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ESE - 2018

MAINS EXAMINATION

Questions with Detailed Solutions

MECHANICAL ENGINEERING

PAPER - II

All Queries related to ESE - 2018 Mains Solutions are to be sent to the following email address
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MECHANICAL ENGINEERING

PAPER – 2 _ REVIEW

The syllabus for Section – A (Design Part) is less as compared to Section – B (Production & Industrial Engineering), even though the marks allotted to both sections are same. Maximum questions in Section – A were numerical problems Section – B has more theory part. Thus, students are advised to first concentrate on Section – A. So, if students had fundamental knowledge about the subject they could have easily attempted theory questions as well.

As regards the compulsory questions in 'Section – A' 80% are numerical problems and 20% are theoretical. Further, questions on TOM were having the weightage of 60%. In 'Section – B' the weightage of theoretical and numerical questions were almost equal. It is expected that the above review will help the students in future.

SUBJECT WISE REVIEW

	Subjects	Level	Marks
Section (A)	Mechanics	Easy to moderate	42
	SOM	Easy to moderate	42
	TOM	Easy to tough	96
	MD	Easy to moderate	60
Section (B)	Production	Easy to tough	84
	IM & OR	Easy to moderate	42
	Material Science	Easy to tough	42
	Mechatronics & Robotics	Easy to tough	52
	Maintenance Engineering	Easy	20

Getting 175 to 210 marks is a great achievement in view of the time constraints and QCAB.

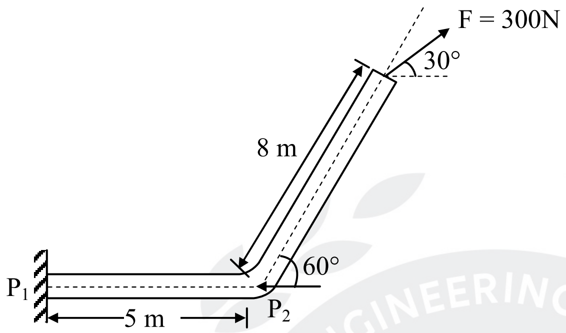
Subjects Experts,

ACE Engineering Academy

SECTION – A

01(a).

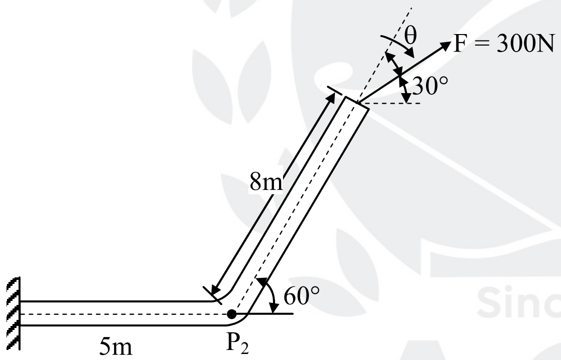
(i). **A flue pipe in a furnace system is rigidly attached to the furnace wall at P_1 as shown in the figure below. Compute the moments at points P_1 and P_2 when a force of 300 N is acting at the end of the pipe.**



(6 M)

01(a)(i).

Sol:



From the diagram, θ+30 = 60

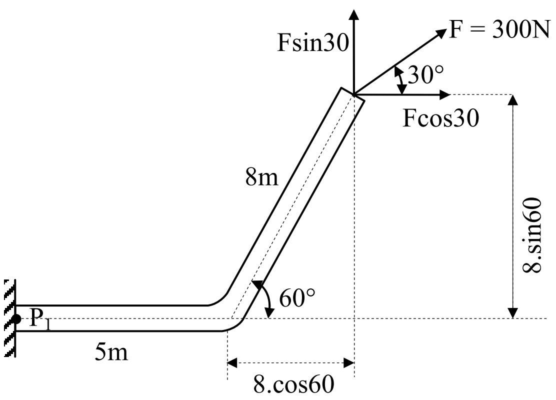
∴ θ = 30°

M_{P2} = F×sinθ×8 = 300×sin30×8 = 1200 Nm (clockwise)

M_{P1} = –Fcos30×8×sin60+Fsin30 {5+8cos 60}

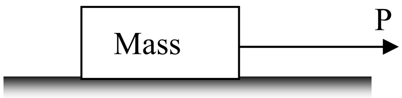
= –450 Nm

= 450 Nm (clockwise)



01(a).

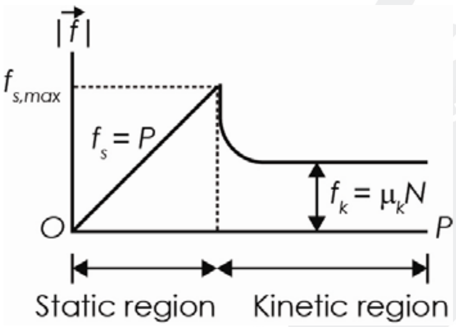
(ii). Consider a solid block of mass 'm' resting on a horizontal surface. When the mass is subjected to a horizontal force 'P' it will experience a frictional force resisting the motion. Draw and show the variation of frictional force F vs. applied force P even if it continues to shift from no motion (static friction) domain to motion domain (kinetic friction).



(6 M)

01(a)(i).

Sol:



where,

μ_k = coefficient of kinetic friction,

N = normal reaction

f_k = kinetic friction

f_s = static friction

f_{smax} = limiting friction

P = applied force

01(b). Draw and show the bending moment diagram and shear force diagram of a beam of length 'L' subjected to a uniformly distributed loading for the following boundary conditions :

(i) Cantilever beam

(ii) Simply supported beam

(iii) Beam with both ends fixed

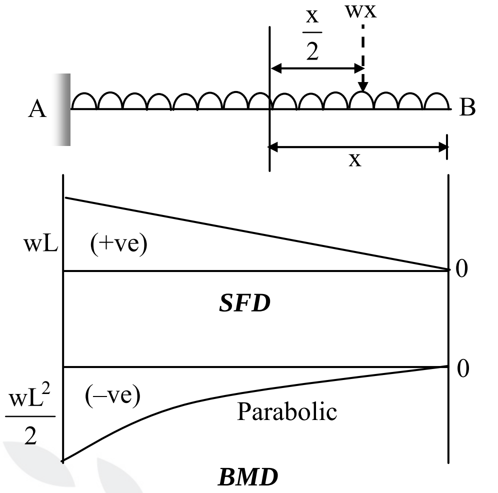
(iv) Beam with one end simply supported and a propped support at 1/4th L from the other end

(12 M)

01(b).

Sol:

(i) Cantilever beam:



Shear force; $F_x = +wx \ (0 \le x \le L)$

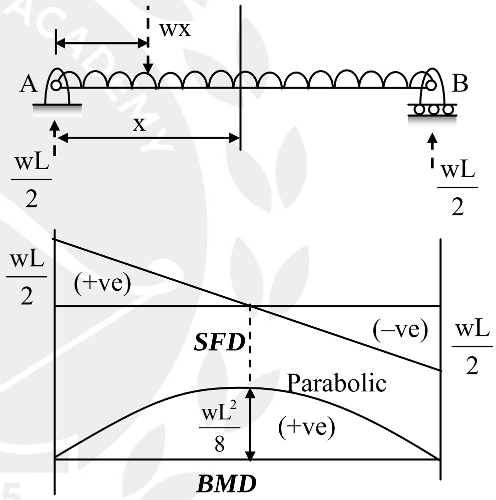
$\Rightarrow F_B = 0$ and $F_A = wL$

Bending moment; $M_x = -wx \times \frac{x}{2}$

$$\Rightarrow M_x = -\frac{wx^2}{2} \ (0 \le x \le L)$$

$$\Rightarrow M_B = 0 \text{ and } M_A = -\frac{wL^2}{2}$$

(ii) Simply supported beam:



Shear force: $F_x = \frac{wL}{2} - wx \ (0 \le x \le L)$

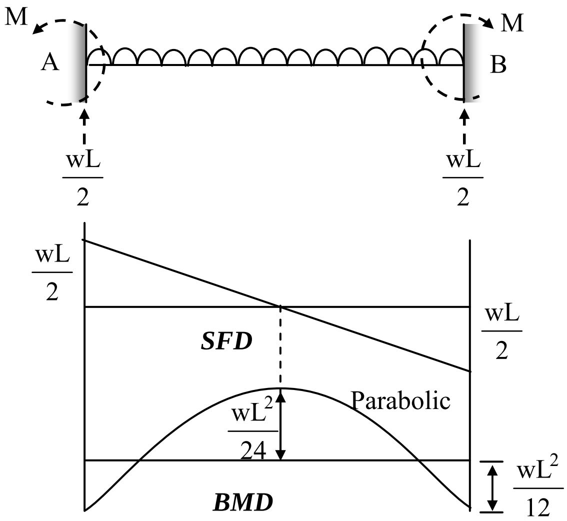
$$\Rightarrow F_A = \frac{wL}{2} \text{ and } F_B = -\frac{wL}{2}$$

Bending moment: $M_x = \frac{wL}{2}x - \frac{wx^2}{2} \ (0 \le x \le L)$

$\Rightarrow$ $M_A = 0$, $M_B = 0$ and

$$M_{\text{At } x=\frac{L}{2}} = \frac{wL^2}{8}$$

(iii) Fixed beam:



Area under BMD = 0

$$-M \times L + 2 \times \frac{2}{3} \times \frac{L}{2} \times \frac{wL^2}{8} = 0$$

$$\Rightarrow M = \frac{wL^2}{12}$$

Shear force: $F_x = \frac{wL}{2} - wx \ (0 \le x \le L)$

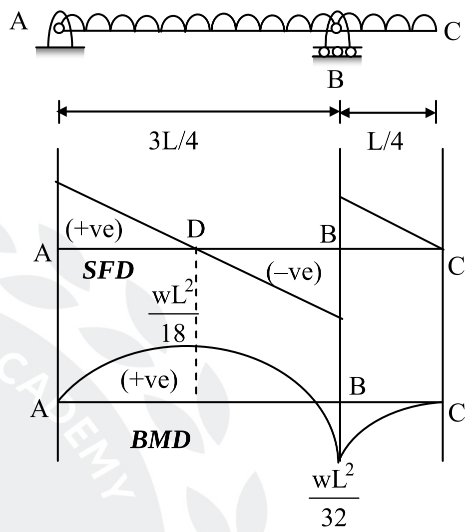
$$\Rightarrow F_A = \frac{wL}{2}, \quad F_B = -\frac{wL}{2}$$

Bending Moment: $M_x = \frac{wL}{2}x - \frac{wx^2}{2} - \frac{wL^2}{12}$

$\Rightarrow \quad M_A = -\frac{wL^2}{12}, M_B = -\frac{wL^2}{12}$ and

$M_{At\ x=\frac{L}{2}} = \frac{wL}{2}\times\frac{L}{2} - \frac{wL^2}{8} - \frac{wL^2}{12} = \frac{wL^2}{24}$

(iv) $\Sigma M_A = 0$



$\Rightarrow wL\times\frac{L}{2} - R_B\times\frac{3L}{4} = 0 \Rightarrow R_B = \frac{wL}{2}\times\frac{4}{3}$

$\Rightarrow R_B = \frac{2wL}{3}$

Also, $\Sigma F_y = 0 \Rightarrow R_A + R_B = wL \Rightarrow R_A = \frac{wL}{3}$

Shear force: AB: $F_x = \frac{wL}{3}x - \frac{wx^2}{2}$

$\Rightarrow \quad F_A = \frac{wL}{3}, F_B = -\frac{5wL}{12}$

BC:(Measuring x from 'c'), $F_x = +wx$

$\Rightarrow \quad F_C = 0$ and $F_B = \frac{wL}{4}$

Bending moment: $M_A = 0$

$\frac{AD}{DB} = \frac{wL/3}{5wL/12} = \frac{4}{5} \Rightarrow \frac{x}{\frac{3L}{4}-x} = \frac{4}{5} \Rightarrow 5x = 3L - 4x$

$\Rightarrow \quad x = L/3 = AD$

$M_D = M_A + [\text{Area SFD}]_A^D = 0 + \frac{1}{2}\times\frac{L}{3}\times\frac{wL}{3} = \frac{wL^2}{18}$

$M_B = M_D + [\text{Area SDF}]_D^B = \frac{wL^2}{18} - \frac{1}{2}\times\frac{5L}{12}\times\frac{5wL}{12} = -\frac{wL^2}{32}$

$M_C = 0$

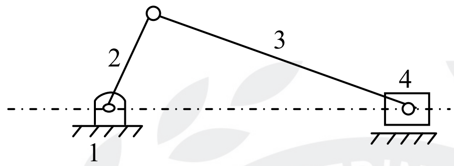
01(c).

(i) Distinguish and differentiate between machine and mechanism. Define the term Inversion of a kinematic chain.

01(c)(i).

Sol: **Mechanism and machine :** A combination of a number of bodies (usually rigid) assembled in such a way that the motion of one causes constrained and predictable motion to the others is known as a mechanism. Thus, the function of a mechanism is to transmit and modify a motion.

A machine is a mechanism or a combination of mechanisms which, apart from imparting definite motions to the parts, also transmits and modifies the available mechanical energy into some kind of desired work. It is neither a source of energy nor a producer of work but helps in proper utilization of the same. The motive power has to be derived from external sources.



A slider-crank mechanism converts the reciprocating motion of a slider into rotary motion of the crank or vice-versa. However, when it is used as an automobile engine by adding valve mechanism etc., it becomes a machine which converts the available energy (force on the piston) into the desired energy (torque of the crank-shaft).

Inversion: By fixing one link in a kinematic chain a mechanism is obtained. By fixing different links, different mechanisms are obtained. Inversion is the process of obtaining different mechanism by fixing different links in a kinematic chain.

01(c)(ii). Discuss about the possible inversions (with figures) of a four bar chain. (12 M)

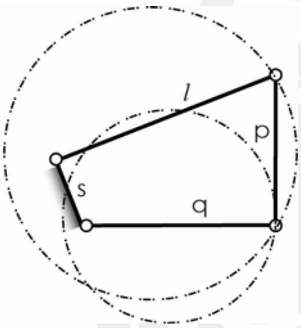
01(c)(ii).

