown in fig E1.11(a), (b), (c) & (d).

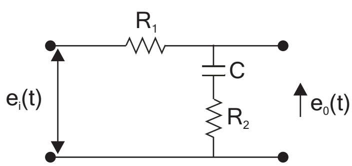


Fig E1.11(a)

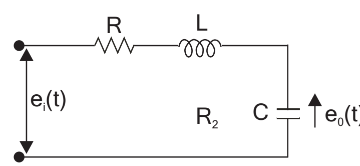


Fig E1.11(b)

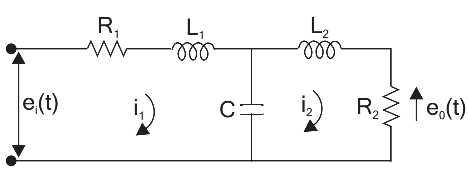


Fig E1.11(c)

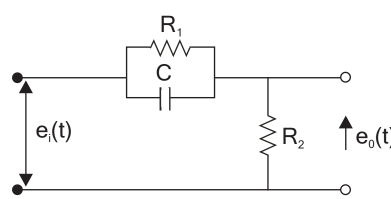


Fig E1.11(d)

E1.12 Find the transfer function of the circuit shown in fig E1.12.

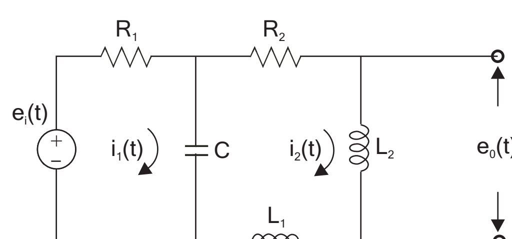


Fig E1.12

E1.13 Consider the positional servomechanism shown in fig E1.12. Assume that the input to the system is reference shaft position θ_R and the system output is the load shaft position θ_L. Draw a block diagram of the system indicating the transfer function of each block. Simplify the block diagram to obtain $\theta_L(s)/\theta_R(s)$. The parameters of the system are given below.

Sensitivity of error detector	K_P	=	10 Volts/rad
Amplifier gain	K_A	=	50 Volts/volt
Motor field resistance	R_f	=	100 Ohms
Motor field inductance	L_f	=	20 Henrys
Motor torque constant	K_T	=	10 Newton-m/amp
Moment of inertia of load	J_L	=	250 Kg-m^2
Coefficient of viscous friction of load	B_L	=	2500 Newton-m/(rad/sec)
Motor to load gear ratio	$\dot{\theta}_L/\dot{\theta}_M$	=	1/50
Load to potentiometer gear ratio	$\dot{\theta}_P/\dot{\theta}_L$	=	1

Motor inertia and friction are negligible.

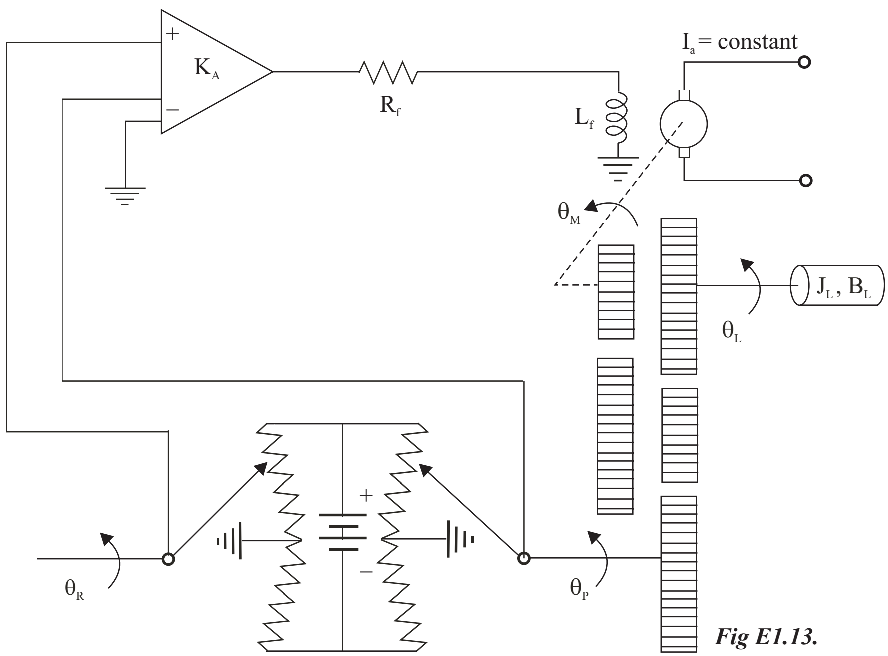


Fig E1.13.

