ESE Mains 2023

Mechanical Engineering

Questions & Solutions

PAPER - 2

ESE ME Paper 2 : Marks Distribution					
S.No.	Subjects	Difficulty Level 2023	2023 Marks	2022 Marks	2021 Marks
1	**Engineering Mechanics**	Moderate	32	32	40
2	**Strength of Materials**	Moderate	72	52	32
3	**Theory of Machines and Vibrations**	Moderate	84	84	104
4	**Machine Design**	Easy	52	72	64
5	**Manufacturing and Engineering Materials**	Moderate	96	84	84
6	**Maintenance Engineering**	Moderate	40	22	12
7	**Industrial Engineering**	Easy	12	42	52
8	**Mechatronics and Robotics**	Moderate	92	92	92
Total		**Moderate to Tough**	**480**	**480**	**480**

Mechanical Engineering

Paper-2

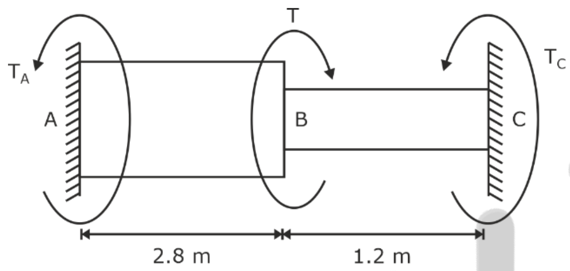
SECTION - 'A'

1.

(a) A circular bar ABC, 4 m long, is rigidly fixed at its ends A and C. The portion AB is 2.8 m long and of 50 mm diameter whereas BC is 1.2 m long and of 25 mm diameter. If the twisting moment of 700 Nm is applied at B, determine the values of the resisting moments at A and C and the maximum stress in each section of the shaft. For the material of the shaft G = 80 GN/m².

[12 Marks]

Sol.



$T_A + T_C = T$ ...(i)

$\theta_1 + \theta_2 = 0$

$T_1 = T_A$

$T_2 = T_A - T$

$$\frac{T_1 L_1}{G_1 J_1} + \frac{T_2 L_2}{G_1 J_2} = 0$$

$$\frac{T_A \times 2.8}{80 \times 10^9 \times \frac{\pi}{32} \times 50^4} + \frac{(T_A - 700) \times 1.2}{80 \times 10^9 \times \frac{\pi}{32} \times 25^4} = 0$$

$T_A = 610.9$ N-m

$T_A + T_C = T$

$T_C = T - T_A = 89.1$ N-m

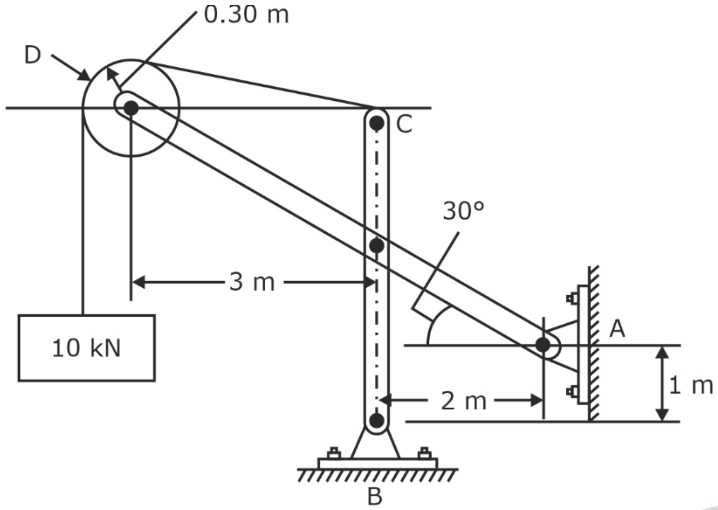
$$(\tau_{max})_{AB} = \frac{T_1}{Z_{p_1}} = \frac{T_1 R_1}{J_1}$$

$$= \frac{610.9 \times 10^3 \times 25}{\frac{\pi}{32} \times 50^4} = 24.89 \text{ MPa}$$

$$(\tau_{max})_{BC} = \frac{T_2}{Z_{p_2}} = \frac{T_2 . R_2}{J_2}$$

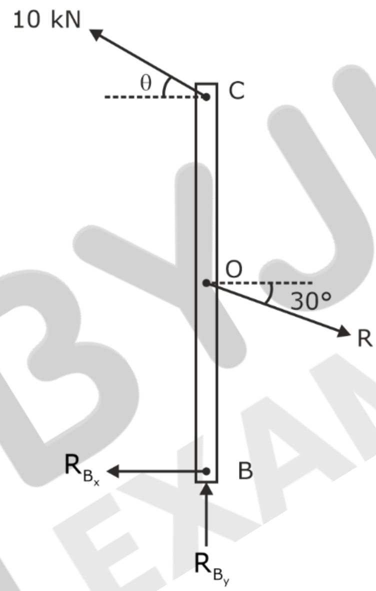
$$= \frac{89.1 \times 10^3 \times 12.5}{\frac{\pi}{32} \times 25^4} = 29.038 \text{ MPa}$$

(b) What are supporting forces for the frame? Neglect all weights except the 10 kN weight.



[12 Marks]

Sol. FBD of link BC



Taking moment about B,

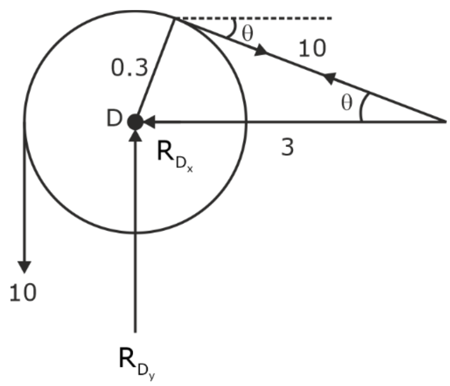
$\Sigma M_B = 0$

$(10 \cos\theta \times BC) = (R \cos 30°)\ OB$ …. (i)

$BC = 1 + 2 \tan 30° + 3 \tan 30° = 3.8867$ m

$OB = 1 + 2 \tan 30° = 2.154$ m

FBD of wheel D



$$\sin\theta = \frac{0.3}{3} \Rightarrow \theta = 5.74°$$

$$R_{D_x} = 10\cos\theta = 9.95 \text{ kN}$$

$$R_{D_y} = 10\sin\theta + 10 = 11 \text{ kN}$$

$$R_D = \sqrt{R_{D_x}^2 + R_{D_y}^2} = 14.33 \text{ kN}$$

$$\tan\alpha = \frac{R_{D_y}}{R_{D_x}} \Rightarrow \alpha = 47.869°$$

From equation (i),

$$10\cos(5.74) \times 3.8867 = R\cos 30° \times 2.154$$

$$\boxed{R = 20.724 \text{ kN}}$$

Now, $\Sigma H = 0$

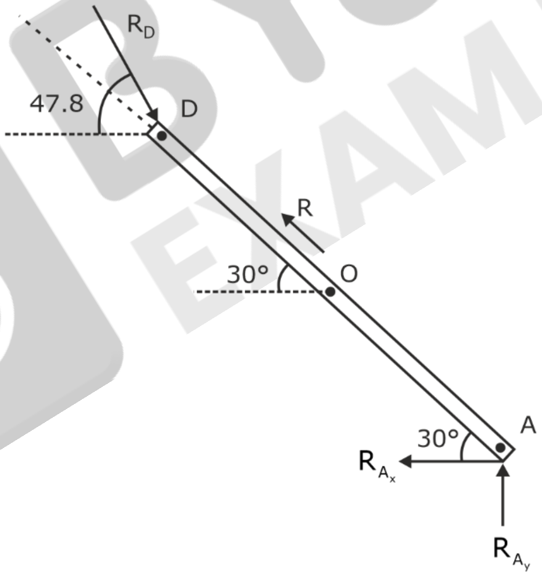
$$R_{B_x} = R\cos 30° - 10\cos 5.74° = 7.99 \text{ kN}$$

$\Sigma V = 0$

$$R_{B_y} = R\sin 30° - 10\sin 5.74° = 9.36 \text{ kN}$$

$$R_B = \sqrt{R_{B_x}^2 + R_{B_y}^2} = 12.31 \text{ kN}$$

FBD of link AD



$\Sigma H = 0$

$$R_{A_x} + R\cos 30° = R_D\cos 47.87°$$

$$R_{A_x} = 14.83\ (\cos 47.87°) - 20.72\cos 30° = -7.996 \text{ kN}$$

$\Sigma V = 0$

$$R_{A_y} + R\sin 30° = R_D\sin 47.87°$$

$$R_{A_y} = 14.83 \times \sin 47.87° - 20.72 \times \sin 30° = 0.638 \text{ kN}$$

$$R_A = \sqrt{R_{A_x}^2 + R_{A_y}^2} = 8.021 \text{ kN}$$

(c) An electronic instrument is to be isolated from a panel that vibrates at frequencies ranging from 25 Hz to 35 Hz. It is estimated that at least 80% vibration isolation must be achieved to prevent damage to the instrument. If the instrument weighs 85 N, find the necessary static deflection of the isolator.

[12 Marks]

Sol.

Given,

$F_t = 0.2\ F_0$

Transmission ratio,

$$0.2 = \frac{\sqrt{1+(2\zeta r)^2}}{\sqrt{(1-r^2)^2+(2\xi r)^2}} \qquad \text{where } r = \frac{\omega}{\omega_n}$$

For $\zeta = 0$,

$$0.2 = \frac{\sqrt{1+0}}{\sqrt{(1-r^2)^2}} = \frac{1}{\pm(1-r^2)}$$

With positive sign $\left(\frac{\omega}{\omega_n}\right)^2 = r^2 = -4$ (Incorrect)

With negative sign $\left(\frac{\omega}{\omega_n}\right)^2 = r^2 = 6$

When frequency range from 25 to 35 Hz

$\omega_{min} = 2\pi \times 25 = 157.079 \text{ rad/s}$

$\omega_{max} = 2\pi \times 35 = 219.91$ rad/s

$$\left(\frac{\omega_{min}}{\omega_n}\right)^2 = 6$$

$$\omega_n = \frac{157.079}{\sqrt{6}} = 64.127 \text{ rad/s}$$

$$\omega_n = \sqrt{\frac{g}{\Delta}}$$

$$64.127^2 = \frac{9.81}{\Delta}$$

$\Delta = 2.385 \times 10^{-3}$ m $= 2.385$ mm

(d) Describe all the inversions of a slider-crank mechanism.

[12 Marks]

Sol.

INVERSIONS OF SINGLE SLIDER CRANK MECHANISM

(i) Crank is fixed

- Whitworth quick return motion mechanism
- Rotary internal combustion engine (Gnome engine)

(ii) Connecting rod is fixed

- Crank and slotted lever quick Return motion mechanism

- Oscillating cylinder engine mechanism

(iii) Piston/slider is fixed

- Hand pump (Pendulum pump/Bull engine)

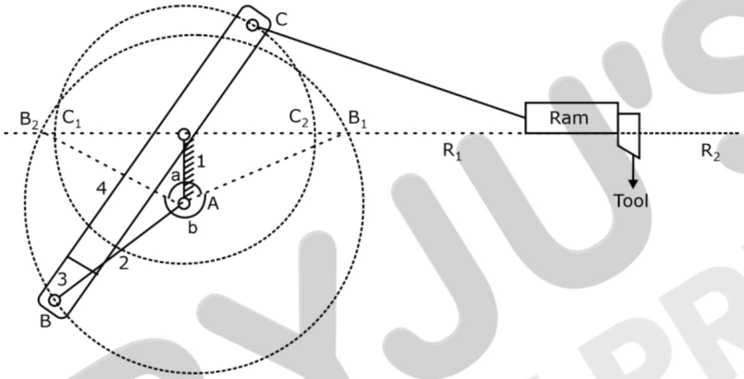
(iv) Cylinder fixed

- Reciprocating IC engine
- Reciprocating compressor

Whitworth quick return motion mechanism

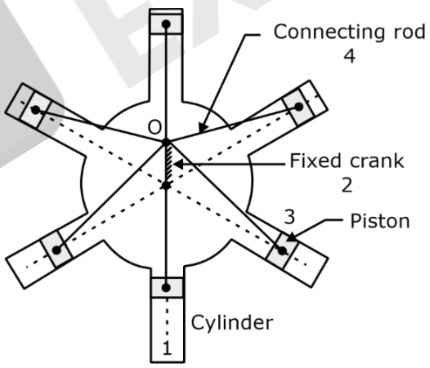
It is an inversion of single slider crank mechanism in which crank is fixed, thus makes a double crank mechanism. In this mechanism, return stroke takes lesser time as compared to the cutting or forward stroke thus it is known as quick return motion mechanism.

The cutting of material takes in forward stroke and there is no cutting of materials occurs in return stroke, thus return stroke is also known as idle stroke.



Rotary Internal combustion engine (Gnome engine)

It consists of several cylinders in one plane, and all revolve about fixed centre O, as shown in the figure. The crank (link 2) is fixed. When the connecting rod (link 4) rotates, the piston (link 3) reciprocates inside the cylinder forming link 1.