Sol: Inversions of Grashof's 4-bar chain

(l + s < p + q): The mechanisms obtained from the Grashof's Kinematic chain are based on the position of the shortest link

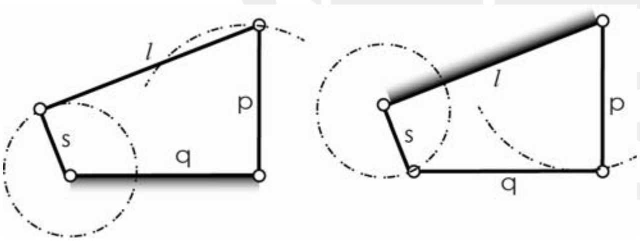
Shortest link fixed:

In this mechanism input link becomes crank, i.e. would complete full revolution and output link also completes full revolution thus becomes *double crank mechanism* (C-C).



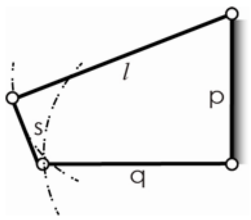
Link adjacent to shortest link is fixed :

Input link becomes crank but output link becomes rocker thus results in *rocker mechanism*(C-R).



Link opposite to the Shortest link is fixed:

In this case both input and output links become rocker and give *Rocker-Rocker mechanism*(R-R).



01(d). Derive the equation for the resultant unbalanced force at any instant of a reciprocating mass of a slider crank mechanism. (12 M)

01(d).

Sol: Reciprocating mass Balancing :

Almost all IC engines using reciprocating engines would produce reciprocating unbalance force

Acceleration in a reciprocating engine, $a = r\omega^2\left(\cos\theta + \frac{\cos 2\theta}{n}\right)$

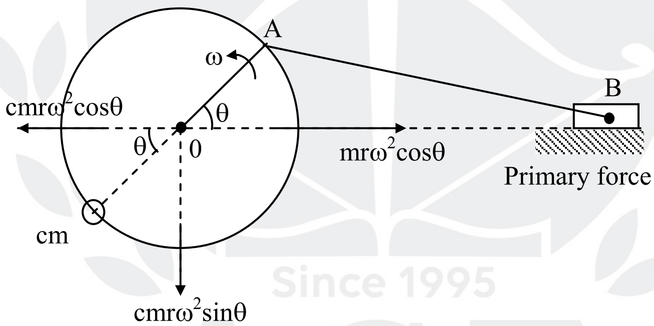
Force produced due to this acceleration, $F = mr\omega^2 \cos\theta + mr\omega^2 \frac{\cos 2\theta}{n} \quad \left(n = \frac{\ell}{r}\right)$

Here $mr\omega^2 \cos\theta$ is primary accelerating force acting along stroke of the cylinder.

$\frac{mr\omega^2 \cos 2\theta}{n}$ is secondary accelerating force.

If $n = \frac{\ell}{r} >> 1$, then secondary force would be neglected.

Mount a counter balancing mass 'cm' diagonally opposite to the crank, with crank radius, r.



As evident from the figure, the primary unbalance force is compensated but vertical force $mr\omega^2 \sin\theta$ is not balanced.

This $mr\omega^2\sin\theta = 0$ at $\theta = 0°$ or $180°$.

$(mr\omega^2) \sin\theta$ is maximum at $\theta = 90°$ or $270°$.

∴ The piston experiences up and down jumps.

To strike a compromise between these two components that are produced by the balancing mass a fraction of reciprocating mass would be balanced.

∴ Primary force balanced = $cmr\omega^2 \cos\theta$

Unbalanced primary force (p) = $(1-c)\, mr\omega^2\cos\theta$

Unbalanced vertical force = $cmr\omega^2 \sin\theta$

Resultant unbalanced force, $R = \sqrt{\left[(1-c)mr\omega^2 \cos\theta\right]^2 + \left[cmr\omega^2 \sin\theta\right]^2}$

01(e). In a pair of mating spur gears, the pitch-diameter of smaller gear is 120 mm. The pair is of standard gear involute having module as 8. If the transmission ratio between the gears is 4:3, then find out

(i) Number of teeth on gear, (ii) Number of teeth on pinion,

(iii) Addendum, (iv) Dedendum,

(v) Whole depth, and (vi) Clearance. (2×6 = 12 M)

01(e).

Sol: PCD of Pinion = 120 mm

Gear ratio = 4:3

Module, m = 8

(i). $D_P = mZ_P$

$\therefore\ 120 = 8 \times Z_P$

$$Z_P = \frac{120}{8} = 15\,\text{Teeth}$$

(ii). $$G = \frac{N_P}{N_G} = \frac{4}{3} = \frac{Z_G}{Z_P}$$

$$\therefore\ Z_G = \frac{4}{3} \times Z_P = \frac{4}{3} \times 15 = 20\,\text{Teeth}$$

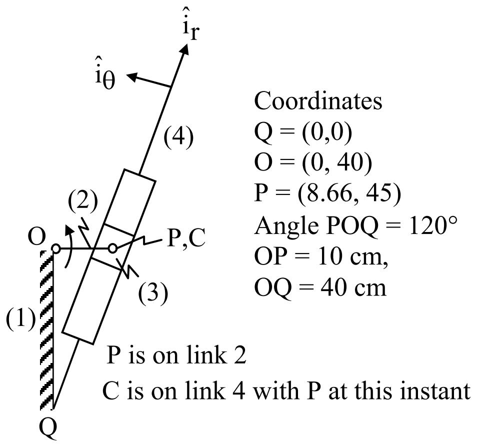
(iii). Addendum = 1 × m = 8 mm

(iv). Dedendum = 1.25 × m = 10 mm

(v). Whole depth = Addendum + Dedendum = 18 mm

(vi). Clearance = Dedendum – Addendum = 2 mm

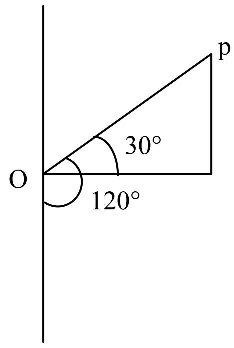
02(a). Compute the velocity and acceleration of the slider in the quick return mechanism shown in the figure below, if the crank rotates at 30 rpm.



(15 M)

02(a).

Sol:

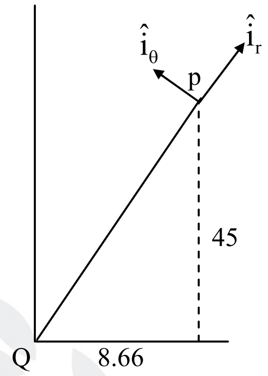


$$\vec{V}_{p_2} = \vec{V}_o + \vec{V}_{p_{2/o}}$$

$$= \vec{\omega}_2 \times \overrightarrow{OP_2}$$

$$= \pi\hat{k} \times 10(\hat{i}\cos 30° + \hat{j}\sin 30°)$$

$$= 10\pi(\hat{j}\cos 30° - \hat{i}\sin 30°)$$



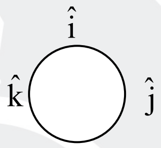
$$\overrightarrow{OP} = 10\left(\hat{i}\cos 30° + \hat{j}\sin 30°\right)$$

$$QP = 8.66\hat{i} + 45\hat{j}$$

$$\vec{a}_{p_2} = \vec{a}_o + a_{p_2/o}$$

$$= \vec{a}^{n}{}_{p_2/o} + \vec{a}^{t}{}_{p_2/o}$$

$$= \vec{\omega}_2 \times \left(\vec{\omega}_2 \times \overrightarrow{OP_2}\right)$$



$$= \pi\hat{k} \times [\pi\hat{k} \times 10(\hat{i}\cos 30° + \hat{j}\sin 30°)]$$

$$= \pi\hat{k} \times 10[\pi\cos 30°\hat{j} - \pi\sin 30°\hat{i}]$$

$$= [\pi^2\cos 30°](-\hat{i}) - \pi^2\sin 30°(\hat{j})] \times 10$$

$$\vec{a}_{p_3} = \vec{a}_{p_2} = [8.547\hat{i} - 4.934\hat{j}] \times 10$$

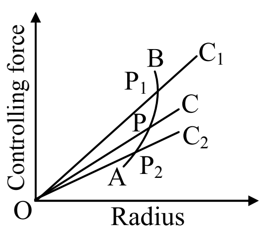
$$\left|\vec{a}_{p_3}\right| = 98.69\,\text{cm/s}^2 = 0.9869\ \text{m/s}^2$$

02(b)(i). Draw and show variation of centrifugal force and controlling force of a governor.

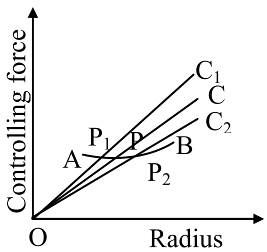
02(b)(i).

Sol: The variations of centrifugal force and controlling force of a governor are shown below.

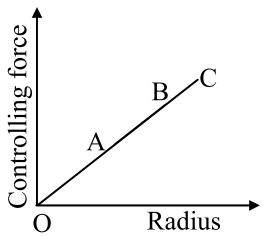
The curve AB shows the controlling force curve and C, C_1 and C_2 represent the centrifugal force curves.



Stable governor



Unstable governor



Isochronous governor

(ii). Define Stability, Sensitivity, Isochronism and Hunting in a governor. (15 M)

02(b)(ii).

Sol: Stability: A governor is said to be stable if it brings the speed of the engine to the required value and there is not much hunting. The ball masses occupy a definite position for each speed of the engine within the working range. Obviously, the stability and the sensitivity are two opposite characteristics.

Sensitiveness: A governor is said to be sensitive when it readily responds to a small change of speed. The movement of the sleeve for a fractional change of speed is the measure of sensitivity.

$$\text{Sensitiveness} = \frac{N_2 - N_1}{N} = \frac{2(N_2 - N_1)}{(N_2 + N_1)}$$

where $N_2 - N_1$ = Speed range from no load to full load.

when N = mean speed

N_1 = minimum speed corresponding to full load conditions

N_2 = maximum speed corresponding to no-load conditions

Isochronisms: A governor with zero range of speed zero is known as an isochronous governor. This mean that for all positions of the sleeve or the balls, the governor has the same equilibrium speed. However, it is not practical due to the friction at the sleeve.

Hunting: A governor is said to be hunting if the speed of the engine fluctuates continuously above and below the mean speed. This is caused by too sensitive governor which changes the fuel supply by a large amount when a small change in speed of rotation takes place.

A governor is said to be isochronous when the equilibrium speed is constant (i.e., range of speed is zero) for Degree of hunting is more in unstable governors.

02(c). The data for 2 sets of spur gears are given below.

	Set – 1	Set -2
Pressure angle	20°	20°
No. of teeth in large gear	40	50
No. of teeth in pinion	20	13
Module	10 mm	10 mm
Addendum	1 module	1 module

Check for the occurrence of Interference. If it occurs, what is the pressure angle to correct it ? (15 M)

02(c).

Sol:

	Set 1	**Set 2**
ϕ	20°	20°
Z_G	40	50
Z_P	20	13
m	10 mm	10 mm
Addendum, a	1 m	1 m

Set 1:

$$G = \frac{Z_G}{Z_P} = \frac{40}{20} = 2$$

$$Z_{G,\min} = \frac{2a}{\sqrt{1+\frac{1}{G}\left(\frac{1}{G}+2\right)\sin^2\phi}-1} = \frac{2\times1}{\sqrt{1+\frac{1}{2}\left(\frac{1}{2}+2\right)\sin^2\phi}-1} = 28.32 \cong 29 \text{ Teeth}$$

$$Z_{P,\min} = \frac{2a}{\sqrt{1+G(G+2)\sin^2\alpha}-1} = \frac{2\times1}{\sqrt{1+2(2+2)\sin^2\theta}-1} = 5.12 \cong 6 \text{ Teeth}$$

$Z_G = 40 > 29$

$Z_P = 20 > 5$

$\therefore$ No interference in set 1

Set 2 :

$$G = \frac{Z_G}{Z_P} = \frac{50}{13} = 3.846$$

$$Z_{G,\min} = \frac{2a}{\sqrt{1+\frac{1}{3.846}\left(\frac{1}{3.846}+2\right)\sin^2 2\theta}-1} = 59.17 \cong 60 \text{Teeth}$$

$$Z_{P,\min} = \frac{2a}{\sqrt{1+3.846(3.486+2)\sin^2 2\theta}-1} = 2.21 \cong 3 \text{Teeth}$$

But, Z_G = 50 Teeth < 60

$\therefore$ Interference occurs on Gear

$Z_P = 13 > 3$

$\therefore$ No interference on Pinion

To avoid interference, pressure angle must be increased

$$50 = \frac{2\times 1}{\sqrt{1+\frac{1}{3.486}\left(\frac{1}{3.846}+2\right)\sin^2\phi}-1}$$

$\therefore$ $1 + 0.26 \times 2.26 \sin^2\phi = 1.0816$

$\sin^2\phi = 0.13886$

$\therefore$ $\phi = 21.879°$

or use $\phi = 22\frac{1}{2}^{\circ}$ as standard involute.

02(d).

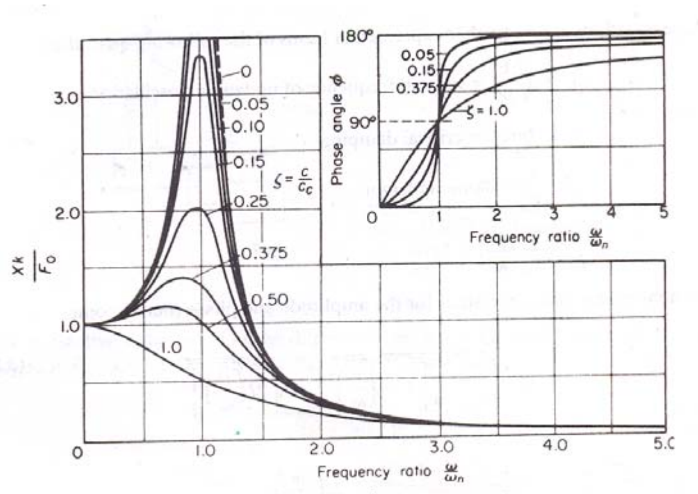
(i). A single degree of freedom system is subjected to an external harmonic force $F(t) = F_0 \sin\omega_0 t$. Define magnification factor (MF) and plot it as a function of damping factor as it varies with respect to frequency ratio. (8 M)

02(d)(i).