E1.14 The schematic diagram of a servo system is shown in fig E1.14. The two-phase servomotor develops a torque in accordance with the equation $T_M = K_1 e_c - K_2\dot{\theta}_M$ where $K_1 = 1\times10^{-5}$ N-m/volt, $K_2 = 0.25\times10^{-5}$ N-m/(rad/sec). The other parameters of the system are : Synchro sensitivity, K_s = 1 Volt/rad. Amplifier gain, K_A = 20 Volt/volt. Tachometer constant, K_t = 0.2 Volt/(rad/sec). Load inertia, $J_L = 1.5\times10^{-5}$ Kg-m^2. Viscous friction, $B_L = 1\times10^{-5}$ N-m/(rad/sec). $\dot{\theta}_M/\dot{\theta}_s=1$, $\dot{\theta}_M/\dot{\theta}_T = 1$. Motor inertia and friction are negligible. Draw the block diagram of the system and therefrom obtain transfer function $\theta_M/\theta_s(s)$.

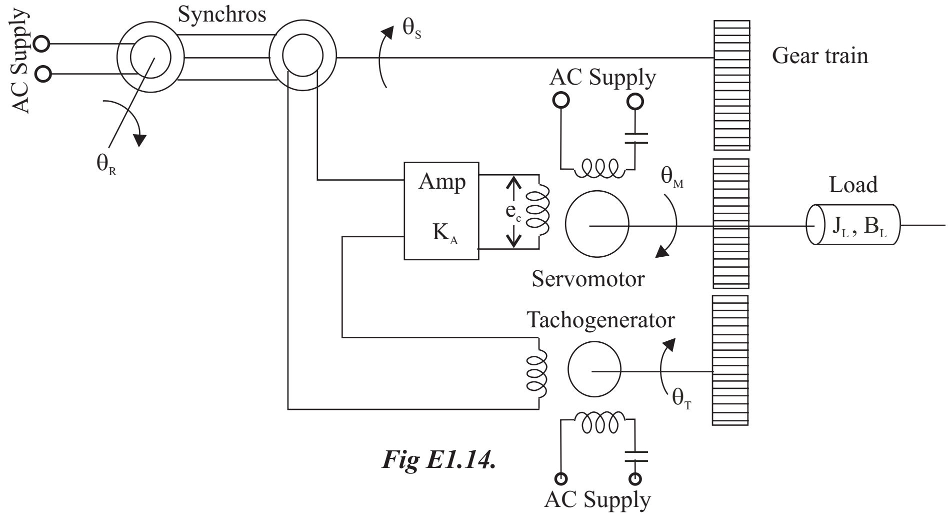


Fig E1.14.

E1.15 An ac-dc servo system is shown in fig E1.15. The sensitivity of the synchro error detector is K_s Volt/rad and the gain of the generator is K_g Volts/field amp. The dc motor is separately excited and has a back emf constant of K_b Volts/(rad/sec) and a torque constant of K_T N-m/amp. Motor inertia and friction are negligible. Draw the block diagram of the system indicating the transfer function of each block. Obtain $\theta_L(s)/\theta_R(s)$.

The system parameters are given below :

K_s	=	30 Volts/rad	K_A	=	5 Volts/Volts
R_f	=	100 Ohms	L_f	=	2 Henrys
K_g	=	100 Volts/field amp	R_a	=	1 Ohm
K_b	=	1 Volts/(rad/sec)	J_L	=	0.5 Kg-m^2
B_L	=	1 N-m/(rad/sec)	$\dot{\theta}_L / \dot{\theta}_M = \dot{\theta}_s / \dot{\theta}_M = 1$		

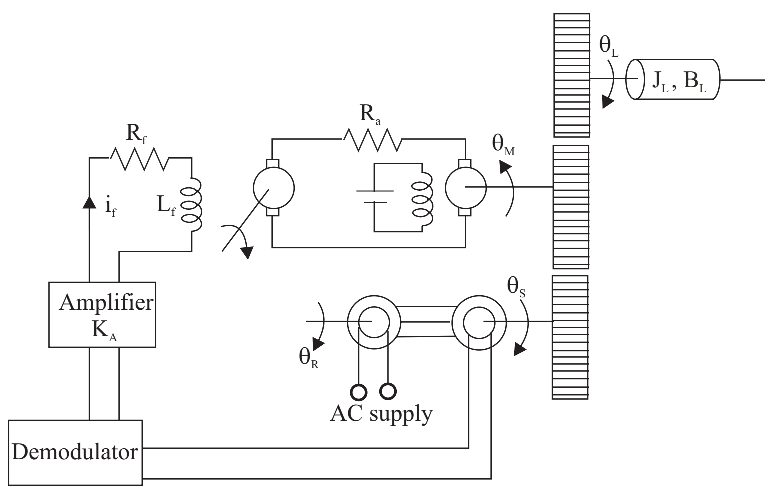
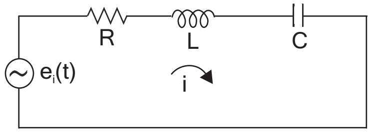


Fig E1.15.