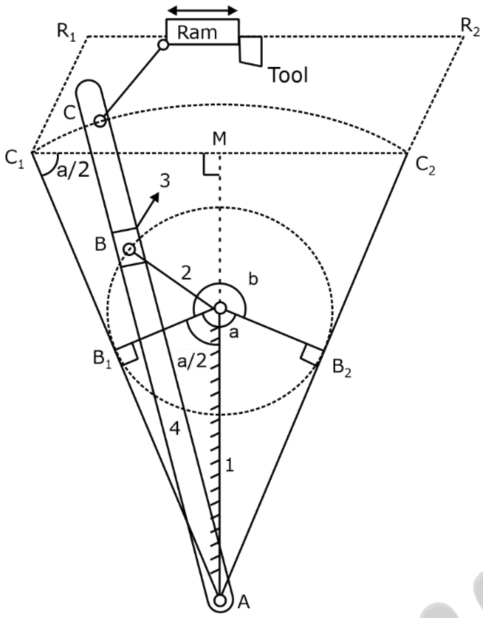
Gnome engine

Crank and slotted lever quick return motion mechanism

It is an inversion of single slider crank mechanism in which connecting rod is fixed.

It is a type of crank rocker mechanism.

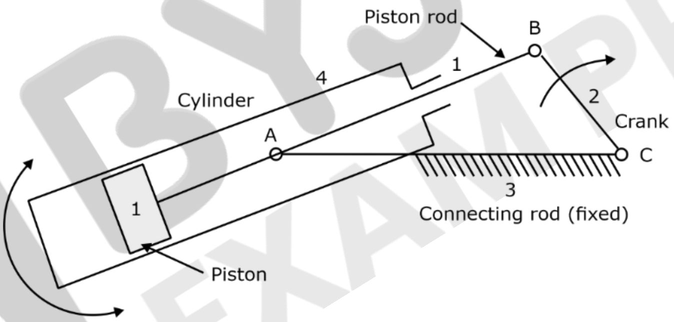
Major advantage is that wide variations in stroke length are possible in this mechanism.



Crank and slotted lever quick return motion mechanism

Oscillating cylinder engine mechanism

Oscillating cylinder engine mechanism is an inversion of single slider crank mechanism in which connecting rod is fixed. It converts rotary motion of crank into oscillatory motion of cylinder.

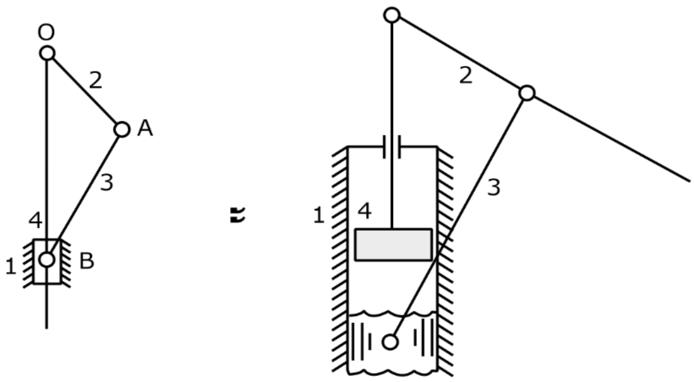


Oscillating cylinder engine mechanism

Hand pump mechanism

If the link 4 of the slider-crank mechanism is fixed, then inversion obtained is the fourth inversion of slider crank mechanism.

Application: Pendulum-pump, Bull engine



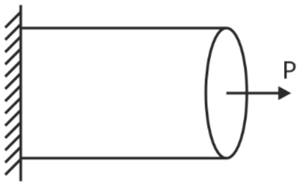
Inversion obtained by fixing slider

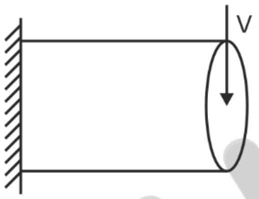
(e) A structure is composed of circular members of diameter d. At a certain position along one member the loading is found to consist of a shear force of 10 kN along with an axial tensile load of 20 kN. If the elastic limit in tension of the material of the members is 300 MN/m² and there is to be a factor of safety of 3, estimate the magnitude of d required according to the maximum shear strain energy per unit volume theory. Poisson's ratio v = 0.3.

[12 Marks]

Sol. Given,

$N = 3$, $S_{yt} = 300$ MPa, $\nu = 0.3$





Axial stress, $\sigma_a = \frac{P}{A} = \frac{20}{A}$ kN/mm^2

Shear stress, $\tau_s = \frac{V}{A} = \frac{10}{A}$ kN/mm^2

$$\sigma_{1,2} = \frac{\sigma_{xx} + \sigma_{yy}}{2} \pm \sqrt{\left(\frac{\sigma_{xx} - \sigma_{yy}}{2}\right) + \tau_{xy}^2}$$

$\sigma_{xx} = \sigma_a$, $\sigma_{yy} = 0$, $\tau_{xy} = \tau_s$

$$\sigma_{1,2} = \frac{20}{2A} \pm \sqrt{\left(\frac{20}{2A}\right)^2 + \left(\frac{10}{A}\right)^2}$$

$$\sigma_1 = \frac{24.142}{A} \text{ kN/mm}^2$$

$$\sigma_2 = \frac{-4.142}{A} \text{ kN/mm}^2$$

According to maximum shear strain energy

$$\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2 \le \left(\frac{S_{yt}}{N}\right)^2$$

$$\left(\frac{24.142}{A}\right)^2 + \left(\frac{-4.142}{A}\right)^2 - \frac{24.142}{A} \times \frac{-4.142}{A} = \left(\frac{300 \times 10^{-3}}{3}\right)^2$$ (1 MPa = 10^{-3} kN/mm^2)

$$\frac{700}{A^2} = 0.1^2$$

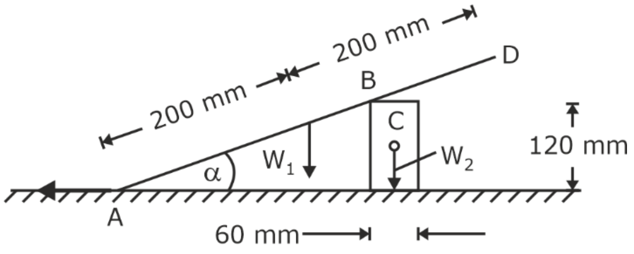
Or $A = 264.575$ mm^2

Or $\frac{\pi}{4}d^2 = 264.57$ mm^2

Or d = 18.35 mm

2.

(a) The rod AD is pulled at A and it moves to the left. If the coefficient of dynamic friction for the rod at A and B is 0.4, what must the minimum of W_2 be to prevent the block from tipping when α = 20°? With this value of W_2, determine the minimum coefficient of static friction between the block and the supporting plane needed to just prevent the block from sliding. Take W_1 = 100 N.



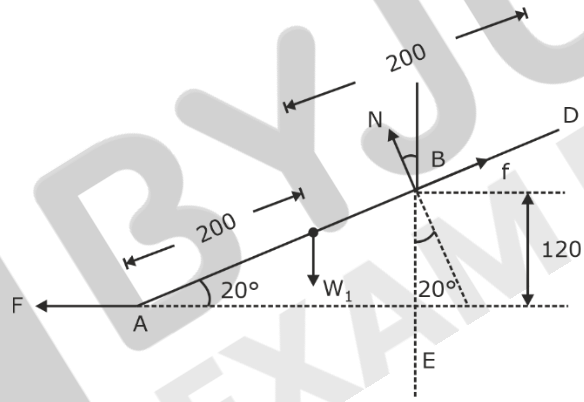
[20 Marks]

Sol. Given,

W_1 = 100 N

α = 20°

FBD of load AD



$\Sigma M_A = 0$

$W_1 \times 200 \cos 20° = (N \cos 20°)\, AE + N \sin 20° \times 120$

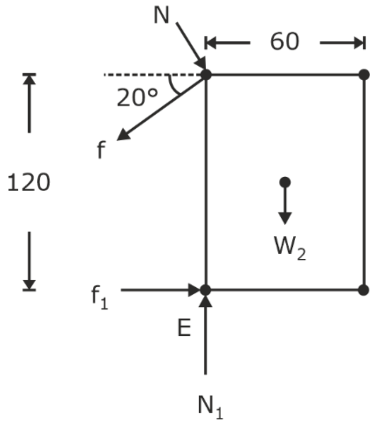
$W_1 \times 200 \cos 20° = (N \cos 20 \times AE) + (N \sin 20° \times 120)$

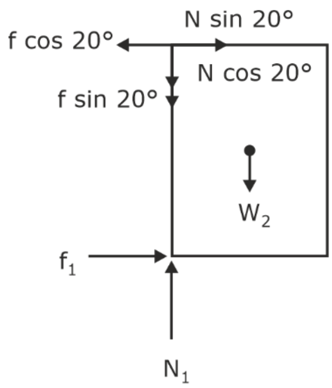
Now $AE = \dfrac{BE}{\tan 20°} = 329.69$ mm

$N = \dfrac{100 \times 200 \cos 20°}{329.69 \times \cos 20° + 120 \times \sin 20°}$

N = 53.67 N

FBD of block W_2





As the block W_2 is at the verge of tippy, hence normal reaction on the block due to ground will be shifted to point E.

$\Sigma M_E = 0$

$(W_2 \times 30) + (N \sin 20° \times 120) = f \cos 20° \times 120$

$$W_2 = \frac{(f\cos 20° - N\sin 20°) \times 120}{30}$$

$W_2 = (\mu\ N \cos 30° - N \sin 20°) \times 4$

$W_2 = (0.4 \times \cos 20° - \sin 20°) \times 53.67 \times 4$

$W_2 = 7.268$ N

$\Sigma V = 0$

$N_1 = W_2 + N \cos 20° + f \sin 20°$

$N_1 = 7.268 + (53.67 \cos 20°) + (0.4 \times 53.69 \times \sin 20°)$

$N_1 = 65.044$ N

$\Sigma H = 0$

$f \cos 20° = N \sin 20 + f_1$

$f_1 = f \cos 20° - N \sin 20°$

$f_1 = (0.4 \times 53.67 \cos 20°) - (53.67 \sin 20°)$

$f_1 = 1.817$ N

Minimum coefficient of static friction

$$\mu_1 = \frac{f_1}{N_1} = \frac{1.817}{65.044} = 0.028$$

(b) **(i)** Define pitch point, addendum, module and pressure angle as applied to toothed gears.

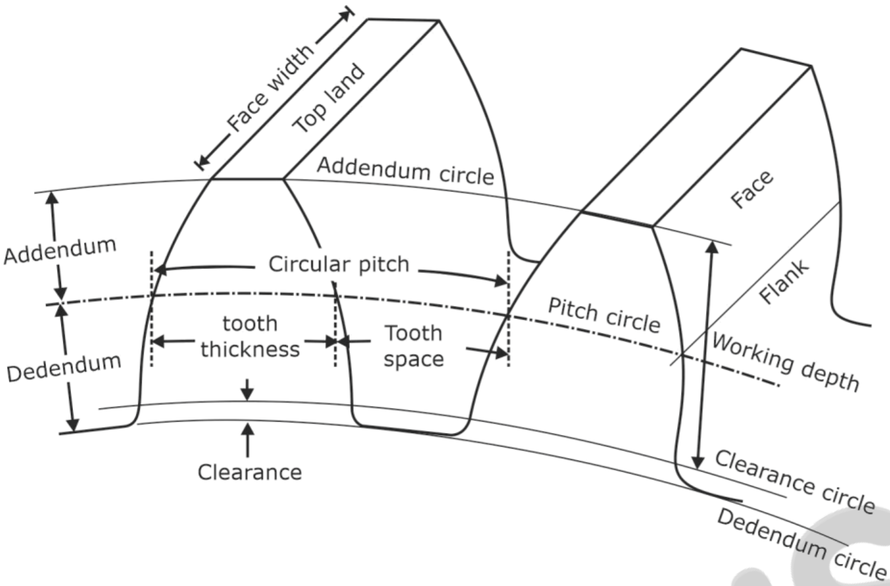
[8 Marks]

(ii) Compare involute curve with cycloidal curve for the profiles of gear teeth.

[12 Marks]

Sol.

(i)



(i) Pitch point – It is a common point of contact between two pitch circles.

(ii) Addendum – It is the radial height of a tooth from the pitch circle to the top land. Its standard value is one module.

(iii) Module - It is the ratio of the pitch diameter in mm to the number of teeth. The term is used in SI units in place of the diametral pitch.

$$m = \frac{d}{T}$$

Also $$p_c = \frac{\pi d}{T} = \pi m$$

(iv) Pressure angle or angle of obliquity (ϕ) – The angle between the line of action and the common tangent to the pitch circles is known as the pressure angle or the angle of obliquity.

The pressure angle must be kept small for more power transmission and less pressure on the bearings.

Standard pressure angles are 20° and 25°. Gears with 14.5° pressure angles have become almost obsolete.

(ii)

Cycloidal Teeth	Involute Teeth
(a) Pressure angle varies from maximum at the beginning of engagement; reduces to the maximum at the end of engagement resulting in the less smooth running of the gears.	Pressure angle is constant throughout the engagement of teeth. This results in smooth running of the gears.
(b) It involves double curve for the teeth i.e., epicycloid and hypocycloid. This complicates the manufacturer.	It involves single curve for the teeth. This results the simplicity of manufacturing and of tools.
(c) These are costlier due to manufacturing difficulties.	These are cheaper due to the simplicity of manufacturing.

(d) Exact centre-distance is required to transmit a constant velocity ratio.	A little variation in the centre-distance does not affect the velocity ratio.
(e) Phenomenon of interference does not occur at all.	Interference can occur if the condition of the minimum number of teeth on a gear is not followed.
(f) Teeth have spreading flanks and thus are stronger.	The teeth have radial flanks thus are weaker as compared to the cycloidal form for the same pitch. Two convex surfaces are in contact, and thus there is more wear.

(c) A single plate clutch (both sides effective) is required to transmit 27 kW at 1600 rpm. The outer diameter of the plate is limited to 30 cm, and intensity of pressure between the plates is not to exceed 0.1 N/mm². Assuming uniform wear and a coefficient of friction 0.3, find the required inner diameter of the plates, and axial force necessary to engage the clutch.