Sol: Magnification factor: It is the ratio of steady state amplitude to zero frequency deflection i.e. $\frac{X}{X_{st}}$ is defined as magnification factor.

Magnification factor, $$\frac{X}{X_{st}} = \frac{1}{\sqrt{\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2+\left(2\xi\frac{\omega}{\omega_n}\right)^2}}$$

where, X_{st} is static deflection $= \frac{F_0}{k}$



Note: $MF \to 1$ as $\frac{\omega}{\omega_n} \to 0$, $MF \to 0$ as $\frac{\omega}{\omega_n} \to \infty$

$MF < 1$ as $\frac{\omega}{\omega_n} = \sqrt{2}$ for any value $\xi > 0$

$\xi = 0$, $MF \to \infty$ @ $\frac{\omega}{\omega_n} = 1$

$\xi \simeq 0$, $MF = \frac{1}{2\xi}$ @ $\frac{\omega}{\omega_n} = 1$

(ii). A machine part having a mass of 2.5 kg vibrates in a viscous medium. A harmonic exciting force of 30 N acts on the part and causes a resonant amplitude of 14 mm with a period of 0.22 seconds. Find the damping coefficient. (7 M)

02(d)(ii).

Sol: $m = 2.5$ kg, $F_o = 3$ N

$A = 14$ mm at resonance i.e. $\omega = \omega_n$

$T = 0.22$ seconds

$$\therefore \quad \omega_n = \omega = \frac{2\pi}{T} = \frac{2\pi}{0.22} = 28.56 \text{ rad/s}$$

(i). But $\omega_n = \sqrt{\frac{K}{m}}$

$$\therefore \quad K = \omega_n^2 \times m = (28.56)^2 \times 2.5 = 2039.17 \text{ N/m}$$

(ii). $$A = \frac{F_o}{K \times \sqrt{(1-q^2)^2 + (2\xi q)^2}}$$

But $q = 1$, $\therefore$ $A = \frac{F_o}{K \times 2\xi}$

$$14 \times 10^{-3} \text{m} = \frac{30}{2039.17 \times 2 \times \xi}$$

$$\therefore \quad \xi = 0.5254$$

(iii). But, $\xi = \frac{C}{C_C}$

$$\therefore \quad C = \xi \times C_c = \xi \times 2\sqrt{Km}$$

$C = 75.02$ N-s/m

03(a).

(i). Define, discuss and differentiate :

(A) Centers of mass vs Centroid

(B) Mass moment of inertia vs Area moment of inertia

(C) Centroid of Lines, Areas and Volumes **(7 M)**

03(a).

Sol:

(A) Centre of mass v/s centroid

- Centre of mass is the centre of gravity and it is a point where entire mass of body is considered to be concentrated.
- Centroid is the geometric centre of the body.
- If the object has uniform density, then both will be at same point.
- In general, centre of mass is applied to 3–D bodies, i.e bodies with a mass, while centroid is applied to plane areas

(B) Mass M.I v/s Area M.I

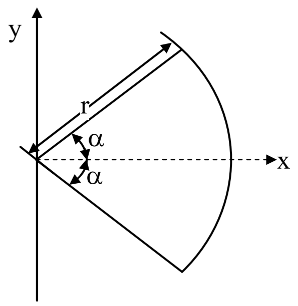
- Mass M.I represents distribution of mass, while area moment of inertia represent distribution of area.
- Mass M.I represents inertia of body to angular rotation while area moment of inertia represents property which is useful against bending loading, deflection.

(C) (i) Centroid of line, $x_G = \frac{\int \bar{x}\, dL}{\int dL}; y_G = \frac{\int \bar{y} dL}{\int dL}$

(ii) Centroid of area, $x_G = \frac{\int \bar{x}\, dA}{\int dA}; y_G = \frac{\int \bar{y} dA}{\int dA}$

(iii) Centroid of volume, $x_G = \frac{\int \bar{x}\, dV}{\int dV}; y_G = \frac{\int \bar{y} dV}{\int dV}; z_G = \frac{\int \bar{z} dV}{\int dV}$

(ii). Locate the centroid of a circular arc as shown in the figure below.



(8 M)

03(a)(ii).

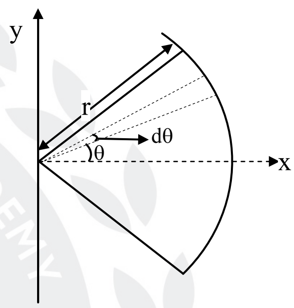
Sol: Since, the arc is symmetrical about x axis,

so y-coordinate of centroid i.e $y_c = 0$

Calculation of x co-ordinate :

Let us take an element at an angle θ subtending dθ at centre.

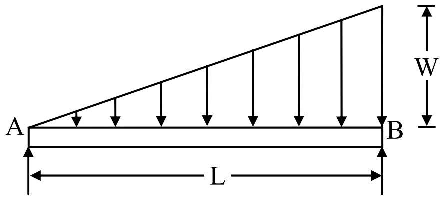
Length of this element = rdθ



$$\text{x co-ordinate, } x_c = \frac{\int x\,d\ell}{\int d\ell}$$

$$x_c = \frac{\int_{-\alpha}^{\alpha} (r\cos\theta)\times r\,d\theta}{\int_{-\alpha}^{\alpha} (r\,d\theta)} = \frac{r^2\int_{-\alpha}^{\alpha}\cos\theta\,d\theta}{r\int_{-\alpha}^{\alpha} d\theta} \Rightarrow x_c = \frac{r[\sin\theta]_{-\alpha}^{\alpha}}{2\alpha} = \frac{r\sin\alpha}{\alpha}$$

03(b). Draw the Shear force diagram and Bending moment diagram of a simply supported beam carrying a uniform varying load from zero at one end to 'w' per unit length at the other end. Compute the maximum B.M and its location.

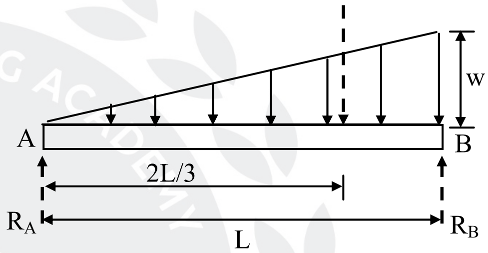


(15 M)

03(b).

Sol: *Reactions:*

Equilibrium of forces in vertical direction,



$$\Sigma Fy = 0 \Rightarrow R_A + R_B = \frac{1}{2} \times w \times L \text{ ………. (1)}$$

Taking moment about A,

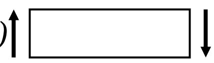
$$R_B \times L - \left(\frac{1}{2} \times w \times L\right) \times \left(\frac{2}{3} L\right) = 0$$

$$\therefore \quad R_B = \frac{wL}{3}$$

By using equation (1), $R_A = \dfrac{wL}{6}$

Shear force:

Sign convention for shear force at a section is as follows :

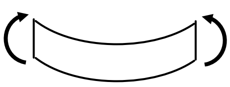


$$(S.F)_A = R_A = \frac{wL}{6}$$

$$(S.F)_B = -R_B = -\frac{wL}{3}$$

Bending moment:

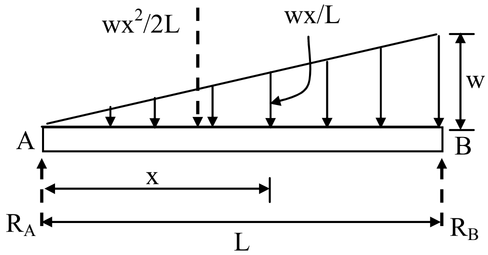
Sign convention for bending moment at a section is as follows :



Sagging (+ve)

$(BM)_A = (BM)_B = 0$

To find the maximum bending moment, consider the section at a distance x from A.



$$(SF)_{At\,x} = R_A - \frac{1}{2}\times\frac{wx}{L}\times x = \frac{wL}{6} - \frac{wx^2}{2L}$$

Bending moment is maximum at the section where shear force is zero

$$\therefore \quad 0 = \frac{wL}{6} - \frac{wx^2}{2L}$$

$$\Rightarrow \quad x = \frac{L}{\sqrt{3}}$$

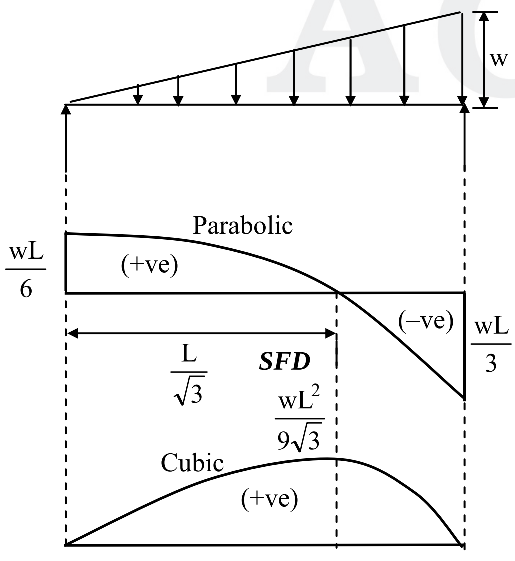
At $x = \frac{L}{\sqrt{3}}$, bending moment is maximum.

$$M_{max} = M_{x=\frac{L}{\sqrt{3}}} = R_A \times x - \frac{wx^2}{2L}\times\frac{x}{3}$$

$$= \frac{wL}{6}\times\frac{L}{\sqrt{3}} - \frac{wL^2}{6L}\times\frac{L}{3\sqrt{3}} = \frac{wL^2}{6\sqrt{3}}\left(1-\frac{1}{3}\right)$$

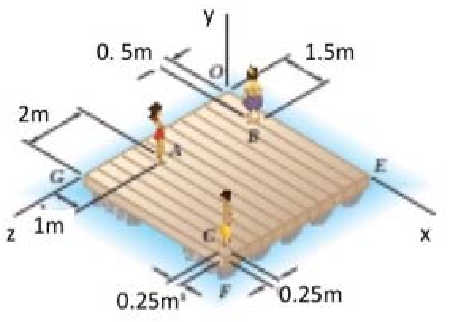
$$\Rightarrow \quad M_{max} = \frac{wL^2}{9\sqrt{3}}$$

The shear force and bending moment diagrams from the above computed values are drawn below.



03(c).

(i). Three children are standing on a 5 m × 5 m raft as shown in the figure below.



The weights of the children at points A, B and C are 375 N, 260 N and 400 N, respectively. Determine the magnitude and the point of the resultant of their weights. (10 M)

03(c)(i).

Sol: The resultant of the weights = 375 + 260 + 400 = 1035 N

The position of child A, $\vec{r}_A = 3\hat{k} + 1\hat{i}$

The position of child B, $\vec{r}_B = 0.5\hat{k} + 1.5\hat{i}$

The position of child C, $\vec{r}_C = 4.75\hat{k} + 4.75\hat{i}$

In vector form, weight of the children can be written as

$\vec{W}_A = -375\hat{j}$, $\vec{W}_B = -260\hat{j}$, $\vec{W}_C = -400\hat{j}$

Moment of the weights about 'O' can be written as :

$$\sum M_o = \vec{r}_A \times \vec{W}_A + \vec{r}_B \times \vec{W}_B + \vec{r}_C \times \vec{W}_C$$

$$= (3\hat{k} + \hat{i}) \times -375\hat{j} + (0.5\hat{k} + 1.5\hat{i}) \times -260\hat{j} + (4.75\hat{k} + 4.75\hat{i}) \times -400\hat{j}$$

$$= 3155\hat{i} - 2665\hat{k} \text{ ....(i)}$$

Let the resultant be at a coordinate (z, x) in z-x plane

Moment of resultant, $\sum M_R = (z\hat{k} + x\hat{i}) \times 1035(-\hat{j})$

$$\sum M_R = 1035z\hat{i} - 1035x\hat{k} \text{ ....(ii)}$$

Equating (i) and (ii)

$1035z = 3155$

$\Rightarrow z = 3.048$ m

$1035x = 2665$

$\Rightarrow x = 2.575$ m

(ii). In a two dimensional system acted by various forces as specified below.

- **forces are collinear**
- **forces are concurrent at a point**
- **forces are parallel to each other**
- **general**

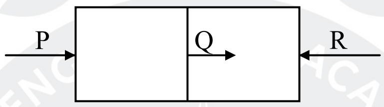
Draw the free body diagram and equation defining them. (5 M)

03(c)(ii).

Sol:

(i) Forces are collinear:

Resultant force = P + Q – R

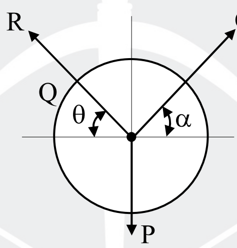


(ii) Concurrent Forces:

$\Sigma F_x = Q.\cos\alpha - R.\cos\theta$

$\Sigma F_y = Q.\sin\alpha + R.\sin\theta - P$

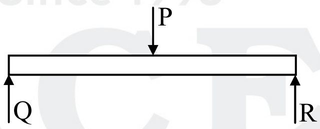
$$\text{Resultant} = \sqrt{\sum F_x^2 + \sum F_y^2}$$



(iii) Forces parallel to each other:

$\Sigma F_y = Q + R - P$

Resultant = ΣF_y

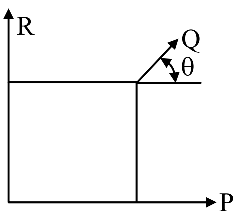


(iv) General forces:

$\Sigma F_x = P + Q.\cos\theta$

$\Sigma F_y = R + Q\sin\theta$

$$\text{Resultant} = \sqrt{\sum F_x^2 + \sum F_y^2}$$



In each case, for equilibrium, resultant force must be zero.