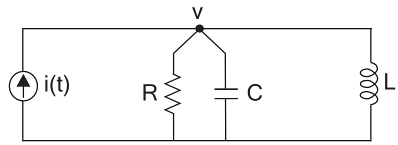
ANSWER FOR EXERCISE PROBLEMS

E1.1 The transfer function is $\frac{X(s)}{F(s)} = \frac{1}{(Ms^2 + Bs + K)}$



f(t)→e(t) M→L K→1/C
v→i B→R

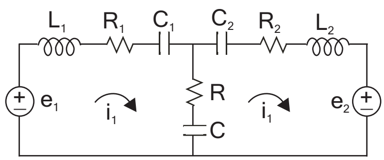
Force-voltage analogous circuit



f(t)→i(t) M→C K→1/L
v→v B→1/R

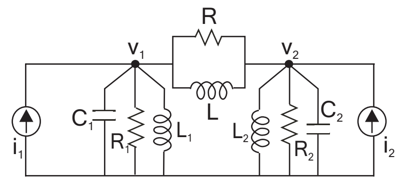
Force-current analogous circuit

E1.2



$f_1 \to e_1$ $M_1 \to L_1$ $B \to R$
$f_2 \to e_2$ $M_2 \to L_2$ $K_1 \to 1/C_1$
$v_1 \to i_1$ $B_1 \to R_1$ $K_2 \to 1/C_2$
$v_2 \to i_2$ $B_2 \to R_2$ $K \to 1/C$

Force-voltage analogous circuit



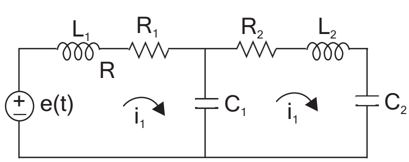
$f_1 \to i_1$ $M_1 \to C_1$ $B \to 1/R$
$f_2 \to i_2$ $M_2 \to C_2$ $K_1 \to 1/L_1$
$v_1 \to v_1$ $B_1 \to 1/R_1$ $K_2 \to 1/L_2$
$v_2 \to v_2$ $B_2 \to 1/R_2$ $K \to 1/L$

Force-current analogous circuit

E1.3(a)

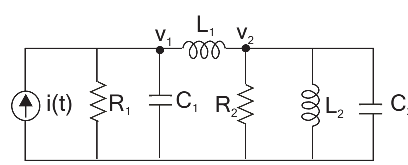
$$M_1 \frac{dv_1}{dt} + B_1 v_1 + B(v_1 - v_2) + K_1 \int v_1 dt + K \int (v_1 - v_2)\, dt = f_1(t)$$

$$M_2 \frac{dv_2}{dt} + B_2 v_2 + B(v_2 - v_1) + K_2 \int v_2 dt + K \int (v_2 - v_1)\, dt = f_2(t)$$



$f(t) \to e(t)$ $M_1 \to L_1$ $B_2 \to R_2$
$v_1 \to i_1$ $M_2 \to L_2$ $K_1 \to 1/C_1$
$v_2 \to i_2$ $B_1 \to R_1$ $K_2 \to 1/C_2$

Force-voltage analogous circuit



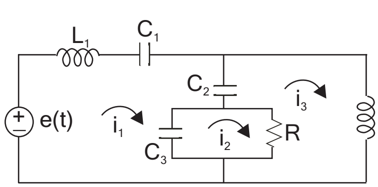
$f(t) \to i(t)$ $M_1 \to C_1$ $B_2 \to 1/R_2$
$v_1 \to v_1$ $M_2 \to C_2$ $K_1 \to 1/L_1$
$v_2 \to v_2$ $B_1 \to 1/R_1$ $K_2 \to 1/L_2$