[20 Marks]

Sol.

Given

$n = 2$, $P = 27$ kW, $N = 1600$ rpm, $D_0 = 30$ mm, $p_{max} = 0.1$ MPa

To get: D_i by UWT and W_a = axial force

$$\text{Power,}\quad P = \frac{2\pi NT}{60} \quad \Rightarrow T = 161144.34\ \text{N} - \text{mm}$$

$$T_f = n\mu\pi\, p_{max}\, R_i(R_0^2 - R_i^2)$$

$$161144.34 = 2 \times 0.3\pi \times 0.1 \times R_i\left(150^2 - R_i^2\right)$$

$$R_i^3 - 22500 R_i + 854897.27 = 0$$

$R_i = 125.186$ mm and 41.075 mm

We will consider lager value, hence $R_i = 125.186$ mm

Inner diameter, $D_i = 250.372$ mm

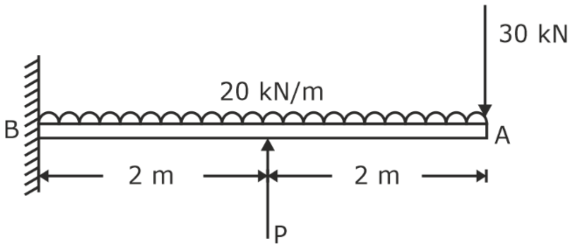
W = axial force required

$W = p \times 2\pi R_i (R_0 - R_i)$

$W = 1952.2$ N

3.

(a) Find the slope and deflection at the tip of the cantilever shown in the figure. What load P must be applied upwards at mid-span to reduce the deflection by half? EI = 20 MN/m²



[20 Marks]

Sol.

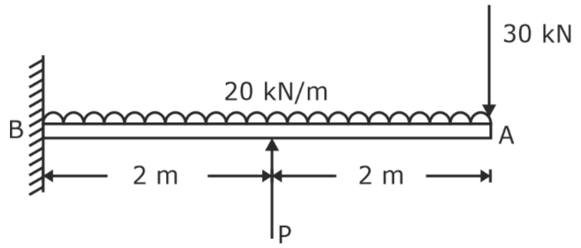
Given,

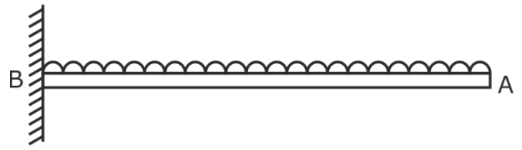
w = 20 kN/m

L = 4 m

P_1 = 30 kN

EI = 20 MPa





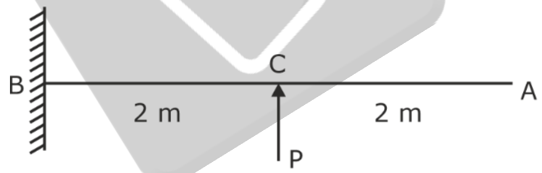
Deflection at free end due to uniformly distributed load, $y_A = \frac{-wL^4}{8EI}$

Deflection at free end due to point load 30 kN, $y_A = -\frac{P_1L^3}{3EI}$

Total deflection at free end,

$$y_A = \frac{-wL^4}{8EI} - \frac{P_1L^3}{3EI} = \frac{10^3}{20\times10^6}\left(-\frac{20\times4^4}{8} - \frac{30\times4^3}{3}\right)$$

$y_A = 64 \times 10^{-3}$ m = 64 mm



Now, for y_A = 32 mm (After applying load P)

$$y_{A,\,due\,to\,P} = y_C + \theta_C\,(AC)$$

$$64 - 32 = \frac{P(L/2)^3}{3EI} + \frac{P(L/2)^2}{2EI} \times AC$$

$$32 = \frac{P(2)^3}{3\times20\times10^6} + \frac{P(2)^2}{2\times20\times10^6} \times 2$$

P = 96 kN

(b) The axes of a three-cylinder air compressor are 120° apart and their connecting rods are connected to a common crank. The length of each connecting rod is 200 mm and the stroke is

160 mm. The mass of the reciprocating parts per cylinder is 2 kg. Find the maximum primary and secondary forces acting on the frame of the compressor when running at 2500 rpm.

[20 Marks]

Sol.

Given,

Stroke length = 160 mm

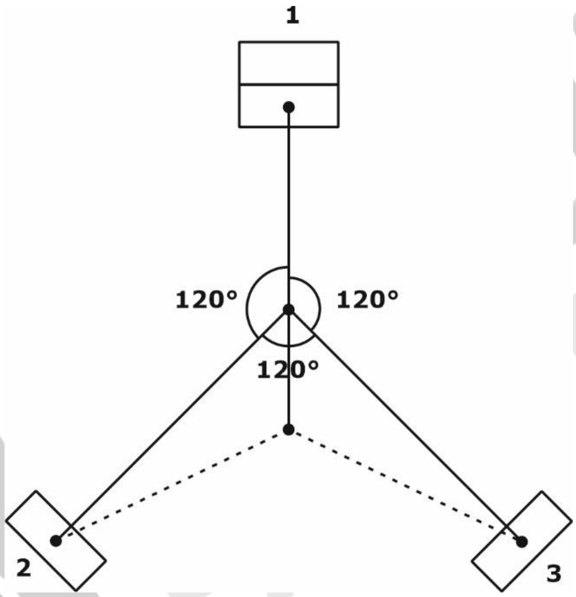
Crank radius, $r = \frac{160}{2} = 80 \text{ mm} = 0.08 \text{ m}$

Connecting rod length, l = 200 mm

Obliquity ratio, $n = \frac{l}{r} = \frac{0.2}{0.08} = 2.5$

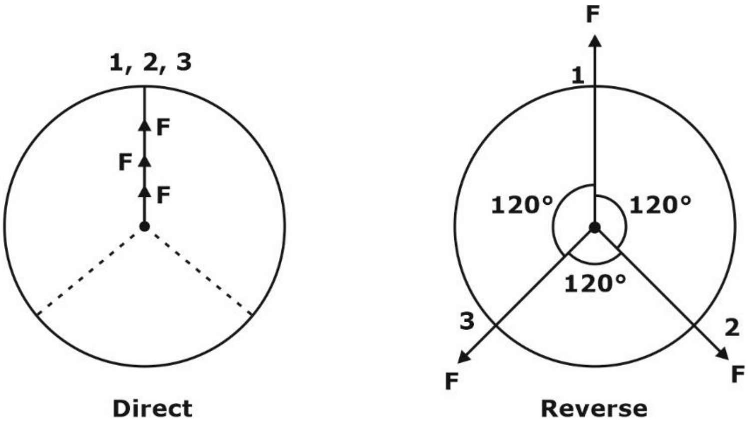
m = 2 kg

N = 2000 rpm



Position of primary crank (θ)			Position of secondary crank (2θ)	
Cylinder	**Direct**	**Reverse**	**Direct**	**Reverse**
1	0	0	0	0
2	120	–120	240	–240
3	240	–240	480	–480

Primary unbalanced force

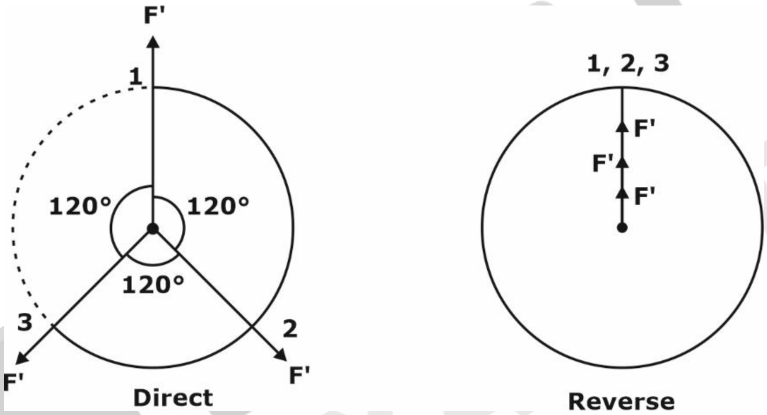


Primary direct unbalanced = 3 × F

$$F_{d,P} = 3 \times \frac{m}{2} r\omega^2$$

Reverse direct unbalanced force $F_{R,P} = 0$

Secondary unbalance force



Secondary direct unbalanced force, $F_{d,S} = 0$

Secondary reverse unbalanced = $3 \times F'$

$$F_{RS} = 3 \times \frac{m}{2} \frac{r}{4n} (2\omega)^2 = \frac{3}{2} \frac{mr\omega^2}{n}$$

$$(F_P)_{max} = F_{d,P} + F_{R,P}$$

$$= \frac{3}{2} mr\omega^2 + 0 = \frac{3}{2} mr\omega^2$$

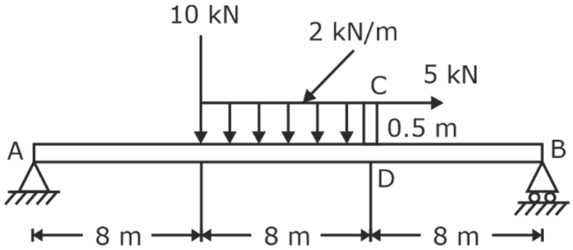
$$= \frac{3}{2} \times 2 \times 0.08 \times \left(\frac{2\pi \times 2500}{60}\right)^2 = 16.449 \text{ kN}$$

$$(F_s)_{max} = F_{d,S} + F_{R,S}$$

$$= 0 + \frac{3}{2} \frac{mr\omega^2}{n}$$

$$= \frac{3}{2} \times \frac{2 \times 0.08}{2.5} \times \left(\frac{2\pi \times 2500}{60}\right)^2 = 6.579 \text{ kN}$$

(c) A simply supported beam AB is shown in the figure. A bar CD is welded to the beam. After determining the supporting forces, sketch the shear force and bending moment diagrams and determine the maximum bending moment.



[20 Marks]

Sol. Support reaction at A and B calculation,

$\Sigma M_B = 0$

$R_A \times 24 = 10 \times 16 + (2\times8) \times 12 - 2.5$

$R_A = 14.5625$ kN

$\Sigma V = 0$

$R_A + R_B = 26$ kN

$R_B = 26 - 14.5625 = 11.4375$ kN

Shear force calculation,

Shear force in AE section $= +R_A = 14.5625$ kN

Shear force in BD section $= - R_B = -11.4375$ kN

Shear force in ED section $= R_A - 10 - wx$ (Where x is from E point)

$= 4.5625 - 2x$ (Straight line variation)

Shear force at E = 14.5625 kN and 14.5625 – 10 = 4.5625 kN

Shear force at point D $= 4.5625 - 2 \times 8 = 11.4375$ kN

Bending moment calculation,

Bending moment in AE section $= R_A\, x$ (distance x is from A)

Bending moment at E point $= 14.5625 \times 8 = 116.5$ kN-m

Bending moment in ED section $= R_A(8 + x) - 10\, x - wx^2/2$ (x is from E)

Bending moment at D point $= 14.5625 \times (8 + 8) - 10 \times 8 - 2 \times 8^2/2 = 89$ kN-m

Bending moment in BD section $= R_B\, x$ (x is from B)

Bending moment at D point $= 11.4375 \times 8 = 91.5$ kN-m

Maximum bending moment location will be where shear is zero.

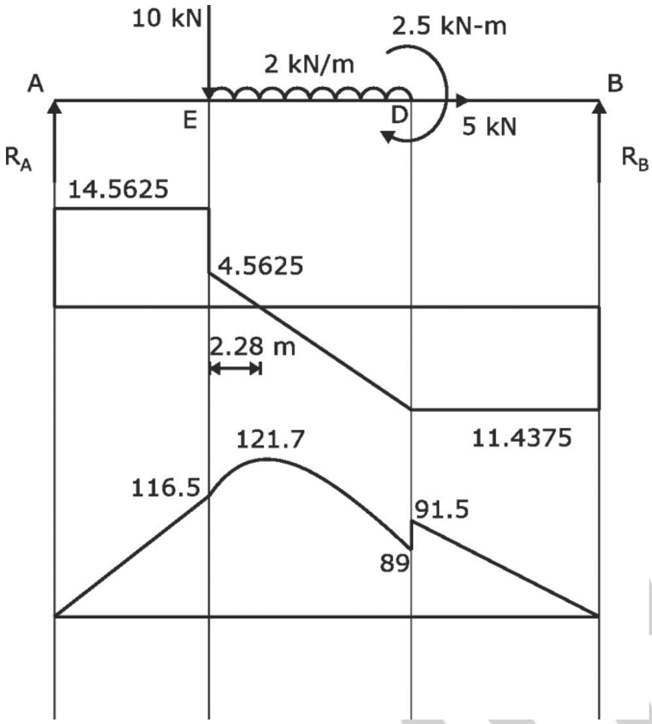
Hence $4.5625 - 2x = 0$

$x = 2.28125$ m from point E

Maximum bending moment,

$M_{max} = R_A\,(8 + 2.28125) - 10 \times 2.28125 - 2 \times 2.28125^2/2$

$M_{max} = 121.704$ kN-m

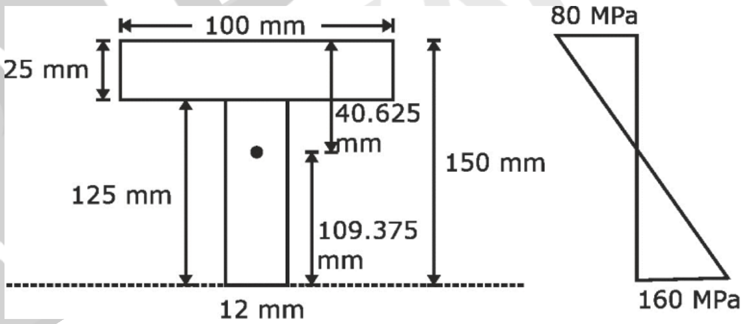


4.