03(d). Two shafts of the material and of same lengths are subjected to same torque. If the first is of a solid circular section and the second shaft is of hollow circular section, whose internal diameter is 2/3 of the outside diameter and the maximum shear stress developed in each shaft is the same, compare weights of the shafts. (15 M)

03(d).

Sol: Torsion formula, $\frac{T}{J} = \frac{\tau}{R}$ ....(1)

$\therefore \frac{T}{\tau} = \frac{J}{R}$

As both shafts (solid and hollow) are subjected to same torque and same maximum shear stress, hence ratio J/R must also be same for them.

(i) For solid shaft, $\frac{J}{R} = \frac{\pi}{32}.d^4\left(\frac{2}{d}\right) = \frac{\pi d^3}{16}$........(2)

(ii) For hollow shaft,

$$\frac{J}{R} = \frac{\pi}{32}.\left(D_o^4 - D_i^4\right)\left(\frac{2}{D_o}\right) = \frac{\pi}{16.D_o}\left\{D_o^4 - \left\{\frac{2}{3}D_o\right\}^4\right\} = \frac{\pi D_o^3}{16}\times\frac{65}{81}\text{.............(3)}$$

From (1) , (2) and (3),

$$\frac{\pi d^3}{16} = \frac{\pi D_o^3}{16}\times\frac{65}{81}$$

$$\therefore \frac{D_o}{d} = \left(\frac{81}{65}.\right)^{1/3} \text{...........(4)}$$

(iii) Weight of solid shaft, $W_s = \frac{\pi}{4}.d^2.L\times\rho_s\times g$

Weight of hollow shaft, $W_H = \frac{\pi}{4}\left(D_o^2 - D_i^2\right)L\times\rho_H\times g = \frac{\pi}{4}\left(D_o^2 - \left(\frac{2}{3}D_o^2\right)\right).L\times\rho_H\times g$

$$W_H = \frac{5}{9}.\frac{\pi}{4}.D_o^2 L\,\rho_H\,g$$

here, $\rho_H = \rho_s$

Thus, $\frac{W_H}{W_S} = \frac{5}{9}\left\{\frac{D_o}{d}\right\}^2 = \frac{5}{9}\left\{\frac{81}{65}\right\}^{2/3} = 0.6433$

Hence, for given conditions, hollow shaft will be 35.67% lighter than the solid shaft.

04(a). Differentiate between uniform pressure and uniform wear theory. What would you conclude, about the effect over friction radius, under following two conditions of operation of a clutch, considering uniform pressure theory and uniform wear theory in both the conditions.

(i) Outer radius = 100 mm, Inner radius = 90 mm

(ii) Outer radius = 100 mm, Inner radius = 25 mm **(20 M)**

04(a).

Sol:

Uniform Pressure Theory	Uniform Wear Theory
1. This theory is applicable only when the friction lining is new.	1. This theory is applicable when the friction lining gets worn out.
2. The friction radius for new clutches is more.	2. The friction or effective radius is less.
3. Torque transmission capacity is more.	3. Torque transmission capacity is less.
4. Wear is directly proportional to radius.	4. Wear is directly proportional to product of pressure and radius.

(i) Outer radius, $r_1 = 100$ mm,

Inner radius, $r_2 = 90$ mm

Uniform pressure theory:

Friction radius, $$r_{fp} = \frac{2}{3}\left(\frac{r_1^3 - r_2^3}{r_1^2 - r_2^2}\right)$$

$$= \frac{2}{3}\left(\frac{100^3 - 90^3}{100^2 - 90^2}\right) = 95.1\,\text{mm}$$

Uniform wear theory:

Friction radius, $$r_{fw} = \frac{r_1 + r_2}{2} = \frac{100+90}{2} = 95\,\text{mm}$$

Since, $r_{fp} \approx r_{fw}$, torque transmission is approximately same in uniform pressure and uniform wear theories.

(ii) Outer radius, $r_1 = 100$ mm

Inner radius, $r_2 = 25$ mm

Uniform pressure theory:

$$r_{fp} = \frac{2}{3}\left(\frac{r_1^3 - r_2^3}{r_1^2 - r_2^2}\right) = \frac{2}{3}\left(\frac{100^3 - 25^3}{100^2 - 25^2}\right) = 70\,\text{mm}$$

Uniform wear theory:

$$r_{fw} = \frac{r_1 + r_2}{2} = \frac{100 + 25}{2} = 62.5\,\text{mm}$$

Since, $r_{fp} > r_{fw}$

Torque transmitted under uniform pressure is much more than that of uniform wear theory.

04(b). Design a flywheel for a single cylinder four-stroke diesel engine, made of cast iron, whose allowable strength is 20 MN/m^2. The engine is running at a speed of 1400 rpm and producing 5 kW of power. Maximum peripheral speed of the flywheel may be up to 24 m/sec. Coefficient of fluctuation of energy may be taken as 2.2 and coefficient of speed fluctuation as 0.015. Density of cast iron may be taken as 7000 kg/m^3. (The effect of overhang of the flywheel on the end may be neglected). (20 M)

04(b).

Sol: Given data:

$\sigma_t = 20$ MN/m^2 , N = 1400 rpm, v = 24 m/s ,

$C_E = 2.2$, $C_S = 0.015$, $\rho = 7200$ kg/m^3

$$\text{Work done/cycle} = E = \frac{P\times 60}{\left(\frac{N}{2}\right)} = \frac{5\times 10^3\times 60}{\left(\frac{1400}{2}\right)} = 428.57\,\text{J}$$

Fluctuation of energy,

$\Delta E = C_E \times E = 2.2 \times 428.57 = 942.86$ J

But $\Delta E = I\omega^2 C_S$

$$\therefore\ 942.86 = \left(\frac{2\pi\times 1400}{60}\right)^2 \times 0.015$$

$\therefore$ $I = 2.924$ kg-m^2

$$\text{Also, } v = \frac{\pi DN}{60} \Rightarrow 24 = \frac{\pi\times D\times 1400}{60}$$

$\Rightarrow D = 0.327$ m

$$\Rightarrow k = \frac{D}{2} = 0.163\,\text{m}$$

Assuming rimmed flywheel, total moment of inertia is contributed by rim only.

$I = m k^2$

$\therefore$ $2.924 = m \times 0.163^2$

$\Rightarrow$ $m = 110.07$ kg

But, $m = \pi D \times A \times \rho$ (here, $A = b \times t$)

$\therefore$ $110.07 = \pi \times 0.327 \times A \times 7200$

$\Rightarrow$ $A = 0.015$ m^2

Assuming, b = 2t,

$\therefore$ 2t × t = 0.015

$\Rightarrow$ t = 86 mm

$\Rightarrow$ b = 172 mm

Cross-section of rim, width b = 172 mm, thickness, t = 86 mm.

Checking for stress,

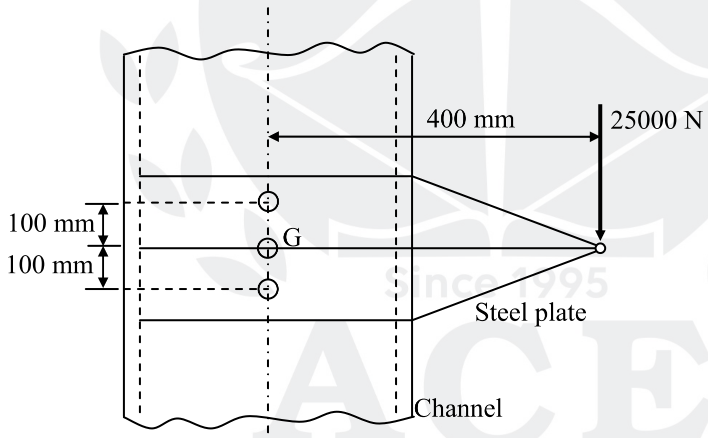
$\sigma_t = \rho v^2$

$= 7200 \times (24)^2 = 4147200$

$= 4.1472 \times 10^6$ N/m^2 $< 20 \times 10^6$ N/m^2

Therefore, design is safe.

04(c). Three M20 bolts are used to connect a steel plate with a channel section structural member as shown in figure. The material of the bolt is 50C4 with σ_u = 660 MPa and σ_y = 460 MPa. Determine the factor of safety, if the plate carries a load of 25000 N at its end. Take area of M20 bolts as 245 mm^2.



(20 M)

04(c).

Sol: Given data:

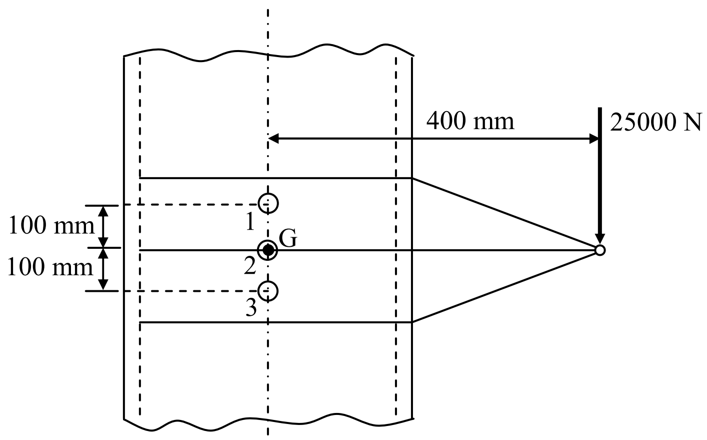
M20 bolts, A = 245 mm^2

σ_u = 660 MPa

σ_y = 460 MPa

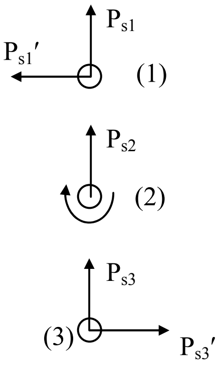
FOS = ?

P = 25000 N



Bolts 1 and 2 are under maximum load.

Design for bolt (1):



$$P_{S_1} = P_{S_2} = P_{S_3} = \frac{25000}{3} = 8333.3\text{N}$$

$$P_{S_1}' = kr_1$$

$$= \frac{P \times e}{r_1^2 + r_2^2 + r_3^2} \times r_1$$

Here, $r_1 = 100$ mm, $r_2 = 0$, $r_3 = 100$ mm

$$\therefore P_{S_1}' = \frac{25000 \times 400}{2 \times 100^2} \times 100 = 5000\text{ N}$$

Resultant shear load on bolt (1):

$$P_s = \sqrt{P_{s_1}^{\ 2} + P_{s_1}'^{\ 2}} = \sqrt{8333.3^2 + 50000^2} = 50689.68\text{ N}$$

$$\tau_{max} = \frac{P_s}{A} = \frac{50689.68}{245} = 206.89\ \frac{\text{N}}{\text{mm}^2}$$

Applying maximum shear stress theory,

$$\tau_{max} = \frac{\sigma_y}{2 \times \text{FOS}}$$

$$\therefore\ 206.89 = \frac{460}{2 \times \text{FOS}} \quad \Rightarrow \text{FOS} = 1.114$$

SECTION - B

05(a). Define unit cell of a space lattice. Derive the effective number of lattice points in the unit cell of cubic lattices. Calculate the packing efficiency and density of silicon which has diamond cubit structure. Use the following properties for silicon :

Atomic No. = 14

Atomic Mass Unit = 1.66×10^{-27} kg

Lattice Parameter = 5.431×10^{-10} m

Assume radius of Si atom in diamond cubic structure to be $\left(\frac{\sqrt{3}}{8}\right)$ times the lattice parameter. **(12 M)**

05(a).

Sol: Unit cell: Smallest number of atoms are arranged in a repetitive manner.

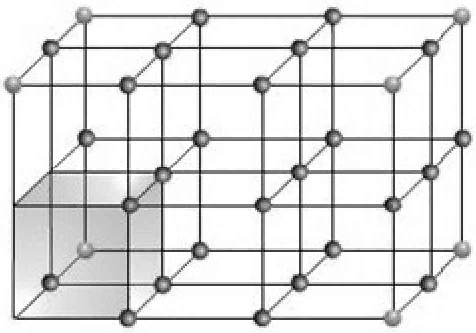


Fig: Space lattice

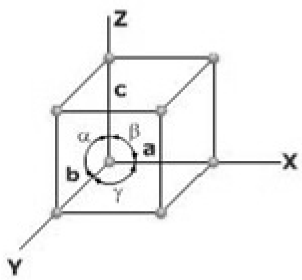


Fig: Unit cell

a, b, c = lattice parameter(s), α, β,γ = interfacial angle(s)

Effective number of atoms / lattice point in cubic unit cell :

1. **Simple cubic structure:**

   $8 \text{ atoms at the corners} \times \frac{1}{8} = 1 \text{atom}$

   Therefore, the unit cell of simple cubic structure contains one atom.

2. **Body centered cubic structure (B.C.C):**

   $8 \text{ atoms at the corners} \times \frac{1}{8} = 1 \text{ atom}$

   1 centre atom = 1 atom

   $\therefore$ **Total = 2 atoms**

   Therefore, the unit cell of B.C.C. structure contains two atoms.

3. Face centered cubic structure (F.C.C.) :

8 atoms at the corners × $\frac{1}{8}$ = 1 atom

6 face centered atoms × $\frac{1}{2}$ = 3 atoms

∴ Total = 4 atoms

Therefore, the unit cell of F.C.C. structure contains four atoms.

Atomic packing factor of Si material :

Si is a diamond cubic structure material. In diamond cubic structure 8 atoms are arranged at corners and 6 atoms are arranged at face centers and 4 atoms are arranged inside unit cell on 4 body diagonals with each atom located at $\frac{a}{4},\frac{a}{4},\frac{a}{4}$ from corner.