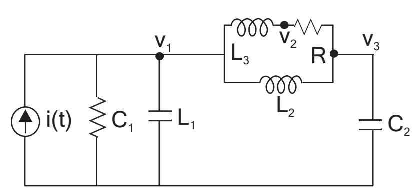
Force-current analogous circuit

E1.3(b)

$$M_1 \frac{dv_1}{dt} + .K_1 \int v_1 dt + K_2 \int (v_1 - v_3)\, dt + K_3 \int (v_1 - v_2)\, dt = f(t)$$

$$K_3 \int (v_2 - v_1) dt + B(v_2 - v_3) = 0 \quad ; \qquad M_2 \frac{dv_3}{dt} + B(v_3 - v_2) + K_2 \int (v_3 - v_1) dt = 0$$





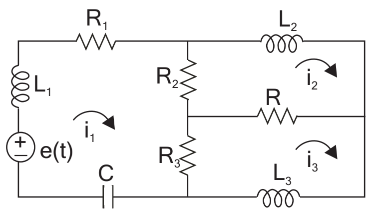
$f(t) \to e(t)$ $M_1 \to L_1$ $K_1 \to 1/C_1$
$v_1 \to i_1$ $M_2 \to L_2$ $K_2 \to 1/C_2$
$v_2 \to i_2$ $B \to R$ $K_3 \to 1/C_3$
$v_3 \to i_3$

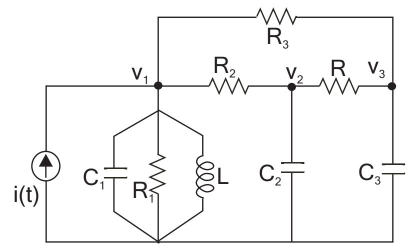
Force-voltage analogous circuit

$f(t) \to i(t)$ $M_1 \to C_1$ $K_1 \to 1/L_1$
$v_1 \to v_1$ $M_2 \to C_2$ $K_2 \to 1/L_2$
$v_2 \to v_2$ $B \to 1/R$ $K_3 \to 1/L_3$
$v_3 \to v_3$

Force-current analogous circuit

E1.4





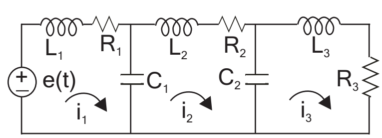
$f(t) \to e(t)$ $M_1 \to L_1$ $B_1 \to R_1$
$v_1 \to i_1$ $M_2 \to L_2$ $B_2 \to R_2$
$v_2 \to i_2$ $M_3 \to L_3$ $B_3 \to R_3$
$v_3 \to i_3$ $B \to R$ $K \to 1/C$

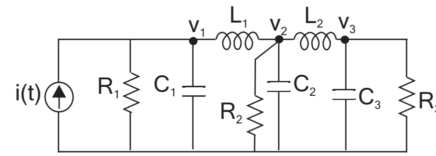
Force voltage-analogous circuit

$f(t) \to i(t)$ $M_1 \to C_1$ $B_1 \to 1/R_1$
$v_1 \to v_1$ $M_2 \to C_2$ $B_2 \to 1/R_2$
$v_2 \to v_2$ $M_3 \to C_3$ $B_3 \to 1/R_3$
$v_3 \to v_3$ $B \to 1/R$ $K \to 1/L$

Force-current analogous circuit

E1.5





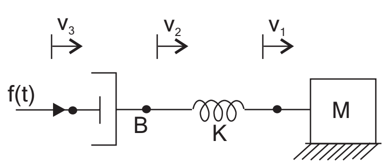
$T(t) \to e(t)$ $J_1 \to L_1$ $B_1 \to R_1$ $K_1 \to 1/C_1$
$\omega_1 \to i_1$ $J_2 \to L_2$ $B_2 \to R_2$ $K_2 \to 1/C_2$
$\omega_2 \to i_2$ $J_3 \to L_3$ $B_3 \to R_3$ $\omega_3 \to i$

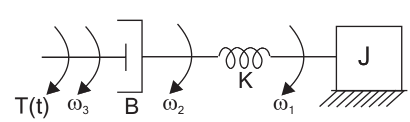
Torque-voltage analogous circuit

$T(t) \to i(t)$ $J_1 \to C_1$ $B_1 \to 1/R_1$ $K_1 \to 1/L_1$
$\omega_1 \to v_1$ $J_2 \to C_2$ $B_2 \to 1/R_2$ $K_2 \to 1/L_2$
$\omega_2 \to v_2$ $J_3 \to C_3$ $B_3 \to 1/R_3$ $\omega_3 \to v_3$

Torque-current analogous circuit

E1.6





$e(t) \to f(t)$ $i_1 \to v_1$ $i_3 \to v_3$ $R \to B$
$i_2 \to v_2$ $L \to M$ $1/C \to K$