(a) A uniform T-section beam is 100 mm wide and 150 mm deep with flange thickness of 25 mm and a web thickness of 12 mm. If the limiting bending stresses for the material of the beam are 80 MN/m^2 in compression and 160 MN/m^2 in tension, find the maximum UDL. that the beam can carry over a simply supported span of 5 m.

[20 Marks]

Sol.



The distance of neutral axis from bottom fibre,

$$\bar{Y} = \frac{A_1 r_1 + A_2 r_2}{A_1 + A_2} = \frac{(100\times25)\times137.5 + (12\times125)\times62.5}{100\times25 + 125\times12}$$

$$\bar{Y} = 109.375 \text{ mm}$$

$$I_{NA} = \frac{12\times125^3}{12} + (12\times125)\times(109.375-62.5)^2 + \frac{100\times25^3}{12} + (100\times25)\times(137.5-109.375)^2$$

I_{NA} = 7356770.833 mm^4

Maximum stress in beam will be at bottom fibre, which is in tension,

$$(\sigma_b)_{max} = \frac{M_{max} y_{max}}{I_{NA}} = 160$$

$$\frac{M_{max}\times10^3\times109.375}{7356770.833} = 160$$

M_{max} = 10761.9 N-m

Maximum bending moment for simply supported beam with UDL,

$M_{max} = \frac{wL^2}{8}$

$\frac{w \times 5^2}{8} = 10761.9$

w = 3443.808 N/m

(b) In a spring-loaded governor of Hartnell type, the weight of each ball is 5 kg and the lift of the sleeve is 5 cm. The speed at which the governor begins to float is 250 rpm, and at this speed the radius of the ball path is 10 cm. The mean working speed of the governor is 20 times the range of speed when friction is neglected. If the lengths of ball and roller arm of the bell crank lever are 12 cm and 10 cm respectively and if the distance between the centre of pivot of bell crank lever and axis of the governor spindle is 14 cm, determine the initial compression of the spring, taking into account obliquity of arms.

[20 Marks]

Sol. $m = 5$ kg, $N_1 = 250$ rpm, $h_1 = 5$ cm

$r_1 = 10$ cm, $a = 12$ cm, $b = 10$ cm

Bottom position:

$r_1 = 10$ cm

$c_1 = r - r_1 = 14 - 10 = 4$ cm

$a_1 = \sqrt{12^2 - 4^2} = 11.314$ cm

$b_1 = \sqrt{10^2 - 2.5^2} = 9.682$ cm

Let, left of sleeve = h

$\frac{h}{(c_1 + c_2)} = \frac{b}{a}$

$c_1 + c_2 = \frac{ha}{b} = \frac{5 \times 12}{10} = 6$ cm

$C_2 = 6 - 4 = 2$ cm ($C_1 = 4$ cm)

$r_2 = r + c_2 = 14 + 2 = 16$ cm

$a_2 = \sqrt{12^2 - 2^2} = 11.832$ cm

Mean speed, $N = \frac{N_1 + N_2}{2}$

As per question, $N = 20(N_2 - N_1)$

$\frac{N_1 + N_2}{2} = 20(N_2 - N_1)$

$39 N_2 = 41 N_1$

$N_2 = \frac{41}{39}N_1 = \frac{41}{39} \times 250 = 262.82$ rpm

At lowest position, friction is neglected.

$m r_1 \omega_1^2 a_1 = \frac{1}{2}F_{s_1} b_1 + mg\,c_1$

$$5\times0.1\times\left(\frac{2\pi\times250}{60}\right)^2\times0.1131 = \frac{1}{2}F_{S_1}\times0.0968+5\times9.81\times0.04$$

$$\Rightarrow F_{S_1} = 760.26\text{ N}$$

At highest position

$$m_2r_2\omega_2^2 a_2 = \frac{1}{2}F_{S_2}b_2 + mg\,c_2$$

$$5\times0.16\times\left(\frac{2\pi\times262.82}{60}\right)^2\times0.118 = \frac{1}{2}F_{S_2}(0.0968)+5\times9.81\times0.02$$

$$F_{S_2} = 1457.14\text{ N}$$

Spring stiffness, $k = \dfrac{F_{S_2}-F_{S_1}}{h} = 13.938$ N/mm

Initial compression $= \dfrac{F_{S_1}}{k} = \dfrac{760.283}{13.938} = 54.546$ mm

(c) **(i)** What are the assumptions made in the Lewis equation for beam strength?

[8 Marks]

(ii) A pair of spur gears with 20° full depth involute teeth consists of a 20 teeth pinion meshing with a 50 teeth gear. The pinion is mounted on a crank shaft of 5 kW engine running at 1200 rpm. The driven shaft is connected to a compressor. The pinion as well as the gear is made of steel having ultimate strength in tension equal to 500 N/mm². The module and face width of the gears are 4 mm and 44 mm. Assume service factor as 2. Using the velocity factor to account for the dynamic load, determine the factor of safety. Take Lewis form factor for 20 teeth equal to 0.320 and for 50 teeth equal to 0.408. Take velocity factor $C_v = \dfrac{3}{3+v}$, where v is the pitch line velocity in m/s.

[12 Marks]

Sol.

(i) The Lewis equation is predicated on the following presumption:

- The radial component (P_r), which causes compressive stresses, is ignored.
- The tangential component (P_t) is assumed to be uniformly distributed across the face width of the gear, and the effect of stress concentration is ignored.
- It is assumed that the contact ratio is 1, and only one pair of teeth is in contact at any given time and bears the entire load.
- The tooth's cross-section changes from free end to fixed end. As a result, a parabola is built within the tooth profile.
- Deflection of the tooth under load is neglected.
- Inertia of rotating part neglected.
- Error, inaccuracy, and irregularity are neglected.

(ii) Given,

Pressure angle, ϕ = 20° , Z_p = 20, Z_G = 50

P = 5 kW at N_P = 1200 rpm, S_{ut} = 500 MPa

Y_P = 0.32, b = 44 mm

$Y_G = 0.408, \quad m = 4$ mm

S = 2 (service factor) $\qquad C_V = \dfrac{3}{3+v}$

$$P = \frac{2\pi N_P T_P}{60}$$

$$5 \times 10^3 = \frac{2\pi \times 1200 \times 20}{60}$$

$$T_P = 39788.6 \text{ N} - \text{mm}$$

T_P = Rated torque of opinion

T_P' = Design torque = $T_P \times 5$ = 79577.472 N-mm

$$F_t = \frac{2T_P'}{D_P} = 1989.45 \text{ N}$$

$$V_P = \frac{\pi D_P N_P}{60} = 5.03 \text{ m/s}$$

$$C_v = \frac{3}{3+V} = 0.374$$

$$F_{dynamic} = \frac{F_{static}}{C_V} \quad (\text{If } C_v < 1)$$

$$F_{dynamic} = \frac{1989.45}{0.374} = 5319.35 \text{ N}$$

$$F_s = mbY\sigma_{per} \quad \left(\text{Where } \sigma_{per} = \frac{S_{ut}}{N}\right)$$

$$F_{dy} = 5319.35 \le F_s$$

$$5319.35 \le mbY\frac{S_{ut}}{N}$$

Both pinion and gear made of same material hence pinion will be weaker gear. Our design calculation will be based on pinion.

5319.35 = 4 × 44 × 0.32 × 500/N

N = 5.29

SECTION - 'B'

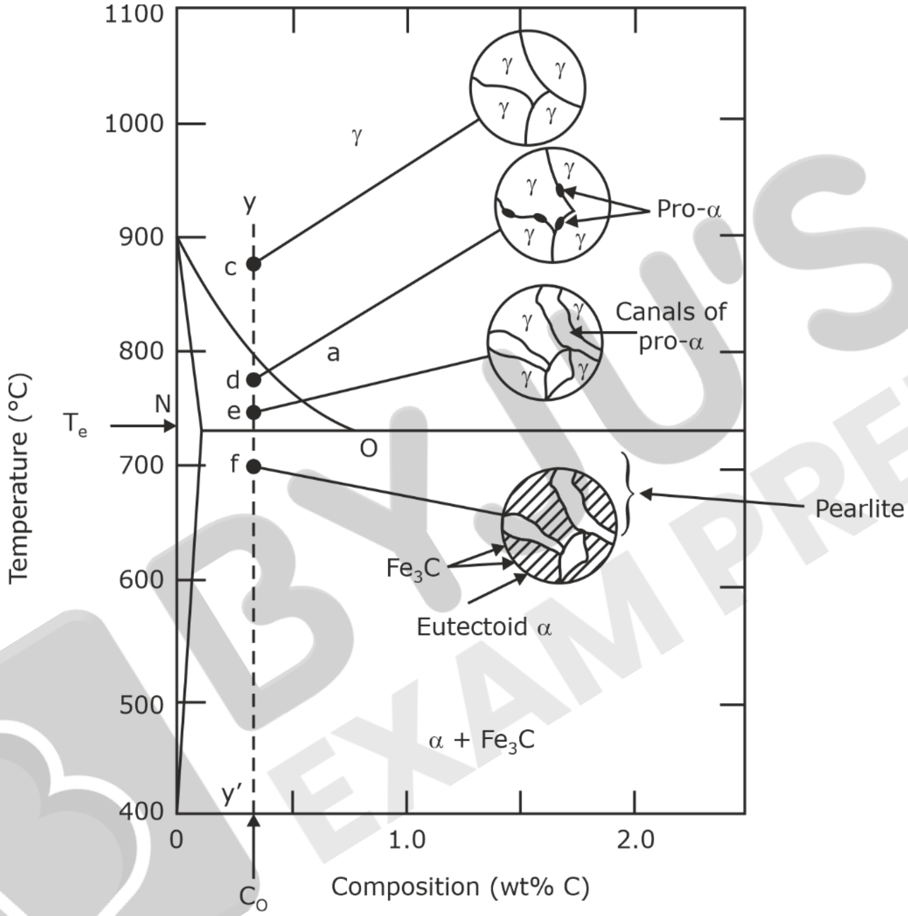
5.

(a) What is the distinction between hypoeutectoid and hypereutectoid steels? Explain the development of microstructure in a hypoeutectoid steel with the help of neatly labelled diagram.

[12 Marks]

Sol. Steels containing carbon upto 0.8% are said to be hypoeutectoid steels while steels with 0.8% to 2.14% C are said to be hypereutectoid steels.

Hypoeutectoid Alloys (<0.8% C): A steel sample in hypo eutectoid steel range is cooled along yy'. At point c, the alloy is entirely in the austenite phase. The moment temperature decreases to point d, ferrite start appearing in the microstructure. This ferrite that appears before eutectoid temperature is called pro- eutectoid ferrite (pro-α). As temperature decreases mass fraction of pro-α will increase and at point e there will be canals of pro a at the grain boundary. As the temperature is lowered just below the eutectoid, to point f, all the y phase that was present at temperature T (and having the eutectoid composition) will transform to pearlite. There will be virtually no change in a phase that existed at point e in crossing the eutectoid temperature. It will normally be present as a continuous matrix phase surrounding the isolated pearlite colonies. It should also be noted that two micro constituents are present, i.e., proeutectoid ferrite and pearlite which will appear in all hypoeutectoid iron-carbon alloys that are slowly cooled to a temperature below the eutectoid.



(b) With the help of schematic diagram, discuss the following:

(i) Single manufacturing cell

(ii) Flexible manufacturing cell

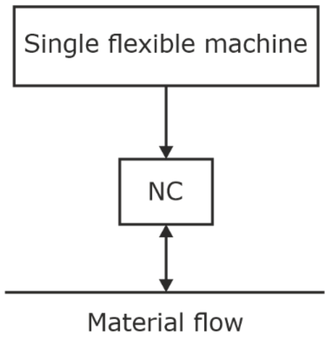
(iii) Flexible manufacturing system

[12 Marks]

Sol.

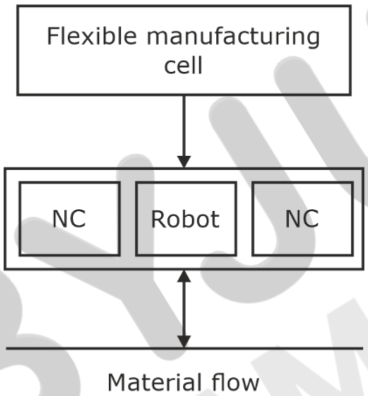
(i) Single manufacturing cell

Single Flexible Machine (SFM) is defined as the production unit formed by NC machine, completed by the manipulation facility to change the objects of the production.



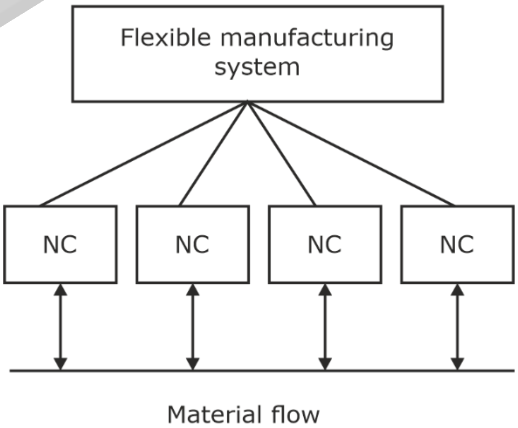
(ii) Flexible manufacturing cell

Flexible Manufacturing Cell (FMC) is the manufacturing system, created by grouping several NC machines, determined for the certain group of parts with the similar sequence of the operations or for the certain type of operations. Characteristic sign of the cell is the mutual material and information interconnection among machines. Usually, they apply for the interoperation manipulations the common manipulation facility.