Effective number of atoms

$$n = \frac{1}{8}\times 8 + \frac{1}{2}\times 6 + 4 = 8 \text{ atoms}$$

Relationship between atomic radius (R) and lattice parametrical

$$8R = \sqrt{3}a \quad \Rightarrow R = \frac{\sqrt{3}a}{8} = \frac{\sqrt{3}\times 5.43\times 10^{-10}}{8} = 1.1756\times 10^{-10}\text{ m}$$

$$V_{uc} = a^3 = \left(\frac{8R}{\sqrt{3}}\right)^3$$

$$= (5.431\times 10^{-10})^3$$

$$\text{Atomic packing factor} = \frac{n\times\frac{4}{3}\pi R^3}{a^3} = \frac{8\times\frac{4}{3}\pi\left(1.175\times 10^{-10}\right)}{\left(5.431\times 10^{-10}\right)^3} = 0.34$$

$$\text{Theoretical density} = \frac{n\times AW}{AN\times V_{uc}}$$

Atomic weight = 2 × 14 = 28 g/mol

$$= \frac{8\times 28\times 10^{-3}}{6.023\times 10^{23}\times\left(5.431\times 10^{-10}\right)^3} = 2322\text{ kg/m}^3$$

05(b). Define a 'sensor'. Describe the following performance terms related to a sensor :

(i) Accuracy

(ii) Sensitivity

(iii) Hysteresis error

(iv) Non-linearity error

(v) Resolution **(12 M)**

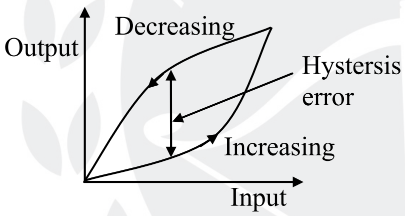
05(b).

Sol: *Sensor:* Sensor is a device used to measure different parameters in any mechatronic system, which is to control. By physical contact it converts non electrical parameters to electrical signal.

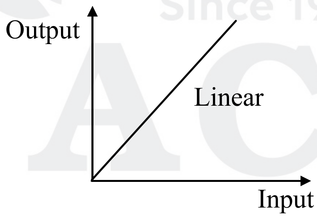
(i) *Accuracy:* Closeness of measured value to the true value of system.

(ii) *Sensitivity:* Ratio of output to input of any system (or) sensor.

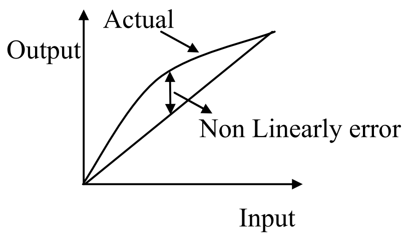
(iii) *Hysteresis error:* It is the difference between sensor outputs, when sensor is subjected to loading (increasing input) and unloading (decreasing input).



(iv) *Non-Linearity error:* If the sensor has linear relationship between input and output it can be shown as straight line as below.



But in reality the maximum difference from straight line to actual values is known as Non-linearity error.



(v) *Resolution:* The smallest input difference, any sensor can measure is known as resolution.

05(c). What is the significance of Ernst and Merchant theory in study of mechanics of chip formation in machining operation ?

Using its principle, find out the cutting force, thrust force and shear force applied in a machining operation of a cast iron component, whose ultimate strength is 370 MPa and coefficient of friction between tool and chip is 0.55. The depth of cut is 3.5 mm and feed of cut is 0.3 mm. The normal rake angle and principal cutting edge angle are 12° and 30°, respectively. (12 M)

05(c).

Sol: Merchant has derived minimum work done criteria shear angle theoretically. According to Merchants theory for minimum work done during machining the shear angle relation can be taken as

$$2\phi + \beta - \alpha = 90^\circ$$

where, ϕ = shear angle,

β = friction angle

α = rake angle of tool

Hence, $\phi = \dfrac{90 + \alpha - \beta}{2}$

For a given tool, the rake angle α is constant. Therefore, as shear angle increases friction angle reduces. Hence, frictional energy losses are reduced. Also when the work done is minimum the shear stress induced is equal to ultimate shear stress of work material and efficiency of energy utilization becomes 100 %.

Data given :

$\tau_u = 370$ MPa, $\mu = 0.55$, $d = 3.5$ mm,

$f = 0.3$ mm, $\alpha = 12°$, $\lambda = 30°$

Because nothing is mentioned in the problem, it is assumed (a) oblique machining.

Hence from the given data,

$$\beta = \tan^{-1}\mu$$

$$= \tan^{-1}(0.55) = 28.81°$$

According to Merchant theory,

$$2\phi + \beta - \alpha = 90$$

$$\phi = \frac{90 + 12 - 28.81}{2} = 36.6^\circ$$

Also $\tau = \tau_u = 370 = \frac{F_s}{A_o} \times \sin\phi$

$$F_s = \frac{370 \times A_o}{\sin\phi}$$

$$= \frac{370 \times d \times f}{\sin\phi} = \frac{370 \times 3.5 \times 0.3}{\sin 36.6} = 651 \text{ N}$$

$$F_c = \text{Cutting force} = \frac{F_s}{\cos(\phi + \beta - \alpha)} \times \cos(\beta - \alpha)$$

$$= \frac{651 \times \cos 16.81}{\cos 53.41} = 1045.3 \text{ N}$$

$$F_T = \text{Thrust force} = \frac{F_s}{\cos(\phi + \beta - \alpha)} \times \sin(\beta - \alpha)$$

$$= \frac{651}{\cos(53.41)} \times \sin(16.81) = 308.6 \text{ N}$$

Shear force = 651 N = F_s

Cutting force = 1045.3 N = F_c

Thrust force = 308.6 N = F_T

05(d). What are the important ingredients (elements) of an FMS ? In what kind of manufacturing scenario, is it best to be employed ? For the same case, or in general, enlist its four major advantages. (12 M)

05(d).

Sol: The important elements of an FMS are as given below:

A. Workstations

- CNC machine tools
- Assembly equipment
- Measuring Equipment
- Washing stations

B. Material handling Equipment

- Load unload stations (Palletizing)
- Robotics
- Automated Guided Vehicles (AGVs)
- Automated Storage and retrieval Systems (AS/RS)

C. Tool systems

- Tool setting stations
- Tool transport systems

D. Control system

- Monitoring equipments
- Networks

Nowadays customers are demanding a wide variety of products. To satisfy this demand, the manufacturers' "production" concept has moved away from "mass" to small "batch" type of production. Batch production offers more flexibility in product manufacturing. To cater this need, Flexible Manufacturing Systems (FMS) have been evolved.

FMS combines microelectronics and mechanical engineering to bring the economies of the scale to batch work. A central online computer controls the machine tools, other work stations, and the transfer of components and tooling. The computer also provides monitoring and information control. This combination of flexibility and overall control makes possible the production of a wide range of products in small numbers.

Advantages of an FMS:

- Flexibility to change part variety
- Higher productivity
- Higher machine utilization
- Less rejections
- High product quality
- Reduced work-in-process and inventory
- Better control over production
- Just-in-time manufacturing
- Minimally manned operation
- Easier to expand

05(e). A project has seven activities, each with totally deterministic completion time and involved cost. These activities with other related data are as given in the table below.

Activity	Immediate Predecessor	Normal Time (days)	Normal Cost (Rs. in lakhs)	Crash Time (days)	Crash Cost (Rs. in lakhs)
A	–	9	70	6	100
B	A	6	60	4	80
C	A	7	80	4	89
D	A	5	30	4	32
E	B, C	4	70	3	85
F	C, D	6	35	5	43
G	E, F	7	40	4	85

Each day of early completion of the project yields saving in administrative cost of Rs. 2 lakhs and an additional profit of Rs. 5 lakhs.

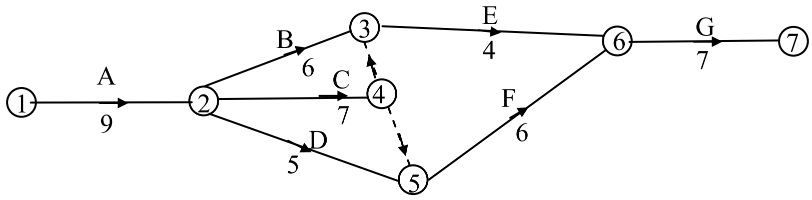
Find out the most economical completion time for the project assuming that crashing cost increases linearly with the decrease in activity duration. (12 M)

05(e).

Sol:

Activity	Immediate Predecessor	Normal Time(N_T) (days)	Normal Cost (N_C) (₹. in lakhs)	Crash Time(C_T) (days)	Crash Cost(C_C) (₹. in lakhs)	Cost slope $= \frac{C_C - N_C}{N_T - C_T}$	Possible No.of Days Crashing
A	–	9	70	6	100	10	3
B	A	6	60	4	80	10	2
C	A	7	80	4	89	3	3
D	A	5	30	4	32	2	1
E	B, C	4	70	3	85	15	1
F	C, D	6	35	5	43	8	1
G	E, F	7	40	4	85	15	3

$\sum$ Normal cost = 385 Lakhs



Paths in Network	I	II
ABEG → 9+6+4+7 = 26	26	26
ACEG → 9+7+4+7 = 27	25	24
ACFG → 9+7+6+7 = 29	27	26
ADFG → 9+5+6+7 = 27	27	26

Longest path is ACFG, least cost slope activity is C which has a cost slope of 3 Lakhs and it can be crashed by 2 days.

Saving in administrative cost per day = 2 Lakhs

Increase in profit = 5 Lakhs

Net savings per day = 7 Lakhs

Now cost for 27 days schedule

$$= \sum \text{Normal cost} + \text{No.of days crashed} \times \frac{\text{crash cost}}{\text{day}} - \text{No.of days crashed} \times \frac{\text{savings}}{\text{day}}$$

$= 385 + 2 \times 3 - 2 \times 7 = 377$ Lakhs.

Now two paths ACFG and ADFG are critical activities.

Crashing A → cost is 10 L/day

Crashing F → cost is 8 L/day

Crashing G → cost is 15 L/day

Crashing C & D → cost is 5 L/day

So crash C&D by 1 day

New cost for 26 day schedule = Previous cost + Crash cost – savings

$= 377 + 1 \times 5 - 1 \times 7 = 375$ Lakhs

Now three paths ABEG; ACFG; ADFG are critical activities

Crashing A → Cost is 10 L/day

Crashing E & F → Cost is 23 L/day

Crashing G → Cost is 15 L/day

On further crashing, cost of project increases rather than decreasing. Further crashing is not advisable. Economical completion schedule is 26 days & 375 Lakhs.

06(a). Define 'phase' of a system. Mention Gibbs' phase rule and describe the terms in it. Lead and tin have complete liquid solubility and limited solid solubility. Describe the binary phase diagram involving lead and tin. Explain how this phase diagram helps in identifying composition for electrical solder and plumbing solder. (15 M)

06(a).

Sol: Phase: Any homogenous, physically distinct and mechanically separable portion of a system is known as a phase. For example if two liquids are immiscible (i.e., benzene and water) they will form two separate phases. And if two liquids are miscible (i.e., alcohol and water), they will form one liquid phase only. Two solid solutions of different compositions may exist together and forms two phases.

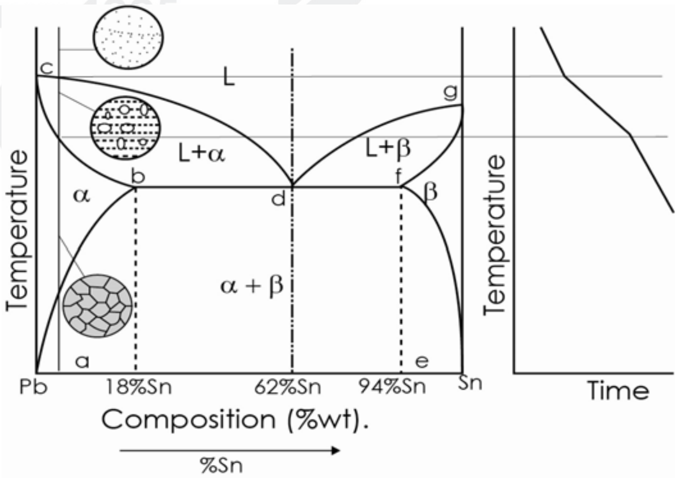
Gibbs Phase Rule: The number of degrees of freedom (F) of the system is related to the number of components (C) and of phases (P) by the phase rule equation:

$F = C - P + 2$

where, P is the number of phases, F is the number of degrees of freedom and C is the number of components.

In practical conditions for metallurgical and materials systems, pressure can be treated as a constant (1atm). Thus condensed Gibbs phase rule is written as $P + F = C + 1$

Eutectic binary system: Many of the binary systems with limited solubility are of eutectic type – eutectic alloy of eutectic composition solidifies at the end of solidification at eutectic temperature. E.g.:Cu-Ag,Pb-Sn.



Soft solders are an alloy of tin and lead.

Tin content	Lead content	Uses
65 %	35 %	Electrical solder
50 %	50 %	Tinman's solder for general work
30 %	70 %	Plumber's solder for pluming joints

06(b). Describe different heat treatment processes of steels with the help of Iron-Carbon equilibrium diagram. On a T–T–T diagram of plain carbon steel, show the following processes and the resulting phases :

- **Water quench to room temperature**
- **Hot quench to 300°C, hold for 5 h and water quench**
- **Hot quench to 450°C, hold for 1 h and water quench**

On the same T–T–T diagram, show the Austempering and Martempering processes.

(15 M)

06(b).

Sol: In all the heat treatment processes, steel is slowly heated to a predetermined temperature and then cooled at different cooling rates. The structure of the resultant steel will solely depend upon the heating temperature and the rate of cooling. Figure 1 shows the iron-carbon diagram for steel and the various temperature ranges for different heat treatment processes.