Analogous mechanical translational system

$e(t) \to T(t)$ $i_1 \to \omega_1$ $i_3 \to \omega_3$ $R \to B$
$i_2 \to \omega_2$ $L \to J$ $1/C \to K$

Analogous mechanical rotational system

E1.7 (a) $\frac{C}{R} = \frac{G_1G_2 + G_1G_3}{1 + G_1H_2 + G_1 + G_1G_2H_1 + G_1G_3H_1}$

(b) $\frac{C}{R} = \frac{G_1G_2(1 + G_3)(G_4 + G_5)}{1 + (1 + G_3)(G_4 + G_5)H_2 + (1 + G_3)(G_4 + G_5)G_2H_1}$

(c) $\frac{C}{R} = \frac{G_1G_2 + G_1G_3}{1 + G_1G_2H_1 + G_1G_2 + G_1G_3 + G_2H_2 + G_3H_2}$

(d) $\frac{C}{R} = \frac{G_1G_2G_3}{1 + G_2G_3H_2 + G_1G_2H_1 + G_1G_2G_3}$

E1.8 $\frac{G_1G_2G_3 + G_4 + G_2G_3G_4H_1 + G_2G_4H_2 + G_1G_2G_4H_3}{1 + G_2G_3H_1 + G_2H_2 + G_1G_2H_3}$

E1.9 (a) $\frac{C(s)}{R(s)} = \frac{G_1G_2G_3}{1 + G_1G_2H_1 + G_2G_3H_2 + G_1G_2G_3}$

(b) $\frac{C}{R} = \frac{A_{12}A_{23}A_{34}A_{45}A_{56} + A_{13}A_{34}A_{45}A_{56} + A_{12}A_{23}A_{34}A_{46} + A_{13}A_{34}A_{46}}{1 - (A_{12}A_{21} + A_{34}A_{43} + A_{56}A_{65}) + (A_{12}A_{21}A_{34}A_{43} + A_{12}A_{21}A_{56}A_{65} + A_{34}A_{43}A_{56}A_{65}) - (A_{12}A_{21}A_{34}A_{43}A_{56}A_{65})}$

(c) $\frac{C}{R} = \frac{G_1G_2G_3G_4(1 + G_5G_6 + G_6G_7) + G_4G_5G_6G_7(1 + G_1G_2 + G_2G_3)}{1 + G_1G_2 + G_2G_3 + G_5G_6 + G_6G_7 + G_1G_2G_5G_6 + G_5G_6G_2G_3 + G_1G_2G_6G_7 + G_2G_3G_6G_7}$

(d) $\frac{x_8}{x_1} = \frac{[G_1G_2G_3G_4][1 - (G_7G_{12} + G_6G_7G_8 + G_{13}) + G_7G_{12}G_{13}]}{1 - [G_2G_9G_{10} + G_{10}G_{11}] + G_2G_3G_5G_6G_9 + G_3G_5G_6G_{11} + G_7G_{12} + G_6G_7G_8 + G_{13}] + G_2G_9G_{10}G_{13} + G_{10}G_{11}G_{13} + G_7G_{12}G_{13}}$

E1.10 $\frac{x_8}{x_1} = G_1G_4G_6G_9 + G_1G_4G_7G_9 + G_1G_3G_5G_8G_9$; $\frac{x_8}{x_1} = G_2G_5G_8G_9$

E1.11 (a) $\frac{E_o(s)}{E_i(s)} = \frac{1 + sR_2C}{1 + s(R_1 + R_2)C}$

(b) $\frac{E_o(s)}{E_i(s)} = \frac{1}{s^2LC + sRC + 1}$

(c) $\frac{E_o(s)}{E_i(s)} = \frac{sR_2C}{(s^2L_1C + sR_1C + 1)(s^2L_2C + sR_2C + 1) - 1}$

(d) $\frac{E_o(s)}{E_i(s)} = \frac{sR_1R_2C + R_2}{sR_1R_2C + (R_1 + R_2)}$

E1.12 $$\frac{C(s)}{R(s)} = \frac{s^2 L_2 C}{[s R_1 C + 1][s^2 (L_1 + L_2) C + s R_2 C + 1] - 1}$$

E1.13 $$\frac{\theta_L(s)}{\theta_R(s)} = \frac{1}{s(0.1s + 1)(0.2s + 1) + 1}$$

E1.14 $$\frac{\theta_M(s)}{\theta_R(s)} = \frac{13.33}{s^2 + 3.5s + 13.33}$$

E1.15 $$\frac{\theta_L(s)}{\theta_R(s)} = \frac{15 \times 10^3}{s^3 + 54s^2 + 200s + 15 \times 10^3}$$