(iii) Flexible Manufacturing System

Flexible Manufacturing System (FMS) is understood as the grouping of several manufacturing machines without mutual dependence of their activity, for example AGV transport system. Machines are first of all the machining centres, machines determined for the special operations as to produce the gearing operations and so on. Characteristic sign of their activity are the longer operation times.



(c) **(i)** Express unilateral and bilateral tolerances with the help of diagram considering normal size 24.00 mm and tolerance 0.030 mm.

[6 Marks]

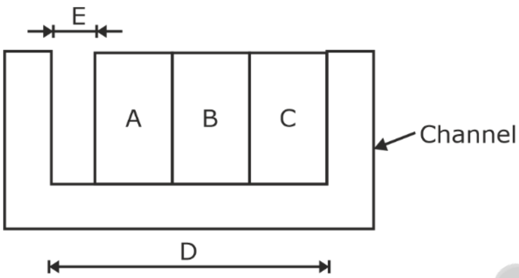
(ii) Three blocks A, B and C are to be assembled in a channel of dimension D as shown in figure. Determine the tolerance that must be assigned to D, if it is essential that the minimum gap E is not less than 0-005 mm. The dimensions of blocks are:

A = 0.75 ± 0.003 mm

B = 1.0 ± 0.005 mm

C= 1.125 ± 0.004 mm

Consider basic dimension of channel D = 2.894 mm.



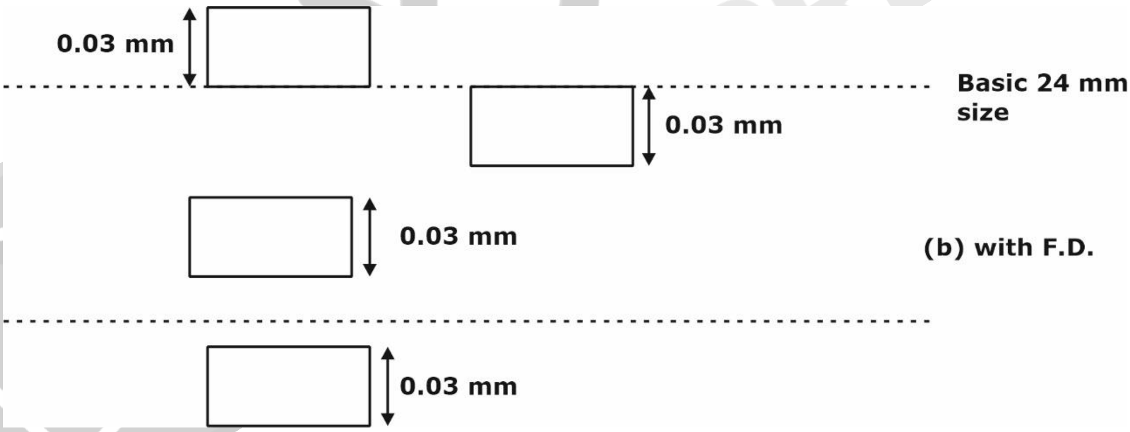
[6 Marks]

Sol.

(i) Unilateral tolerance

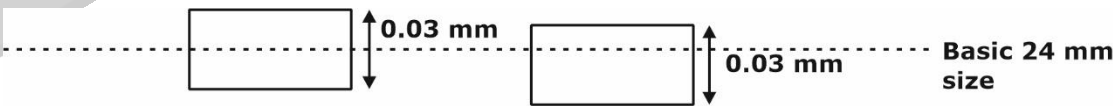
If we allow dimensions of a part to vary on one side of basic or nominal site (Either above or below).

(a) Without F.D.



(b) Bilateral tolerance

Here dimension of a part are allowed to vary both sides of basic size



(ii) A_{max} = 0.75 + 0.08 = 0.753

A_{min} = 0.75 – 0.003 = 0.747

B_{max} = 1.0 + 0.005 = 1.005

B_{min} = 1.0 – 0.005 = 0.995

C_{max} = 1.125 + 0.004 = 1.129

C_{min} = 1.125 – 0.004 = 0.121

$E_{max} = D_{max} - A_{min} - B_{min} - C_{min}$

$E_{min} = D_{min} - A_{max} - B_{max} - C_{max}$

Given, E_{min} = 0.005 mm

0.005 = D_{min} – 0.753 - 1.005 - 1.129

D_{min} = 2.892 mm

Basic size of D is 2.894 mm.

Dimension of D = 2.894 ± 0.002

Tolerance = 0.004

(d) **(i)** Why is it necessary to schedule debris sampling for wear debris?

[6 Marks]

(ii) Wear particles of spherical shape were found in a wear debris sample. What is the possible mode of failure for such case? Justify.

[6 Marks]

Sol.

(i) Scheduling debris sampling for wear debris is important for several reasons:

Maintenance and Condition Monitoring: Sampling and analysing wear debris can provide valuable insights into the condition of machinery and equipment. By monitoring the types, quantities, and characteristics of wear debris particles, maintenance personnel can assess the health of components and identify potential issues before they lead to equipment failure or breakdowns. Regular scheduling of debris sampling allows for proactive maintenance planning and helps optimize equipment performance.

Failure Analysis: When machinery or equipment fails, analysing wear debris can aid in determining the root cause of the failure. By examining the particles present in the debris, experts can identify the specific wear mechanisms, such as abrasion, adhesion, fatigue, or erosion, that contributed to the failure. This information is crucial for implementing corrective measures and preventing similar failures in the future.

Trend Analysis: Regularly sampling and analysing wear debris over time allows for trend analysis. By comparing the debris characteristics from different sampling periods, maintenance personnel can detect changes in wear patterns and particle distributions. These trends can reveal gradual component degradation, abnormal wear rates, or the presence of contaminants, which may indicate the need for maintenance actions or adjustments to operating conditions.

Lubricant Assessment: Wear debris sampling is often performed in conjunction with lubricant analysis. The presence of certain types of wear particles in lubricants can indicate the condition of specific components or the effectiveness of the lubrication system. By scheduling debris sampling alongside lubricant analysis, maintenance professionals can obtain a comprehensive understanding of the machinery's health and lubrication performance.

Quality Assurance: In some industries, such as aerospace or automotive manufacturing, debris sampling is critical for quality assurance purposes. By inspecting wear debris, manufacturers can ensure that components and machinery meet required specifications and that the manufacturing processes are optimized for minimal wear or failure risks.

In summary, scheduling debris sampling for wear debris is necessary to maintain equipment health, diagnose failures, detect trends, assess lubrication effectiveness, and ensure quality control in various industries. It allows for informed decision-making, proactive maintenance planning, and improved operational reliability.

(ii) The presence of spherical wear particles in a wear debris sample can suggest a specific mode of failure known as rolling fatigue or spalling. Rolling fatigue occurs when two contacting surfaces, such as rolling bearings, gears, or rolling elements in a bearing, experience repeated rolling and sliding motion under load. This cyclic loading and movement can lead to material fatigue and the formation of small cracks on the surface.

As the cracks propagate, small particles of material begin to detach from the surface, resulting in spherical wear particles. These particles are typically smooth and rounded due to the rolling action that generates them. The size and composition of the particles can provide further insights into the specific component or system experiencing this mode of failure.

It's important to note that the identification of spherical wear particles alone may not provide a definitive diagnosis of the failure mode. Additional analysis, such as examining the surface condition of the components, evaluating the lubrication system, and considering other factors like operating conditions and maintenance practices, would be necessary to confirm the exact cause of the failure.

(e) Each unit of an item costs a company ₹ 40. Annual holding costs are 18% of unit cost for interest charges, 1% for insurance, 2% allowances for obsolescence, ₹ 2 for building overheads, ₹ 1.50 for damage and loss, and ₹ 4 miscellaneous cost. Annual demand for the item is constant at 1,000 units and each order costs ₹ 100 to place.

(i) Calculate EOQ and the total costs associated with stocking the item.

(ii) If the supplier of the item will only deliver batches of 250 units, how are the stock holding costs affected?

(iii) If the supplier relaxes his order size requirement, but the company has limited warehouse space and can stock a maximum of 100 units at any time, what would be the optimal ordering policy and associated costs?

[12 Marks]

Sol.

Annual demand, D = 1000 units/yr

Unit cost, C = ₹ 40/unit

Holding cost, C_h = (18 + 1 + 2)% of 40 + (2 + 1.5 + 4) = ₹ 15.9 unit/yr

Ordering cost, C_o = ₹ 100/ order

(i) EOQ, $Q^* = \sqrt{\dfrac{2DC_o}{C_h}} = 112.15$ units

$TIC^* = \sqrt{2DC_oC_h}$ = ₹ 1783.25 ₹

Total stock holding cost = $\dfrac{Q^*}{2} \times C_h = \dfrac{112.15}{2} \times 15.9 = 891.625$ ₹

(ii) If Q = 250 units

$HC = \dfrac{Q}{2} \times C_h = \dfrac{250}{2} \times 15.9$ = ₹ 1987.5

Increase in stock holding cost = 1987.5 – 891.625

= ₹ 1095.875

(iii) If Q = 100 units

$$TIC = \frac{D}{Q}C_o + \frac{Q}{2}C_h$$

$$= \frac{1000}{100} \times 100 + \frac{100}{2} \times 15.9 = ₹\ 1795$$

6.

(a) **(i)** The voltage-length characteristic of a direct current (dc) arc is given by V (20+ 40 l) volts, where l is the length of the arc in cm. The power source characteristic is approximated by a straight line with an open circuit voltage = 80 V and a short circuit current 1000 amp. Determine the optimum arc length and the corresponding are *power.

[12 Marks]

(ii) Enlist the most common defects encountered in sand mould casting. Describe the reasons for Scab and Misrun.

[8 Marks]

Sol.

(i) V – I characteristics

V = 20 + 40l (l = arc length in cm)

Open current voltage, V_0 = 80 V

Short circuit current, I_S = 1000 A

Optimum arc length and corresponding power = ?

$$\frac{V}{V_0} + \frac{I}{I_S} = 1$$

$$V = V_0 - \frac{V_0}{I_S} I$$

For stable arc, $V_t = V_a$

$$80 - \frac{80}{1000} I = 20 + 40\, l$$

I = 750 – 500 l

$$P = VI = (20 + 40l)(750 - 500l)$$

For maximum power or optimum arc length,

$$\frac{dP}{dl} = 0$$

$$(20 + 40l)(-500) + (750 - 500l)(40) = 0$$

$$l_{OPT} = 0.5 \text{ cm}$$

P_{max} = 20000 W = 20 kW

(ii) **Most common defects in sand mould casting:**

1. Gas defects

(a) Blow hole

(b) Pinhole

(c) Porosity

(d) Scab

2. Moulding material or methods defects

(a) Drop and dirt

(b) Cuts and washes

(c) Scab

(d) Rat tail

3. Gating design

(a) Shrinkage cavities

4. Pouring metal defects

(a) Misrun

(b) Cold shuts

5. Metallurgical defects

(a) Hot tears or cracks

6. Other defects

(a) Mould shift

(b) Core shift

Scab: These are the projections on the casting which occurs when a portion of the mould face or core lifts and the metal flows beneath in a thin layer. These are rough, irregular projection on the surface containing embedded sand.

Misrun: A misrun casting is one that remains incomplete due to the failure of metal of fill the entire mould cavity, due to in-sufficient fluidity.

(b) **(i)** Compare gray, malleable, white and nodular cast irons with respect to (I) composition and heat treatment, (II) microstructure, and (III) mechanical properties.

[12 Marks]

(ii) Make a schematic plot showing the tensile engineering stress-strain behaviour for mild steel and label the salient points. State the reason of occurrence of two yield points in mild steel. Also, explain the following on the basis of the plot (I) Ductility, (II) Resilience, and (III) Toughness.

[8 Marks]

Sol.

(i) **Gray cast iron:**

The carbon and silicon contents of gray cost irons vary between 2.5 and 4.0 wt% and 1.0 and 3.0 wt%, respectively. For most of these cast irons, the graphite exists in the form of flakes (similar to corn flakes), which are normally surrounded by an a-ferrite or pearlite matrix, the microstructure of a typical gray iron. Because of these graphite flakes, a fractured surface takes on a gray appearance, hence its name.

Mechanically, gray iron is comparatively weak and brittle in tension as a consequence of its microstructure; the tips of the graphite flakes are sharp and pointed and may serve as points of stress concentration when an external tensile stress is applied. Strength and ductility are much higher under compressive loads.

White and Malleable Cast Iron: For low-silicon cast irons (containing less than 1.0 wt% Si) and rapid cooling rates, most of the carbon exists as cementite instead of graphite.