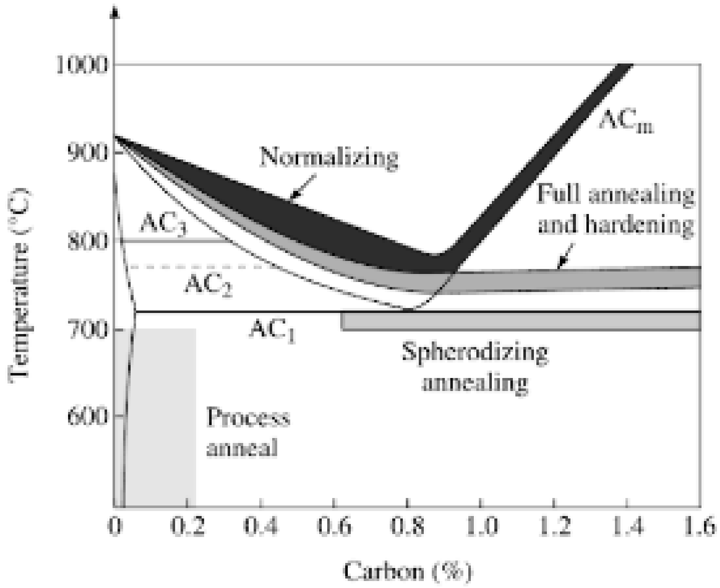


Fig1: Heat treatment processes on Iron carbon equilibrium diagram

The cooling paths are indicated in figure (2) and the microstructures obtained are listed as follows:

- **Water-quench to room temperature**

  a. Martensite

- **Hot-quench to 300°C and hold 5 h, water quench**

  b. Lower bainite (coarse bainite)

- **Hot-quench to 450°C and hold 1 h, water quench**

  c. Upper bainite (fine bainite)

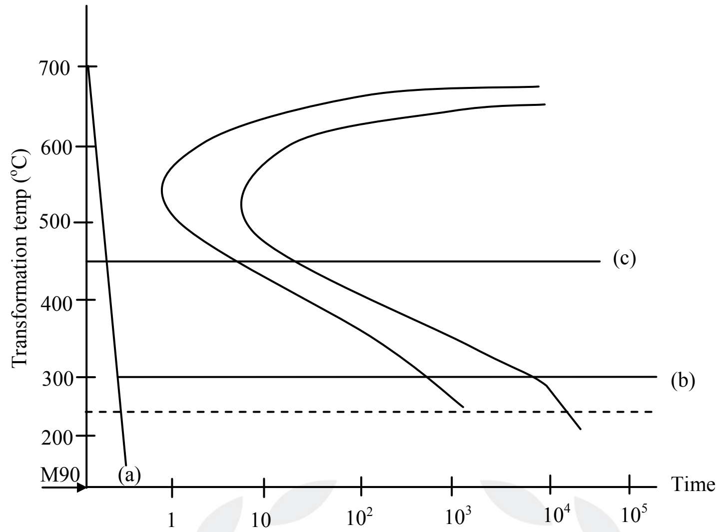
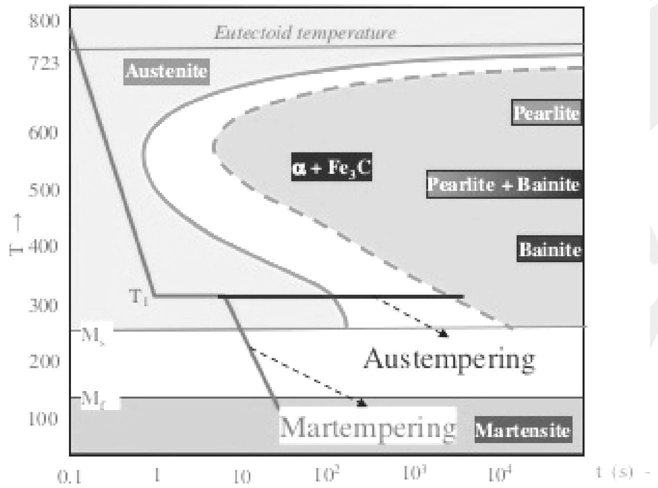


Fig 2: Isothermal transformation diagram for a eutectoid plain-carbon steel indicating various cooling paths.

Martempering is a modified quenching procedure used to minimize distortion and cracking that may develop during uneven cooling of the heat-treated material. It involves cooling the austenized steel to temperature just above Ms temperature, holding it there until temperature is uniform followed by cooling at a moderate rate to room temperature before austenite-to-bainite transformation begins. The final structure of martempered steel is tempered Martensite.



Austempering is different from martempering in the sense that it involves austenite-to bainite transformation. Thus, the structure of austempered steel is bainite. Advantages of austempering are improved ductility, decreased distortion and disadvantages are need for special molten bath; process can be applied to limited number of steels.

The smaller the grain size, the more frequent is the pile up of dislocations. With decrease in grain size, the mean distance of a dislocation can travel decreases and soon starts pile up of dislocations at grain boundaries. This leads to increase in yield strength of the material.

06(c). A manufacturer of textile dyes can use two different processing routes for producing a particular type of dye. Route 1 uses drying press A, and route 2 uses drying press B. Both routes require the same mixing vat to blend chemicals for the dye before drying. The following table shows the time requirements and capacities of these processes :

Process	**Time Requirements (hour/kg)**		
Mixing	**2**	**2**	**54**
Dryer A	**6**	**0**	**120**
Dryer B	**0**	**8**	**180**

Each kilogram of dye processed using route 1 uses 20 litres of chemicals, whereas each kilogram of dye processed on route 2 uses only 15 litres. The difference results from differing yield rates of the drying presses. Consequently, the profit per kilogram processed on route 1 is Rs. 500 and on route 2 is Rs. 650. A total of 450 litres of input chemicals is available. Write the constraints and objective function to maximize profits.

Use the graphic method to find the optimal solution, and also non-utilised part of the processes. (15 M)

06(c).

Sol:

Process	**Route 1**	**Route 2**	**Capacity**
Mixing	2	2	54
Dryer A	6	0	120
Dryer B	0	8	180
Chemical	20	15	450
Profit/kg	500 x	650 y	
Z_{max} =	500 x	650 y	

$Z_{max} = 500\,x + 650\,y$

Subject to

$2x + 2y \le 54$ Mixing

$6x \le 120$ Dryer A

$8y \le 180$ Dryer B

$20x + 15y \le 450$ Chemical

$x, y \ge 0$

Converting to intercept form

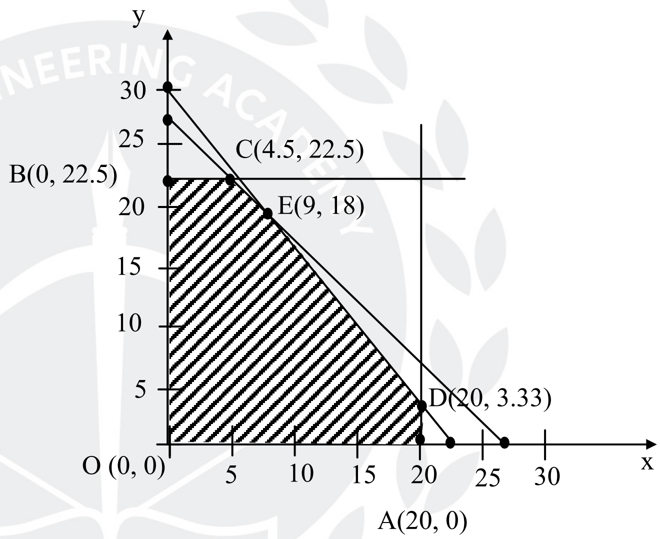
$\frac{x}{27} + \frac{y}{27} \le 1$ ………. (1)

$\frac{x}{20} \le 1$ ……….. (2)

$\frac{y}{22.5} \le 1$ ……… (3)

$\frac{x}{22.5} + \frac{y}{30} \le 1$ ……….. (4)

$x, y \ge 0$



By solving equation (1) and (4)

$x = 9, \quad y = 18$

By solving equation (1) and (3)

$x = 4.5, \ y = 22.5$

By solving equation (2) and (4)

$x = 20, y = 3.33$

$Z_{max} = 500x + 650y$

$Z_0 = 0$

$Z_A = 500 \times 20 + 650 \times 0 = 10{,}000$

$Z_B = 500 \times 0 + 650 \times 22.5 = 14{,}625$

$Z_C = 500 \times 4.5 + 650 \times 22.5 = 16{,}875$

$Z_D = 500 \times 20 + 650 \times 3.33 = 12{,}164.5$

$Z_E = 500 \times 9 + 650 \times 18 = 16{,}200$

Optimum is at (C)

$x = 4.5$

$y = 22.5$

$Z_{max} = 16{,}875$

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06(d). A plant is capable of producing 10,000 units of an item in a year. Demand of this item is not increasing and is going to remain constant in future as well. Annual demand of this item is going to stay at 5,000 units. Set-up cost of Rs. 10,000 has to be incurred every time a new batch of this item is launched for production. Each unit of the item, after its manufacture, costs Rs 320. Inventory carrying cost of the finished item is 10% of its cost when held in stock for one year.

Determine the economic production lot size and the number of batches to be taken each year for production assuming all these batches are to be of equal size. Also determine inventory cycle and production cycle (the time during which the plant shall be busy in an inventory cycle for producing the item) length. (15 M)

06(d).

Sol: Annual Demand = A = 5000 Units

Production rate = p = 10000 units/year

Consumption rate = r = 5000 units/year

Set-up cost = S = ₹ 10,000/-

Cost per unit = C = ₹ 320//

Inventory carrying cost = I = 10%

$$EPQ = \sqrt{\frac{2AS}{CI}\left(\frac{p}{p-r}\right)}$$

$$= \sqrt{\frac{2\times5000\times10000}{320(0.1)}\times\left(\frac{10,000}{10,000-5,000}\right)} = 2500 \text{ units}$$

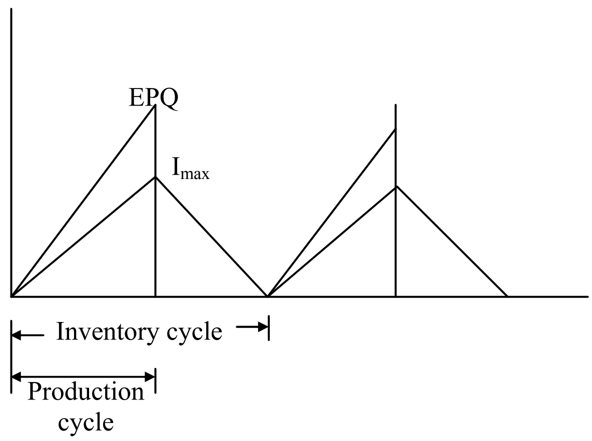
$$\text{No.of batches} = \frac{A}{EPQ} = \frac{5000}{2500} = 2$$

$$\text{Inventory cycle} = \frac{EPQ}{A}\times \text{Time period}$$

$$= \frac{2500}{5000}\times 1 = 0.5 \text{ years}$$

Production cycle = $t_p \times p = EPQ$

$$t_p = \text{Production time} = \frac{EPQ}{p} = \frac{2500}{10000} = \frac{1}{4}\text{years}$$



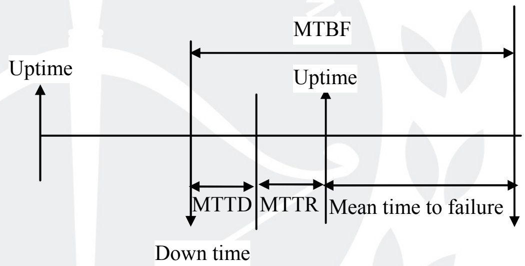
07(a). Time between failure of a machine is known to be exponential with mean value of 9000 hours (about 1 year of operation). The company issues one-year warranty on this machine. What are the chances that a breakdown repair will be required from the company during the warranty period ?

The machine has run without fail for 4,500 hours. What are the further chances of breakdown repair under warranty period ? (20 M)

07(a).

Sol: Mean time between failures (MTBF) is the critical characteristic for repairable system and is mean or average time between two successive failures of the system. MTBF is obtained by running an item or equipment for a predetermined length of time under specified conditions. The average length of a time between failures can be determined as

$$\text{MTBF} = \frac{\text{Total operating hours for all items}}{\text{Total number of failures}} = \frac{\text{No. of cycles}}{\text{Total no. of failures}}$$



MTBF representation of a system during its working period

MTBF can be expressed as inverse of failure rate 'λ'. However, exponential distribution is a distribution which is fully defined by a single parameter that governs the scale of the distribution function

$$f(x) = \lambda e^{-\lambda t}, t \geq 0, \lambda > 0$$

where t = time, λ = failure rate

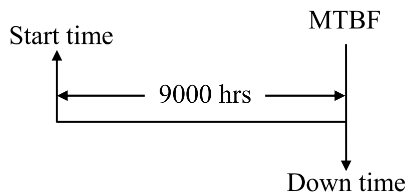
Case (i):

The machine mean time between failures is 9000 hrs.

The company given warranty is 1 year.

Since the MTBF is 9000 hrs and company warranty is exactly one year which is equal to MTBF.

According to statistical theory behind the statistics of confidence intervals, the statistical average becomes two as the no of samples increase.



The MTBF of 9000 hrs for one module for one year. No. of expected failure will be 1 at the end of period.

$$MTBF = \frac{T}{R} = \frac{9000}{1}$$

Chances for getting break down within warranty period is one.

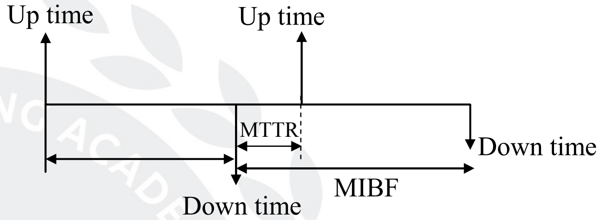
Reliability of machine $R(t) = e^{-t/MTBF} = e^{-1} = 0.3677$ => 36.8%

Chances for failures over a period one year is 63.2% For t = 9000 hr, MTBF = 9000 hrs.