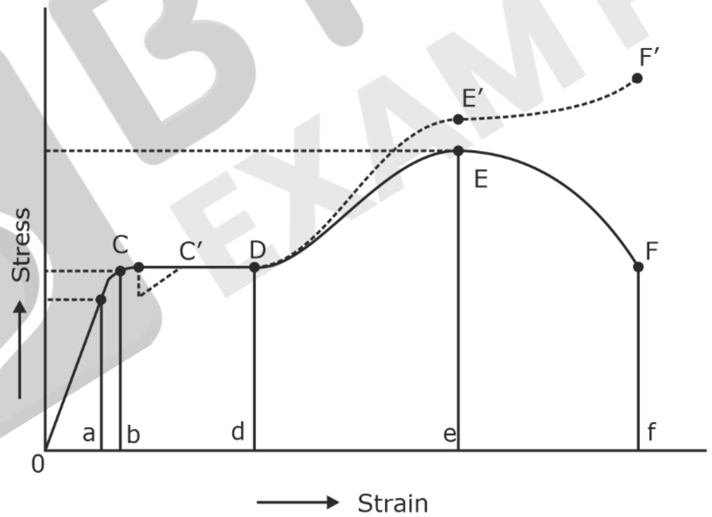
A fracture surface of this alloy has a white appearance, and thus it is termed white cast iron. Thick sections may have only a surface layer of white iron that was "chilled" during the casting process; gray iron forms at interior regions, which cool more slowly. As a consequence of large amounts of the cementite phase, white iron is extremely hard but also very brittle, to the point of being virtually unmachinable. Its use is limited to applications that necessitate a very hard and wear resistant surface, without a high degree of ductility - for example, as rollers in rolling mills. Generally, white iron is used as an intermediary in the production of yet another cast iron, malleable iron.

Heating white iron at temperatures between 800 and 900°C (1470 and 1650°F) for a prolonged time period and in a neutral atmosphere (to prevent oxidation) causes a decomposition of the cementite, forming graphite, which exists in the form of clusters or rosettes surrounded by a ferrite or pearlite matrix, depending on cooling rate. The microstructure is similar to that for nodular iron which accounts for relatively high strength and appreciable ductility or malleability. Representative applications include connecting rods, transmission gears, and differential cases for the automotive industry, and also flanges, pipe fittings, and valve parts for railroad, marine, and other heavy-duty services.

Nodular Cast Iron : Adding a small amount of magnesium and/or cerium to the gray iron before casting produces a distinctly different microstructure and set of mechanical properties. Graphite still forms, but as nodules or sphere-like particles instead of flakes. The resulting alloy is called nodular or ductile iron.

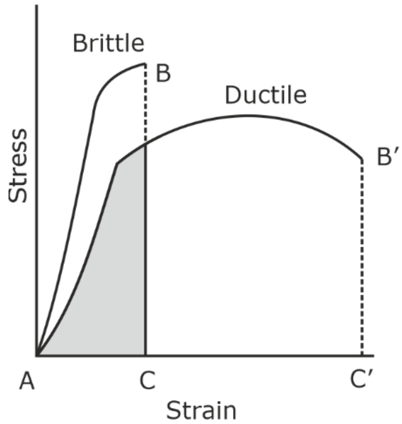
The matrix phase surrounding these particles is either pearlite or ferrite, depending on heat treatment; it is normally pearlite for an as-cast piece. However, a heat treatment for several hours at about 700°C (1300°F) will yield a ferrite matrix. Castings are stronger and much more ductile than gray iron. In fact, ductile iron has mechanical characteristics approaching those of steel. For example, ferritic ductile irons have tensile strengths ranging between 380 and 480 MPa (55000 and 70000 psi), and ductility (as percent elongation) from 10% to 20%. Typical applications for this material include valves, pump bodies, crank-shafts, gears, and other automotive and machine components.

(ii)



Schematic plot showing tensile engineering stress-strain behaviour for mild steel

If the material is stressed beyond point B, the plastic stage will reach i.e., on the removal of the load, the material will not be able to recover its original size and shape. A little consideration will show that beyond point B, the strain increases at a faster rate with any increase in the stress until the point C is reached. At this point, the material yields before the load and there is an appreciable strain without any increase in stress. In case of mild steel, it will be seen that a small load drops to D, immediately after yielding commences. Hence for mild steel there are two yield points C and D. The point C and D are called the upper and lower yield points respectively. The stress corresponding to yield point is known as yield point stress. Ductility: Ductility is an important mechanical property. It is a measure of the degree of plastic deformation that has been sustained at fracture. A material that experiences very little or no plastic deformation upon fracture is termed brittle. The tensile stress-strain behaviours for both ductile and brittle materials are schematically illustrated in Figure below.

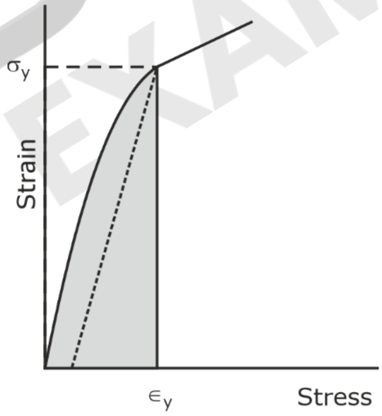


Schematic representations of tensile stress-strain behaviour for brittle and ductile materials loaded to fracture

Resilience is the capacity of a material to absorb energy when it is deformed elastically and then, upon unloading, to have this energy recovered. The associated property is the modulus of resilience, U_r, which is the strain energy per unit volume required to stress a material from an unloaded state up to the point of yielding.

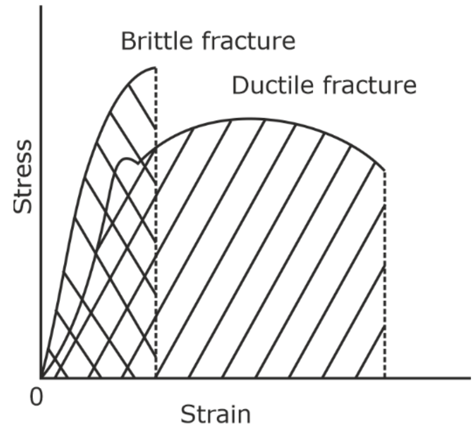
Computationally, the modulus of resilience for a specimen subjected to a uniaxial tension test is just the area under the engineering stress-strain curve taken to yielding.

$$U_r = \int_0^{\epsilon_y} \sigma d \epsilon$$



Schematic representations showing how modulus of resilience (corresponding to the shaded area) is determined from the tensile stress-strain behaviour of a material.

Toughness is a measure of the ability of a material to absorb energy up to fracture. Specimen geometry as well as the manner of load application are important in toughness determinations. For dynamic (high strain rate) loading conditions and when a notch (or point of stress concentration) is present, notch toughness is assessed by using an impact test. Furthermore, fracture toughness is a property indicative of a material's resistance to fracture when a crack is present.



(c) **(i)**

(I) Derive the characteristic equation for the piezoelectric accelerometer supporting a mass (M) on a spring of stiffness (K) and viscous damper with damping coefficient (C). Assume the input and output displacement to be (x_i) and (x_0) respectively.

(II) What is the amplitude ratio for a frequency response analysis assuming input displacement to be sinusoidal?

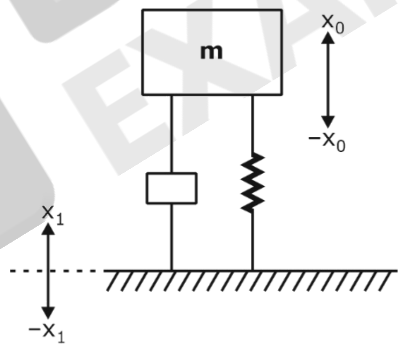
[10 Marks]

(ii) An accelerometer is designed with a seismic mass of 0.05 kg, a spring constant of 5000 N/m, and a damping constant of 30 NS/m. If the accelerometer is mounted to an object experiencing displacement x_i = 5 sin (100t) mm, find an expression for the steady state relative displacement of seismic mass relative to housing as a function of time $x_r(t)$.

[10 Marks]

Sol.

(i)



Input displacement, $x_0(t) = x_i \sin \omega t$

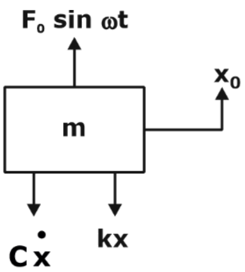
$$a_i(t) = \frac{\partial_i^2 x_0(t)}{\partial t^2} = x_i \omega^2 \sin \omega t$$

Let, $A_i = \omega^2 x_i$ = Amplitude of acceleration

Relative displacement of mass

$x_0(t) = x_0 \sin(\omega t - \phi)$

FBD of mass



$$m\ddot{x} + c\dot{x} + kx = F_0 \sin\omega t$$

$$\ddot{x} + \left(\frac{c}{m}\right)\dot{x} + \frac{kx}{m} = \frac{F_0}{m}\sin\omega t$$

Above equation is a 2nd order differential equation, solving it we get

$x_0(t) = x_0 \sin(\omega t - \phi)$

where, $x_0 = \dfrac{\left(\frac{\omega}{\omega_n}\right)^2 x_i}{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left(2\zeta\frac{\omega}{\omega_n}\right)^2}$ and $\tan\phi = \dfrac{2\zeta\frac{\omega}{\omega_n}}{1-\left(\frac{\omega}{\omega_n}\right)^2}$

Amplitude ratio,

$$\frac{x_0}{x_i} = \frac{\left(\frac{\omega}{\omega_n}\right)^2}{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left(2\zeta\frac{\omega}{\omega_n}\right)^2}$$

(ii) m = 0.05 kg

k = 5000 N/m

C = 30 N-s/m

x_i = 5 sin (100t)

Relative displacement, $x_r(t) = x_r \sin(\omega t + \phi)$

Where, $x_r = \dfrac{x_1\left(\frac{\omega}{\omega_n}\right)^2}{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left(2\zeta\frac{\omega}{\omega_n}\right)^2}$

Given, x_i = 5 mm, ω = 100 rad/s

$$\omega_n = \sqrt{\frac{k}{m}} = \sqrt{\frac{5000}{0.05}} = 316.22 \text{ rad/s}$$

$$\zeta = \frac{c}{2\sqrt{km}} = \frac{30}{2\sqrt{5000\times 0.05}} = 0.949$$

$$x_r = \frac{5\left(\frac{100}{316.22}\right)^2}{\left[1-\left(\frac{100}{316.22}\right)^2\right]^2 + \left(2\times 0.949\times\frac{100}{316.22}\right)^2} = 0.427 \text{ mm}$$

Now, $\tan\phi = \dfrac{2\times 0.949\times \dfrac{100}{316.22}}{1-\left(\dfrac{100}{316.22}\right)^2} \Rightarrow \phi = 33.69° = 0.588$ radian

Hence, $x_r(t) = 0.427 \sin(100t + 0.588)$

7.

(a) **(i)** An engine is to be designed to have a minimum reliability of 0.8 and minimum availability of 0.98 over a period of 2×10^3 hours. Determine MTTR and frequency of failures of engine.

[8 Marks]

(ii) Explain the mechanism of chip formation. What are the conditions that result in the formation of

(I) Continuous chips without built up edge,

(II) Continuous chips with built up edge,

(III) Discontinuous chips?

[12 Marks]

Sol.

(i) Reliability, R = 0.8

Availability, A = 0.98

Time, T = 2×10^3 hours

Availability, $A = \dfrac{MTBF}{MTBF + MTTR}$

$R = e^{-\lambda t}$

$0.8 = \exp(-\lambda \times 2 \times 10^3)$

$\lambda = 1.116 \times 10^{-4}$ favour/hr

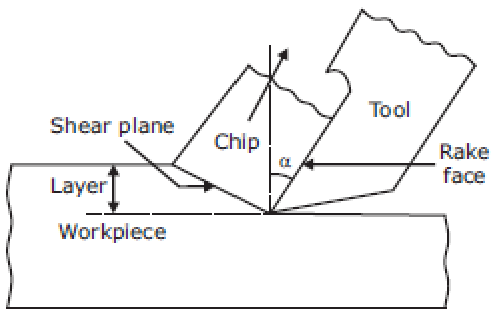
$MTBF = \dfrac{1}{\lambda} = \dfrac{1}{1.116}\times 10^4 = 8962.84$ hr

$A = \dfrac{MTBF}{MTBF + MTTR}$

$0.98 = \dfrac{8962.84}{8962.84 + MTTR}$

MTTR = 182.9 hr ≈ 183 hr

(ii) When the force is applied by the tip of the tool along lengthwise direction in the layer of the workpiece material, the material starts deforming plastically and sliding over a rake face of the tool, inducing shear stresses in the layer of the material. Further application of force by the tool, the shear stresses in the layer of the material increase continuously.



Chip formation during metal cutting

At some point of time, the shear stress-induced becomes greater than or equal to the ultimate shear strength of the material. Therefore, shearing or cracking takes place at the tip of the tool, and it propagates towards the surface of the workpiece producing a shear plane. This is known as tearing. So, the mechanics of chip formation is "shearing and tearing".

Now, during the machining of ductile workpieces, because of the higher toughness value, this crack will get absorbed by the material, and it disappears same where in the middle so that a continuous chip will produce.

Whereas in the case of brittle material, the crack is immediately coming on the work surface leading to discontinuous chips due to less toughness.

The conditions for the various types of chips are:

(i) Continuous chips without BUE:

(a) Ductile material

(b) Small uncut thickness

(c) High cutting speed

(d) Large rake angle

(e) Suitable cutting fluid

(ii) Continuous chips with BUE:

(a) Stronger adhesion between chips and tool face

(b) Low rake angle

(c) Large uncut thickness

(iii) Discontinuous chips:

(a) Low cutting speed

(b) Brittle work material

(c) Small rake angle

(d) Large uncut thickness

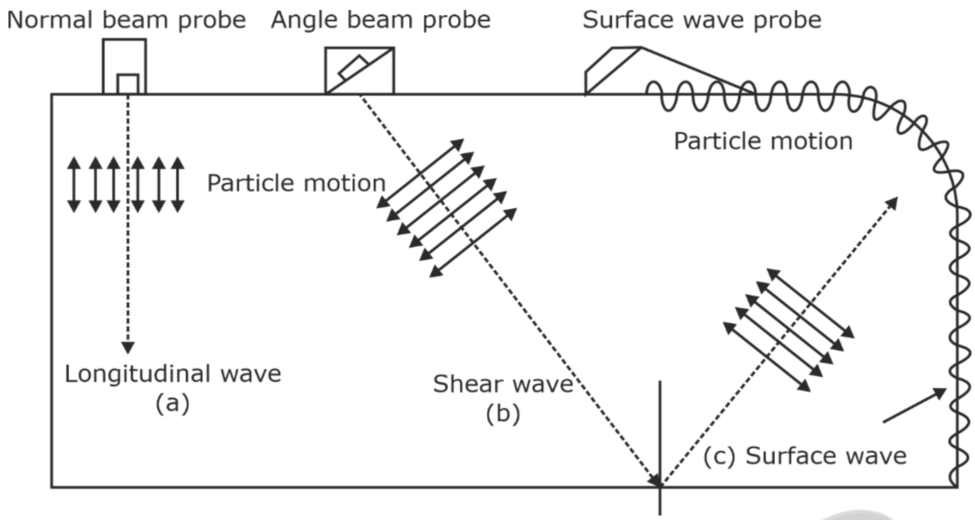
(b) Explain with the working principle a suitable Non-Destructive Testing (NDT) technique to be used for detecting surface as well as fully embedded defects for a wide range of materials including polymers. Also, list the other NDT techniques with reasoning that are not suitable for inspection of above-described requirements.

[20 Marks]

Sol. One suitable non-destructive testing (NDT) technique that can detect both surface and fully embedded defects in a wide range of materials, including polymers, is Ultrasonic Testing (UT).

Working Principle of Ultrasonic Testing:

UT utilizes high-frequency sound waves, typically in the range of 0.5 to 20 MHz, to inspect materials for defects. The basic principle involves the transmission of ultrasonic waves into the material through a transducer. The transducer generates the sound waves, which travel through the material and encounter boundaries or defects.



When the ultrasonic waves encounter a boundary or defect within the material, such as a crack, void, or inclusion, some of the waves are reflected back towards the transducer. The reflected waves are received by the transducer and converted into electrical signals, which are then analyzed to determine the presence, location, and characteristics of the defects.

In the case of surface defects, the ultrasonic waves will partially reflect back from the material's surface. By analyzing the time-of-flight and amplitude of the reflected waves, surface defects can be detected and characterized.

For fully embedded defects, the ultrasonic waves will travel through the material until they encounter the defect. The presence of the defect will cause a significant reflection or scattering of the ultrasonic waves back to the transducer. By analyzing the received signals, the size, shape, and location of the embedded defects can be determined.

Other NDT techniques that may not be suitable for the inspection of both surface and fully embedded defects in a wide range of materials, including polymers, include:

(i) Visual Inspection: While visual inspection is a valuable method for detecting surface defects, it may not be effective for fully embedded defects that are not visible from the surface.

(ii) Magnetic Particle Testing (MT): MT is primarily used for detecting surface-breaking defects in ferromagnetic materials. It relies on the magnetic fields generated by defects to attract magnetic particles. It is not suitable for detecting defects in non-magnetic materials or fully embedded defects.

(iii) Liquid Penetrant Testing (PT): PT is effective for detecting surface-breaking defects, but it may not be suitable for fully embedded defects that are not accessible from the surface.

(iv) Eddy Current Testing (ET): ET is commonly used for detecting surface cracks or defects in conductive materials. It relies on electromagnetic induction to detect changes in electrical conductivity caused by defects. However, it may not be suitable for detecting fully embedded defects or defects in non-conductive materials.

It's important to note that the selection of an appropriate NDT technique depends on the specific requirements, material properties, and the nature of the defects to be detected.

(c) **(i)** A 12-bit Analog-to-Digital Converter operating at a sampling rate of 5 kHz is used with a sensor. What is the size of computer memory (in bytes) required to store 20 seconds of sensor data? What will be the memory size in case a 8-bit Analog to Digital Converter is used? Why is it not possible to connect sensors such as accelerometers, strain gauges and thermocouple directly to a microprocessor or computer?

[12 Marks]

(ii) A CNC machine tool table is powered by a servo motor, lead screw and optical encoder. The lead screw has a pitch of 5 mm and is connected to the motor shaft with a gear ratio of 16 : 1. The optical encoder connected directly to the lead screw generates 200 pulses per revolution of the lead screw. The table moves a distance of 100 mm at a feed rate of 500 mm/min.

Determine the pulse count received by the control system to verify that the table has moved exactly 100 mm.

[8 Marks]

Sol.

(i) To calculate the memory size required to store sensor data, we need to consider the sampling rate, resolution of the Analog-to-Digital Converter (ADC), and the duration of data collection.

Here's the calculation for both scenarios:

Using a 12-bit ADC:

The ADC has a resolution of 12 bits, which means it can represent 2^12 (4096) discrete levels.

Each sample will require 12 bits of memory.

The sampling rate is 5 kHz, which means 5,000 samples will be taken per second.

Memory size required for 20 seconds of data:

20 seconds * 5,000 samples/second * 12 bits/sample = 1,200,000 bits

Converting to bytes:

1,200,000 bits / 8 bits/byte = 150,000 bytes

Therefore, 20 seconds of sensor data from a 12-bit ADC at a 5 kHz sampling rate would require 150,000 bytes of memory.

Using an 8-bit ADC:

The ADC has a resolution of 8 bits, allowing it to represent 2^8 (256) discrete levels.

Each sample will require 8 bits of memory.

Memory size required for 20 seconds of data:

20 seconds * 5,000 samples/second * 8 bits/sample = 800,000 bits

Converting to bytes:

800,000 bits / 8 bits/byte = 100,000 bytes

Therefore, 20 seconds of sensor data from an 8-bit ADC at a 5 kHz sampling rate would require 100,000 bytes of memory.

Now, let's address why sensors such as accelerometers, strain gauges, and thermocouples cannot be connected directly to a microprocessor or computer:

(i) Signal Conditioning: Many sensors, including accelerometers, strain gauges, and thermocouples, produce analog signals that need to be conditioned or converted to a suitable digital format for processing by a microprocessor or computer. This involves amplification, filtering, linearization, and sometimes conversion to digital signals using ADCs.

(ii) Voltage/Current Levels: Sensors often have specific voltage or current output levels that may not directly match the input requirements of microprocessors or computers. Signal conditioning circuits can adjust and scale the sensor output to meet the input requirements of the digital system.

(iii) Noise and Interference: Sensors may be sensitive to noise and electromagnetic interference present in the environment. Signal conditioning circuits can include shielding, filtering, and grounding techniques to minimize the impact of noise on the sensor signals.

(iv) Calibration and Accuracy: Sensors require calibration to ensure accurate and reliable measurements. Signal conditioning circuits can incorporate calibration techniques to compensate for sensor inaccuracies and variations.

(v) Compatibility: Microprocessors and computers typically operate on digital signals and have specific communication protocols (such as SPI, I2C, UART) for data transfer. Sensor outputs need to be converted to digital signals and may need to adhere to specific communication protocols for seamless integration with microprocessors or computers.

In summary, connecting sensors directly to microprocessors or computers is not feasible due to the need for signal conditioning, voltage/current level adjustments, noise reduction, calibration, and compatibility with digital systems. Signal conditioning circuits bridge the gap between sensor outputs and the requirements of microprocessors or computers, ensuring accurate and reliable data acquisition and processing.

(ii)

Given: P = 5mm Gear ratio = 16:1

Distance travelled by table for 1 revolution of lead screw = 5 mm

So, number of revolution of lead screw for 100 mm distance travelled by table =

$$\frac{100}{5} = 20 \text{ revolution}$$

Number of pulses required for 1 revolution of lead screw = 200

So, total number of pulses required for 20 revolution of lead screw = 20 x 200 4000 pulses

As lead screw is connected to motor shaft then number of revolutions turned by motor shaft

$= 16 \times 20 = 320$ revolution

So, total number of input pulses required = $320 \times 200 = 64000$ pulses

8.

(a) An automatic door is designed to open the door when a person approaches and close automatically after five seconds. The door is operated by an electric motor-based actuator, responsible for sliding the door on rail.

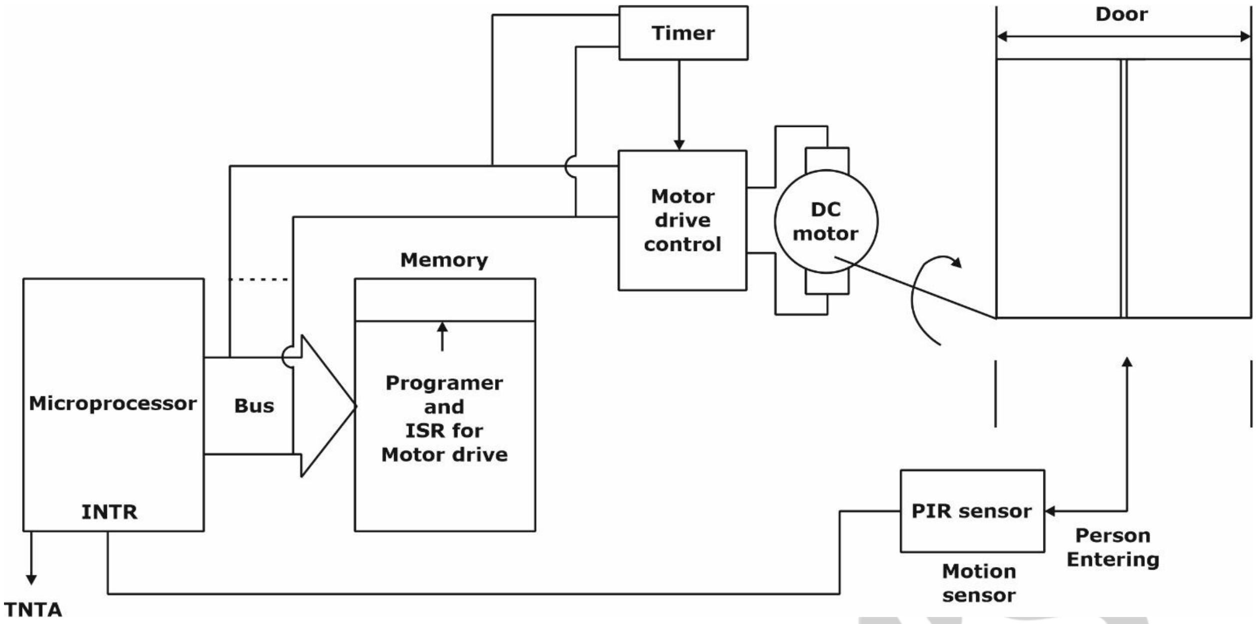
(i) Explain the working mechanism assuming a microprocessor-based control using a schematic diagram of the control system used. Also, specify the primary components of the control system.

(ii) If a microcontroller-based system is used, what would be the merits and demerits of such system?

[20 Marks]

Sol.

(i) Working Mechanism of the Microprocessor-Based Control System for the Automatic Door:



Sensor: The control system starts with a sensor that detects the presence of a person approaching the door. Commonly used sensors for this purpose include infrared motion sensors, ultrasonic sensors, or pressure sensors placed on the floor near the entrance.

Signal Processing: The sensor sends a signal to the microprocessor indicating the presence of a person. The microprocessor receives and processes this signal to initiate the door-opening sequence.

Motor Control: The microprocessor sends signals to control the electric motor-based actuator responsible for sliding the door on the rail. The motor control signals dictate the direction and duration of the motor's operation.

Door Opening: When the microprocessor receives the signal from the sensor, it activates the motor control signals to open the door. The electric motor rotates in the appropriate direction to slide the door open.

Timer: After the door is fully open, a timer is started by the microprocessor to keep track of the elapsed time.

Door Closing: Once the timer reaches the preset duration of five seconds, the microprocessor sends commands to the motor control to close the door. The motor rotates in the opposite direction to slide the door back to its closed position.

Safety Measures: The control system may include safety measures, such as obstacle detection sensors or pressure sensors, to ensure that the door does not close on a person or an object in its path. These safety features can be integrated into the control system to halt the door's movement or reverse its direction if an obstruction is detected.

Primary Components of the Control System:

Sensor: Detects the presence of a person approaching the door.

Microprocessor: Receives signals from the sensor, processes data, and controls the motor based on the program logic.

Motor: An electric motor-based actuator responsible for sliding the door on the rail.

Timer: Keeps track of the elapsed time for the door to close after opening.

Motor Control Circuitry: Controls the motor's operation, including direction and duration.

Safety Measures: Obstacle detection sensors, pressure sensors, or other safety features to prevent accidents.

(ii) Merits and Demerits of a Microcontroller-Based System:

Merits of a Microcontroller-Based System:

Integration: A microcontroller combines the functions of a microprocessor, memory, and input/output interfaces in a single chip, making it compact and easy to integrate into the control system.

Cost-Effectiveness: Microcontrollers are generally more cost-effective compared to separate microprocessors, memory chips, and additional logic components.

Real-Time Control: Microcontrollers can provide real-time control capabilities, allowing precise timing and response to sensor inputs for the automatic door system.

Programmability: Microcontrollers are programmable, allowing flexibility in implementing complex control algorithms and logic for various functionalities of the automatic door.

Demerits of a Microcontroller-Based System:

Limited Processing Power: Microcontrollers generally have limited processing power compared to standalone microprocessors, which can be a constraint when dealing with complex control algorithms or handling large amounts of data.

Limited Memory: Microcontrollers often have limited memory capacities, which can restrict the storage of extensive program code or large data sets.

Development Complexity: Designing and programming a microcontroller-based system requires specialized knowledge and skills in embedded systems programming, which may increase the complexity and development time.