Case (ii):

Total time T = 9000

Expected failure in one year = 2



$$MTBF = \frac{9000}{2} = 4500\,\text{hrs}$$

Failure rate $\lambda = \frac{1}{MTBF}$

$$R(t) = e^{-t/MTBF} = e^{-2} = 0.718 = 71.8\%$$

The survival of component i.e. reliability is only 71.8%

Further chances for breakdown = 1–R(t) = 1–0.718 = 28.2%

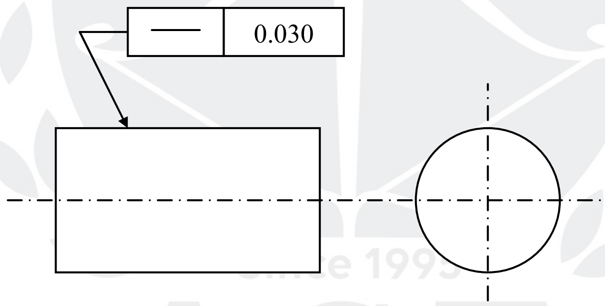
07(b).

(i) Explain in brief, about the geometric characteristics of Flatness, Straightness, Roundness, Profile of a surface and Angularity. Also, show the symbols by which these are represented.

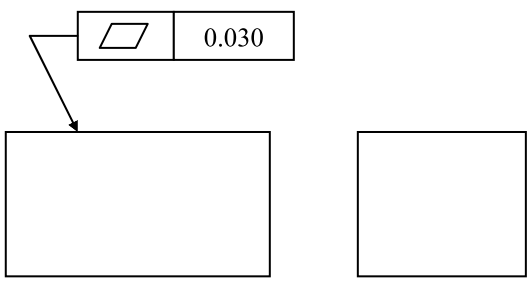
(10 M)

07(b)(i).

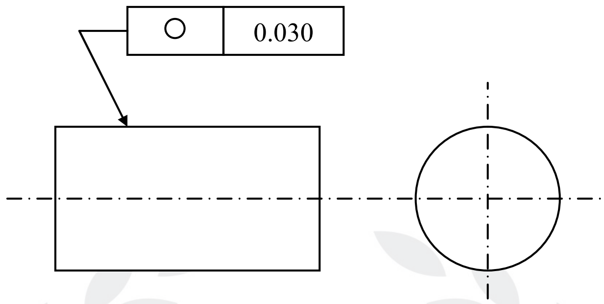
Sol: The following geometric characteristics are used for defining the surface or a component. **Straightness:** A line is said to be straight over a given length, if the variation of the distance of its points from two planes perpendicular to each other and parallel to the generation direction of the line remains within the specified limits. In its normal form or Surface **Straightness**, is a tolerance that controls the form of a line somewhere on the surface or the feature. Axis **Straightness** is a tolerance that controls how much curve is allowed in the part's axis. Straightness can apply to either a flat feature such as the surface of a block, or it can apply to the surface of a cylinder along the axial direction. It is defined as the variance of the surface within a specified line on that surface. The straightness is measured by using two different references (i) with reference to the end points reference (ii) Average reference method. The straightness is indicated by using line. For example

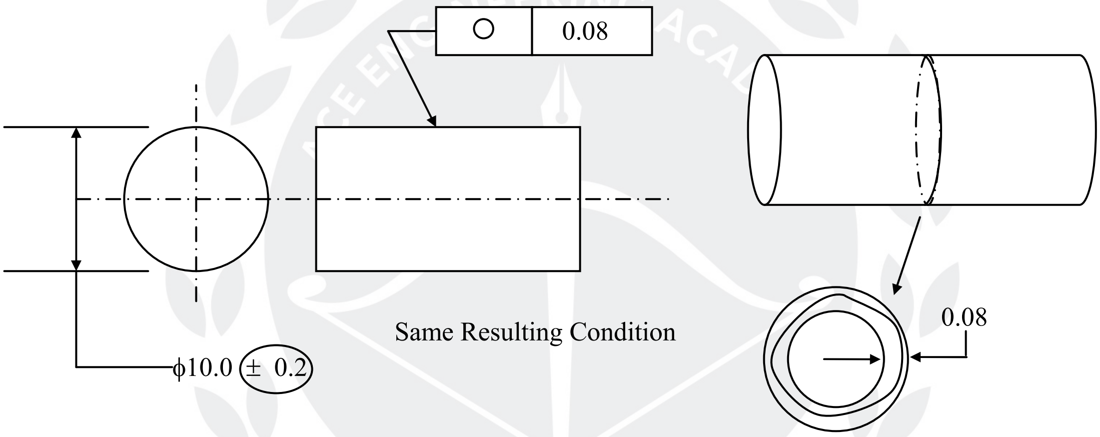


Flatness: The surface is deemed to be flat within a given range of measurement when the variation of the perpendicular distance of its point from geometrical plane parallel to the general trajectory of the plane may be either represented by means of a surface plane or by a family of straight lines obtained by the displacement of a straight edge. It is well known that a surface can be considered to be composed of an infinitely large number of lines. Flatness is the extension of straightness in the two directions. The flatness can be indicated by using symbol.



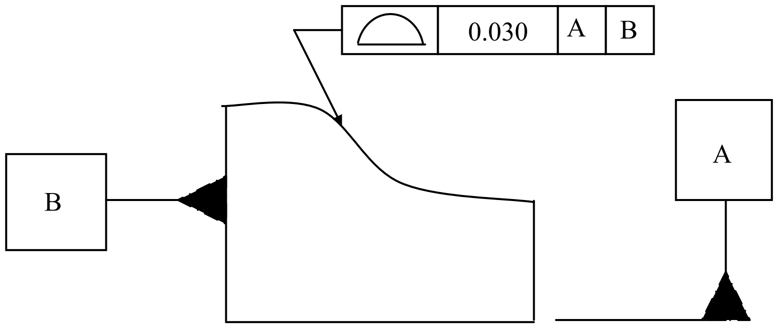
Roundness: Roundness or circularity is defined as the radial uniformity of work surface measured from the center line of the work piece. The error of circularity or out of roundness is defined as the radial distance between the minimum inscribing circle and maximum inscribing circle, which contains the profile of the surface at a section perpendicular to the axis of rotation. The symbol for roundness is



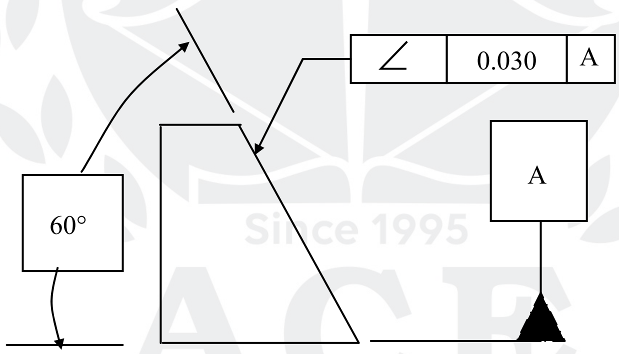


Profile of surface: Profile of a surface describes a 3-Dimensional tolerance zone around a surface, usually which is an advanced curve or shape. If it is called out on a curved surface, like a fillet on a welded part, the entire surface where the radius is, has to fall within the tolerance zone. Profile controls all the points along the surface within a tolerance range that directly mimics the designed profile. Any point on the surface would not be able to vary inside or outside by more than the surface profile tolerance. Usually when surface profile is required, there are no tolerances on the dimensions that describe the surface and use the GD & T callout to give the acceptable range. Sometimes profile of a line is used in conjunction with profile of a surface. In these cases the line profile tolerance will be tighter than the surface tolerance. This ensures that along any specific cross section of the profile, the part will be tightly controlled, while at a looser extent, the total profile is also controlled.

Symbol is



Angularity: Angularity is the symbol that describes the specific orientation of one feature to another at a referenced angle. It can reference a 2D line referenced to another 2D element, but more commonly it relates the orientation of one surface plane relative to another datum plane in a 3-Dimensional tolerance zone. The tolerance does not directly control the angle variation and should not be confused with an angular dimension tolerance such as ± 5°. In fact the angle for now becomes a Basic Dimension, since it is controlled by your geometric tolerance. The tolerance indirectly controls the angle by controlling where the surface can lie based on the datum. See the tolerance zone below for more details. Symbol is



(ii) What are the different zones of an electric arc, generated for the electric arc welding process ? Also explain their characteristics. (10 M)

07(b)(ii).

Sol: During arc welding operation, when the power supply is given and optimum gap is maintained between the Cathode and Anode, there are three zones of electric arc formed between them.

- **Cathode spot:** This is the place where very high velocity negatively charged electrons are generated, which are attracted by the anode and moving towards the anode. Also the positively charged ions are impinging at this zone so that kinetic energy of ions will be converted into heat energy and, therefore, the heat is getting generated at this point. There is a voltage drop taking place in this zone.

- **Plasma zone (Arc zone):** Plasma is the region between electrode and work where mostly flow of charged particles namely negatively charged electrons and positive ions takes place. In this region, uniform voltage drop takes place. Heat generated in this region has minor effect on melting of the work piece and electrode. When some of the ions and electrons are colliding in between the passage, the kinetic energy possessed by both the elements will be spontaneously converted into heat energy. When such sparks are produced continuously, the arc is formed.
- **Anode spot:** This is the place where the high velocity positively charged ions are generated, which are attracted by the cathode and moving towards the cathode. Also the negatively charged ions are impinging at this zone so that kinetic energy of electrons will be converted into heat energy and, therefore, the heat is getting generated at this point.
- Because of velocity of electrons is very much higher than the velocity of irons, the heat generated at the anode is higher than the cathode.

07(c).

(i) What are the various forging defects, which are likely to take place, because of the faulty forging process design ? Explain about any five in brief. (10 M)

07(c)(i).

Sol: The defects produced in forging process are :

- *Unfilled Section (unfilled zone):* As the name implies, in this type of defect some of the forging section remains unfilled. This is also due to less raw material or poor heating. This is due to poor design of die or poor forging technique. This defect can be removed by proper die design, proper availability of raw material and proper heating.
- *Cold Shut*: Cold shut is the discontinuity present due to foldings taking place in the material. This defects occur due to carrying out the closed die forging directly without any preforming operations. These defects also occur due to improper design of forging die. It is also due to sharp corner, and excessive chilling in forge product. To avoid this, the component is produced by using preforming operations. The fillet radius of the die should be increased to remove these defects.
- *Scale Pits:* Scale pits are due to improper cleaning of scales from the raw material. This defect is generally associated with forging in open environment. It is irregular deputations on the surface of forging. It can be removed by proper cleaning of raw material surface before forging.

- *Die Shift*: Die shift is caused by misalignment of upper die and lower die. When both these dies are not properly aligned the forged product does not get proper dimensions. This defect can be removed by proper alignment. It can be done by providing half notch on upper die and half on lower die so that at the time of alignment, both these notches will match or it is also possible by providing dowel pins.
- *Improper Grain Growth:* This defect occurs due to improper flow of metal in casting which changes predefined grain structure of product. It can be removed by proper die design.
- *Flakes:* These are internal cracks occuring due to improper cooling of forged product. When the forge product is cooled quickly, these cracks generally occur which can reduce the strength of forge product. This defect can be removed by proper cooling.
- *Residual Stresses in Forging:* This defect occurs due to improper cooling of forged part. Too much rapid cooling is the main causes of this type of defect. This can be removed by slow cooling of forged part.

(ii) What is Gating ratio ? What is its importance for successful casting operation ? Also, explain its types with their respective suitabilities, with examples. (10 M)

07(c)(ii).

Sol: The ratio of cross sectional area of the *Sprue: Runner: Ingate* in gating system is called as *gating ratio*. Because all the three elements of the gating system such as Sprue, Runner and ingate are in the same horizontal line, out of the three elements the minimum area is considered as choke area and at choke area the velocity of molten metal in the gating system is maximum. Also the maximum velocity of molten metal in the gating system must ensure the laminar flow in the gating system. For this purpose the choke area is designed first. Based on the choke area the other area will be designed later for ensuring the sand erosion and aspiration effect.

The gating ratio will be taken based on the pressure above molten metal in the pouring basin.

If the pressure above molten metal in the pouring basin is equal to atmospheric pressure, it is called as *non-pressurised gating system* and for this the optimum gating ratio can be taken as 1:4:4 or 1 : 2 : 2 .

If the pressure above molten metal in the pouring basin is greater than atmospheric pressure, it is called as *pressurised gating system* and for this the optimum gating ratio can be taken as 1: 2 : 1 .

The non-pressurised gating system is easy to maintain and is used for general purpose applications but due to oxidation problem it cannot be used for casting of highly reactive metal. Hence, for casting of highly reactive metals such as *aluminium and magnesium*, the pressurized gating system is used.

ESE / GATE / PSUs - 2019
ADMISSIONS OPEN

CENTER	COURSE	BATCH TYPE	DATE
HYDERABAD - DSNR	GATE + PSUs - 2019	Regular Batch	8th, 22nd July 2018
HYDERABAD - Kukatpally	GATE + PSUs - 2019	Regular Batch	2nd July 2018
HYDERABAD - Abids	GATE + PSUs - 2020	Morning Batch	15th July 2018
HYDERABAD - DSNR	GATE + PSUs - 2020	Morning Batch	22nd July 2018
HYDERABAD - Kukatpally	GATE + PSUs - 2020	Morning Batch	22nd July 2018
HYDERABAD - DSNR	GATE + PSUs - 2020	Evening Batch	22nd July 2018
HYDERABAD - Kukatpally	GATE + PSUs - 2020	Evening Batch	22nd July 2018
HYDERABAD - DSNR	ESE + GATE + PSUs - 2019	Regular Batch	8th, 22nd July 2018
HYDERABAD - Abids	ESE + GATE + PSUs - 2020	Morning Batch	15th July 2018
HYDERABAD - DSNR	ESE + GATE + PSUs - 2020	Morning Batch	22nd July 2018
HYDERABAD - Kukatpally	ESE + GATE + PSUs - 2020	Morning Batch	22nd July 2018
HYDERABAD - DSNR	ESE + GATE + PSUs - 2020	Evening Batch	22nd July 2018
HYDERABAD - Kukatpally	ESE + GATE + PSUs - 2020	Evening Batch	22nd July 2018
HYDERABAD - Abids	ESE - 2019 (PRELIMS) - G.S	Regular Batch	09th July 2018
DELHI	GATE + PSUs - 2019	Regular Batch	22nd July 2018
PUNE	GATE + PSUs - 2019	Weekend Batch	07th July 2018
PUNE	GATE + PSUs - 2020	Weekend Batch	04th Aug 2018
PUNE	ESE + GATE + PSUs - 2020	Weekend Batch	04th Aug 2018
BHUBANESWAR	GATE + PSUs - 2019	Regular Batch	07th July 2018
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CHENNAI	GATE + PSUs - 2019	Regular Batch	07th July 2018
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PATNA	GATE + PSUs - 2020	Weekend Batch	14th July 2018
VISAKHAPATNAM	GATE + PSUs - 2019	Regular Batch	17th July 2018
VISAKHAPATNAM	GATE + PSUs - 2020	Weekend Batch	08th July 2018
TIRUPATI	GATE + PSUs - 2020	Weekend Batch	14th July 2018

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08(a).