Limited Expandability: Microcontrollers typically have a fixed number of input/output pins, which may limit the expandability and flexibility of the control system if additional features or components need to be integrated in the future.

(b) **(i)** It is desired to measure the angular position of a motor shaft with a set-up using two Hall Sensors A and B and a permanent magnet multi-pole wheel. Explain the logic that is used for measuring the position as well as direction of the motor shaft based on states of output signals from Hall Sensors A and B.

[10 Marks]

(ii) With the help of a schematic diagram, explain the working principle of a resolver. How does the output for resolver differ from that of an encoder?

[10 Marks]

Sol.

(i) To measure the angular position and direction of a motor shaft using two Hall sensors (A and B) and a permanent magnet multi-pole wheel, a technique called quadrature encoding is commonly employed. The output signals from the Hall sensors provide information about the relative position and movement of the motor shaft. Here's how the logic works:

1. Sensor Placement: Hall sensors A and B are positioned adjacent to the permanent magnet multi-pole wheel in such a way that they detect the magnetic field changes as the wheel rotates.

2. Multi-Pole Wheel: The multi-pole wheel has evenly spaced north and south poles around its circumference. The number of poles can vary depending on the required resolution of the angular position measurement.
3. Output Signal States: The Hall sensors generate digital output signals that can be in either a high (H) or low (L) state based on whether they detect a north pole (N) or south pole (S) of the multi-pole wheel.
4. Quadrature Encoding: The logic for measuring the position and direction of the motor shaft is based on the relative states of the output signals from Hall sensors A and B. The following table illustrates the possible combinations of output signal states:

Sensor A	Sensor B	Position	Direction
L	L	0°	Clockwise
L	H	90°	Clockwise
H	H	180°	Clockwise
H	L	270°	Clockwise

Note: The direction is determined based on the clockwise rotation of the multi-pole wheel.

Logic Analysis: By analysing the output signal states of Hall sensors A and B, the logic can determine the angular position and direction of the motor shaft. The output signal states are compared with the table above to determine the position, and the change in states between successive readings indicates the direction of rotation.

For example, if the previous state was (L, L) and the current state is (L, H), it indicates a clockwise rotation of 90 degrees. If the previous state was (L, H) and the current state is (L, L), it indicates a counterclockwise rotation of 90 degrees.

By continuously monitoring and analysing the output signal states of the Hall sensors, the logic can accurately track the angular position and direction of the motor shaft.

It's worth noting that the actual implementation may involve additional considerations, such as debouncing the sensor signals, handling edge cases, and incorporating error correction techniques to ensure robust and accurate position and direction measurement.

(ii) A resolver is an electromechanical device used for measuring the angular position of a rotating shaft. It operates based on the principle of electromagnetic induction.

Working Principle of a Resolver:

1. Stator Windings: The resolver consists of a stator, which includes two mutually perpendicular windings: the primary winding (sinusoidal winding) and the secondary winding (cosinusoidal winding). These windings are typically placed at 90 degrees to each other.
2. Rotor: The rotor is attached to the shaft whose position needs to be measured. It contains a rotating magnetic field generated by an AC excitation signal.
3. Transformer Action: The primary winding of the stator is excited with an AC signal, typically at a frequency of 400 Hz. This excitation signal creates a magnetic field in the primary winding.
4. Electromagnetic Induction: As the rotor rotates, the magnetic field generated by the rotor induces voltages in the secondary winding of the stator. The induced voltages in the secondary winding are proportional to the sine and cosine of the angle between the rotor and the stator windings.

5. Output Signals: The output signals of a resolver are the sine and cosine voltages generated in the secondary winding. These voltages vary in amplitude and phase depending on the angular position of the rotor shaft. The amplitude represents the position, while the phase indicates the direction of rotation.

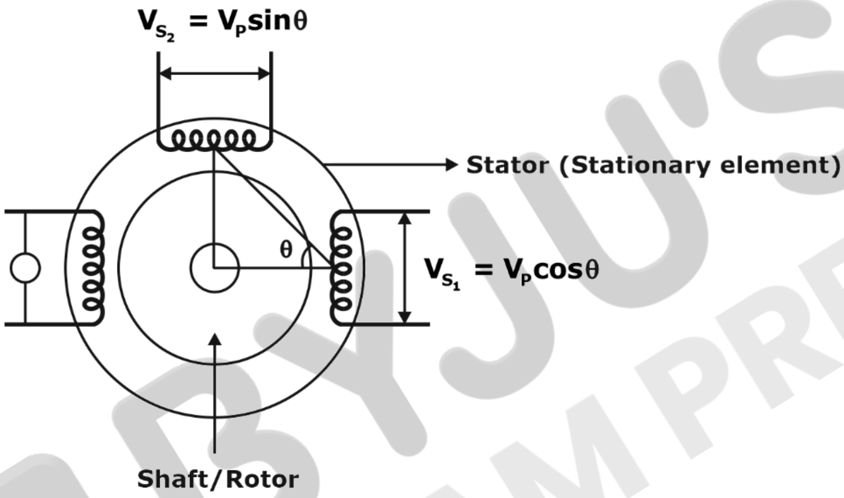
It has 1 primary coil and 2 secondary coils,

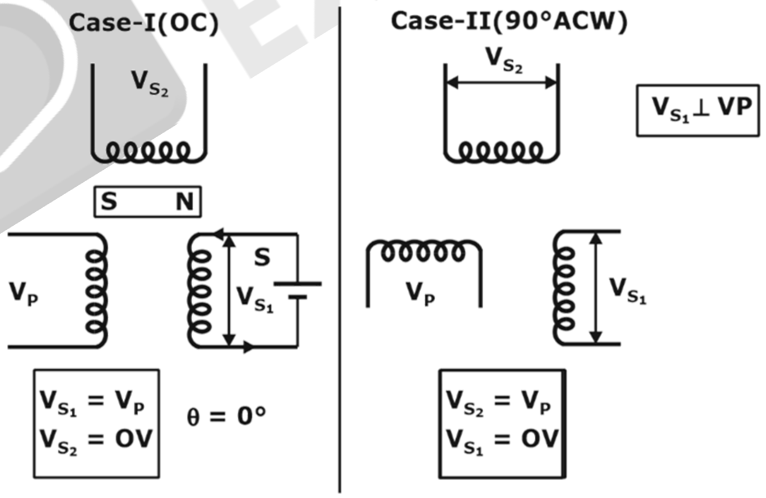
$$\frac{V_{s_1}}{N_{S_1}} = \frac{V_p}{N_P}$$

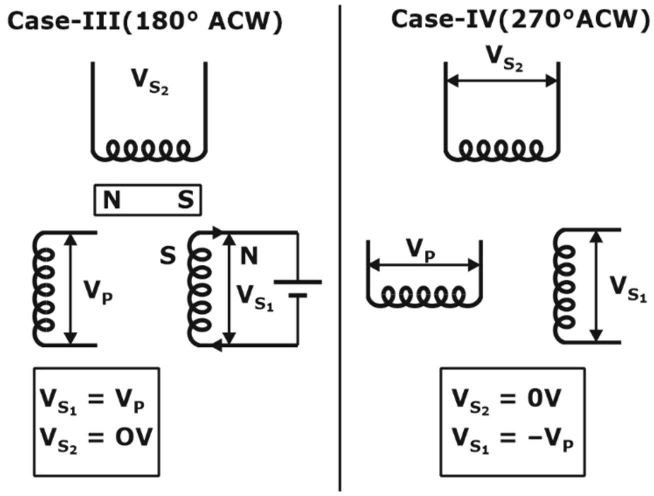
$$N_{S_1} = N_p$$

$$V_{S_1} = V_p$$

$$V_{S_1} = 0 \ \text{(Due to no magnetic field)}$$







Differences between the Output of a Resolver and an Encoder:

1. Analog vs. Digital Output: A resolver provides analog output signals (sine and cosine voltages), while an encoder provides digital output signals (typically in the form of pulses).
2. Continuous vs. Discrete Positioning: A resolver provides continuous position information due to its analog nature. It can provide precise positioning within a rotation, allowing for smooth and accurate control. In contrast, an encoder provides discrete position information, typically in the form of counts or pulses, which requires additional processing to determine the exact position.
3. Resolution: Encoders generally have higher resolution (number of counts per revolution) compared to resolvers. Resolvers typically have lower resolution due to the limitations of the analog output signals.
4. Noise Immunity: Resolvers are known for their high noise immunity since the analog signals are less susceptible to electrical noise and interference. Encoders, especially optical encoders, may be more prone to noise-related issues.
5. Cost: Resolvers tend to be more expensive than encoders, mainly due to their more complex construction and lower production volumes.

Overall, resolvers are well-suited for applications that require high accuracy, robustness, and resistance to noise. They are commonly used in industries such as aerospace, robotics, and industrial automation. Encoders, on the other hand, are widely used in various applications, including motor control, robotics, and positional feedback systems, where digital position data is preferred.

(c) What are the fundamental arm architecture of a basic robot arm on the basis of geometric work envelope? How can these fundamental arm architecture be derived from one another? What arm configurations do Gantry and SCARA robots correspond to? Also, show the geometric work envelope and arm configuration of Gantry and SCARA robots with a suitable figure.

[20 Marks]

Sol. The fundamental arm architectures of a basic robot arm, based on geometric work envelope, include:

1. Cartesian: A Cartesian robot arm has three linear joints, one for each axis (X, Y, Z). This configuration allows the arm to move in a rectangular coordinate system. The work envelope of a Cartesian robot is box-shaped.
2. Cylindrical: A cylindrical robot arm consists of a prismatic joint along the Z-axis and a revolute joint about the Z-axis. This configuration enables the arm to move in a cylindrical coordinate system. The work envelope of a cylindrical robot is cylinder-shaped.
3. Spherical/Polar: A spherical robot arm includes a revolute joint about the Z-axis, a prismatic joint along the Z-axis, and a revolute joint about the Y-axis. This configuration allows the arm to move in a spherical or polar coordinate system. The work envelope of a spherical robot is sphere-shaped.
4. Articulated/Revolute: An articulated robot arm consists of revolute joints connecting multiple segments. This configuration allows for complex movements and flexibility. The work envelope of an articulated robot can vary depending on the number and arrangement of joints.

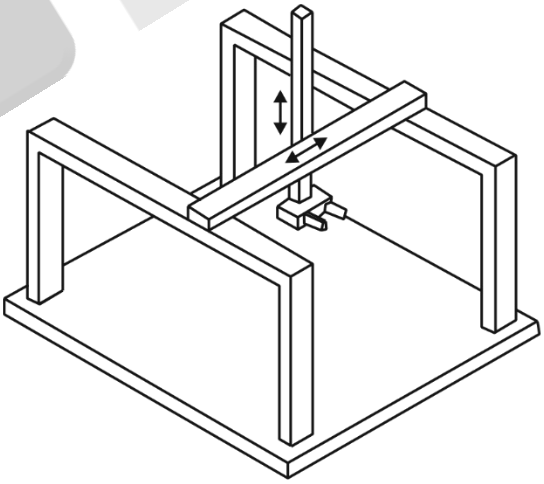
The fundamental arm architectures can be derived from one another through modifications or combinations of joints. For example:

- A Cartesian robot arm can be converted to a cylindrical arm by replacing one of the linear joints with a revolute joint.
- A cylindrical arm can be converted to a spherical arm by adding an additional revolute joint about the Y-axis.
- An articulated arm can be constructed by connecting multiple revolute joints together.

Gantry robots and SCARA (Selective Compliance Assembly Robot Arm) robots correspond to specific arm configurations:

1. Gantry Robot:

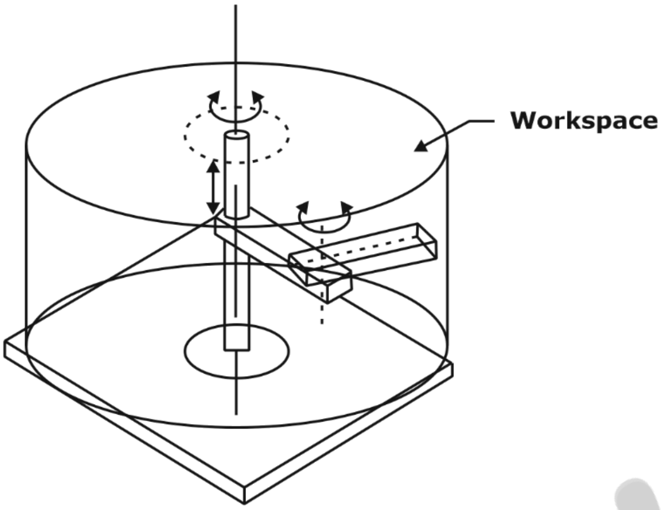
- Arm Configuration: Gantry robots have a Cartesian arm configuration with three linear joints for the X, Y, and Z axes.
- Work Envelope: The work envelope of a Gantry robot is rectangular-shaped.



2. SCARA Robot:

- Arm Configuration: SCARA robots have a combination of revolute and prismatic joints. They typically consist of two parallel revolute joints for planar motion and one prismatic joint for vertical motion.

- Work Envelope: The work envelope of a SCARA robot is cylindrical-shaped, limited to a plane.



***

BYJU'S
EXAM PREP

Outstanding performance by our students in GATE 2021

CONGRATULATIONS TO OUR TOPPERS

27	12	17	100
Ranks in TOP 50	Ranks in TOP 10	Ranks in TOP 20	Ranks in TOP 100

Poojasree (ECE)

Munish (ME)

Divakar (IN)

Parag (ECE)

Harshit (IN)

Amit (CE)

Vatsal (ME)

Hemant (EE)

Rajat (ME)

Abhishek (ECE)