(i) What is a Gating System ? What are the different elements of it ? Explaining 'Aspiration Effect', discuss which of the elements of the Gating System is mostly affected with it and what measures are taken to avoid it. (10 M)

08(a)(i).

Sol: The passage used for pouring of molten metal into the casting cavity is called gating system. The elements used in gating system are :

- Pouring basin: It is acting as reservoir for supplying molten metal to the casting cavity.
- Sprue: It is acting as connecting passage between the pouring basin and runner. It is always vertical and straight tapered circular cross section.
- Runner: It is acting as connecting passage between the bottom of sprue and ingate. It is always horizontal with uniform trepizoidal cross section.
- Ingate: It is the last point of gating system from where the molten metal enters into the casting cavity it is horizontal with uniform trepizoidal cross section

During pouring of molten metal into the casting cavity through the gating system, if somewhere along the gating system if the pressure falls below atmospheric pressure, the pressure difference is existing between outside and inside of gating system and due to this pressure difference the air will start flowing from outside to the inside of the gating system through porosity property of molding sand called as *aspiration or inhalation or breathing effect.*

If the sprue is made as straight cylindrical sprue, at the top of the sprue, the pressure becomes less than atmospheric hence aspiration effect will take place at the top of the sprue.

The aspiration effect is mainly influencing the sprue.

For just avoiding the aspiration effect, parabolic tapered sprue is used. But manufacture of parabolic tapered sprue is difficult hence straight tapered sprue is used so that it avoids the aspiration effect and is easy in manufacturing.

(ii) State how Standard Tolerance Grade, position of Tolerance zone, Upper deviation and Lower deviation, Tolerance class and Fit are designated. (10 M)

08(a)(ii).

Sol: Upper Deviation: The algebraic difference between the maximum limit of size and the corresponding basic size.

Lower Deviation: The algebraic difference between the minimum limit of size and the corresponding basic size.

Fundamental Deviation: It is one of the two deviations which is chosen to define the position of the tolerance zone conveniently.

Tolerance: The algebraic difference between upper and lower deviations. It is an absolute value.

Limits of Size: There are two permissible sizes for any particular dimension between which the actual size lies, maximum and minimum Basic Shaft and Basic hole: The shafts and holes that have zero fundamental deviations. The basic hole has zero lower deviation whereas, the basic shaft has zero upper deviation.

Grade of Tolerance: It is an indication of the level of accuracy.

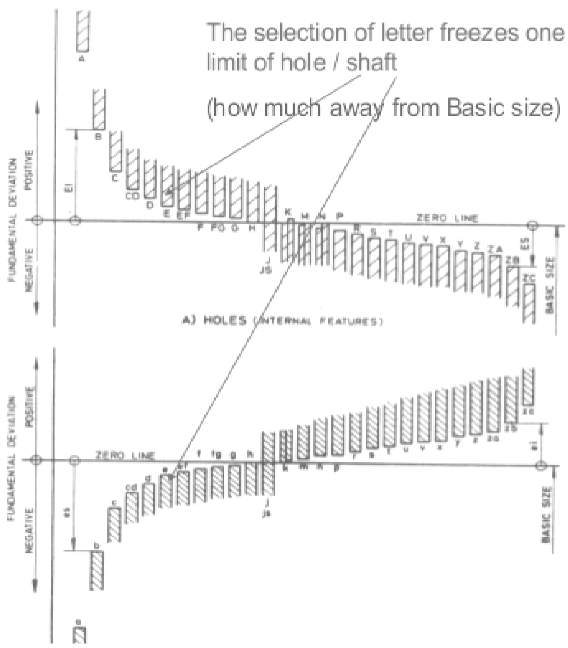
There are 18 grades of tolerances – IT01, IT0, IT1 to IT16

IT01 to IT1 – For production of measuring instruments, gauges, plug gauges.

IT2 to IT 4 – For fits in precision engineering applications, highly important parts

IT5 to IT10 – For General Engineering applications

IT11 to IT14 – For very less important applications such as Sheet metal working or press working casting, general cutting work etc.



Representation of Tolerance

1) Letter Symbol

Basic Size → 45 E8/e7

One can have different possible combinations; eg. 45H6g7, 45H8r6, 45E5p7

E.S. – upper deviation

E.I. – lower deviation

H : lower deviation of hole is zero

h : upper deviation of shaft is zero

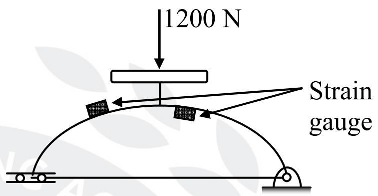
08(b). A mechatronic platform scale is represented by the schematic shown below. It consists of two leaf springs with four strain gauges mounted, two on each leaf spring as shown. Leaf spring span is 300 mm and the cross-section is 300 mm × 4 mm.

The voltage corresponding to weight on the scale is measured as output Wheatstone bridge comprising of four strain gauges mentioned above. Gauge factor of these is 2.1 and they are mounted such that two will read tensile strain and other two will read transverse compressive strain. The Wheatstone bridge has four 100 Ω resistances and input voltage of 6 V. Determine the output voltage of the bridge corresponding to a weight of 1200 N on the weighing platform.

Properties of leaf spring material are

Modulus = 200 GPa

Poisson's ratio = 0.3

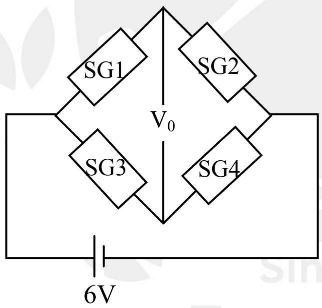


(20 M)

08(b).

Sol: Mechatronic platform scale with leaf springs. Its span is 300 mm, cross-section is 30 mm × 4 mm.

⇒ Wheatstone bridge, with four strain gauges are used to measure output voltage.



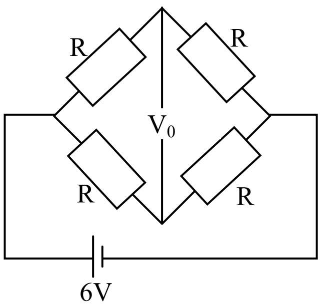
In two strain gauges, tensile strain (+ve) and other two strain gauges compressive strain (-ve).

⇒ Total four strain gauges to four arms, known as full bridge configuration.

Its output voltage is calculated as given below:

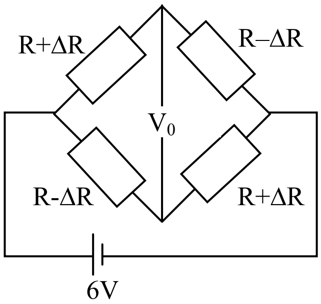
⇒ Tensile strain, R→ R + ΔR (Resistance increases).

⇒ Compressive strain, R → R – ΔR (Resistance decreases).



Initially all are of equal resistances (100 Ω) of strain gauge. So, $V_0 = 0$.

⇒ When force is applied, strain induces. Thus, resistance of all four strain gauges change as shown below:



⇒ Then its output voltage V_0 = Applied voltage × Gauge factor × Strain $= V \times G_f \times \varepsilon$

Given that,

Applied voltage, V = 6V,

Gauge factor, $G_f = 2.1$

Strain can be calculated from Young's modulus (E) as given below.

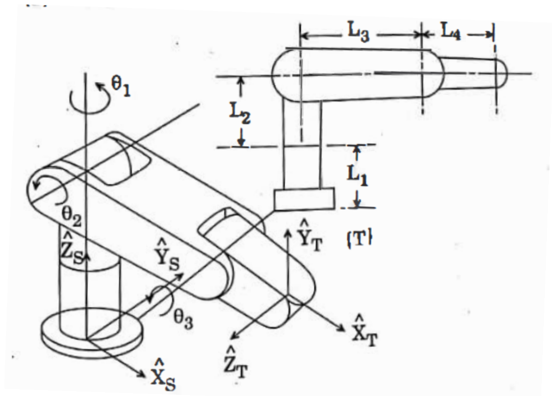
$$E = \frac{\text{Stress}}{\text{Strain}} = \frac{\text{Force/ Area}}{\text{Strain}}$$

$$\therefore\ 200\times10^{9} = \frac{1200/\left(30\times4\times10^{-6}\right)}{\text{Strain}(\varepsilon)}$$

So, $\varepsilon = \frac{1200}{120\times10^{-6}}\times\frac{1}{200\times10^{9}} = 50\mu = 50\times10^{-6}$

Now, $V_0 = V \times G_f \times \varepsilon = 6 \times 2.1 \times 50 \times 10^{-6} = 630 \times 10^{-6} = 630\ \mu V$

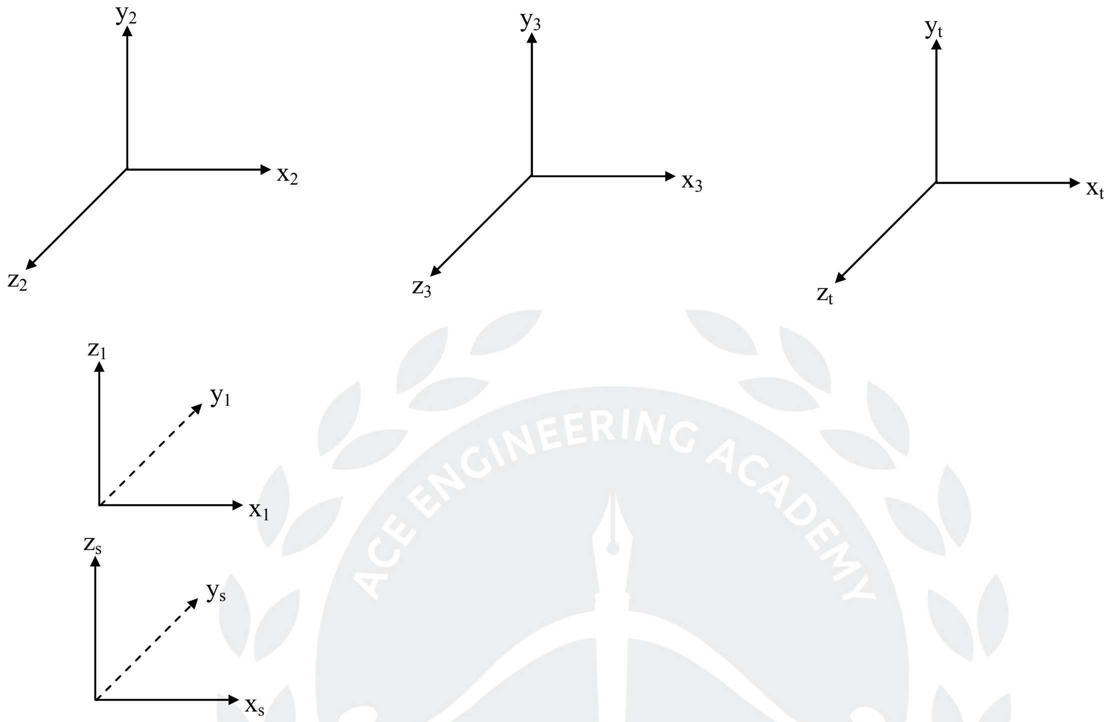
08(c). Arm of 3 DOF manipulator is shown in the figure below. Joints 1 and 2 are perpendicular to each other and joints 2 and 3 are parallel. All joints are shown at their zero location and positive senses of the joint angles are indicated. Assign link frames (0) to (4) for the arm such that (0) represents frame (S) and (4) represents (T). Make a table of D-H. parameters and derive all the information matrices relating (0), (1), (2) and (3) frames.



(20 M)

08(c).

Sol: Arm of 3 DOF manipulator. Link frames 0 to 4 are as follows. Frame {0} represents frame [S] and frame {4} represents frame [T].



⇒ Denavit (D) and Hartenber's (H), D-H parameter table of links and joints.

⇒ 3 DOF has 3 joints (J_1, J_2, J_3) and 4 links.

Link & Joint	Link		Joint	
	a	α	d	θ
1	0	90	L_1	θ_1
2	L_3	0	L_2	θ_2
3	L_4	0	0	θ_3

⇒ Transformation matrices between frame {i} with respect to frame {i–1} as given below.

$$_{i-1}T^{i} = \begin{bmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_i c\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_i s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$_{0}T^{1} = \begin{bmatrix} c_1 & 0 & s_1 & 0 \\ s_1 & 0 & -c_1 & 0 \\ 0 & 1 & 0 & L_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$ {}_1T^2 = \begin{bmatrix} c_2 & -s_2 & 0 & L_3c_2 \\ s_2 & c_2 & 0 & L_3s_2 \\ 0 & 0 & 1 & L_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}_2T^3 = \begin{bmatrix} c_3 & -s_3 & 0 & L_4c_3 \\ s_3 & c_3 & 0 & L_4s_3 \\ 0 & 0 & 1 & L_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

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