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Detailed Solutions

ESE-2019
Mains Test Series

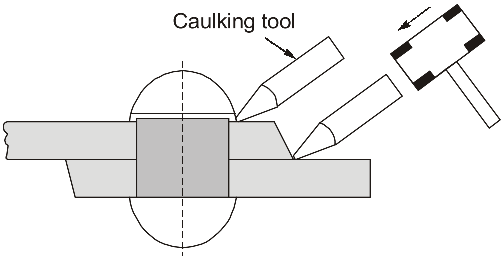
Mechanical Engineering
Test No : 8

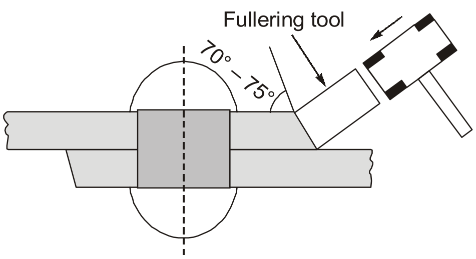
Section A : Machine Design + Mechatronics & Robotics

Q.1 (a) Solution:

Caulking: It is used to obtain leak proof or fluid tight joint in pressure vessels like steam boiler, air receivers and tanks etc. Caulking process is applied to the edges of plates in a lap joint and the edges of strap plate in a butt joint. These edges are first beveled to approximately 70° to 75° and caulking tool is hammered on the edge. It can be done by hand hammer or by use of pneumatic or hydraulic hammer. The blows of caulking tool closes the surface asperities and cracks on the contacting surfaces between two plates and also between the rivet and the plates resulting in leak proof joint. It can not be applied to plates less than 6 mm thickness.

Fullering: Fullering is similar to caulking process except the shape of the tool. In this process, a fullering tool with thickness at end equal to the plate thickness is used in such a way that the greatest pressure due to the blow occur near the joint, given a clean finish with less risk of damaging the plate.





Q.1 (b) Solution:

$$F = \begin{bmatrix} n_x & o_x & a_x & 3 \\ n_y & o_y & a_y & 9 \\ n_z & o_z & a_z & 7 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \left[\begin{array}{c|c} R & D \\ \hline 000 & 1 \end{array}\right]$$

$$R = \text{Rotation matrix} = \begin{bmatrix} n_x & o_x & a_x \\ n_y & o_y & a_y \\ n_z & o_z & a_z \end{bmatrix}$$

We know that, for rotation matrix,

$$\begin{aligned} n_x^2 + n_y^2 + n_z^2 &= 1 && \text{Given, } n_y = 0.5 \\ n_x^2 + 0.5^2 + 0^2 &= 1 \\ n_x &= \pm 0.866 \\ \Rightarrow \qquad n \cdot o &= 0 \\ n_x o_x + n_y o_y + n_z o_z &= 0 \\ \pm 0.866 \times 0 + 0.5 \times o_y + 0 &= 0 \\ o_y &= 0 \\ \Rightarrow \qquad o_x^2 + o_y^2 + o_z^2 &= 1 \\ o_z &= \pm 1 && \text{as, } o_x \text{ and } o_y \text{ are } 0 \\ n \times o &= a \end{aligned}$$

Now, matrix for $n_x = 0.866$ and $o_z = +1$

$$R = \begin{bmatrix} 0.866 & 0 & a_x \\ 0.5 & 0 & a_y \\ 0 & 1 & a_z \end{bmatrix}$$

Expand about 3rd column

So, $n \times o = a$

$$\begin{aligned} i(0.5) - j(0.866) + k(0) &= a_x\hat{i} + a_y\hat{j} + a_z\hat{k} \\ a_x &= 0.5 \\ a_y &= -0.866 \\ a_z &= 0 \end{aligned}$$

Similarly we can get another solution by taking

$$n_x = -0.866 \text{ and } o_z = +1$$

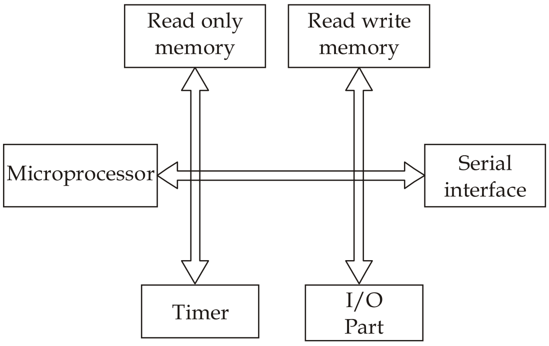
So, transformation matrix is

$$T = \begin{bmatrix} \pm 0.866 & 0 & +0.5 & 3 \\ 0.5 & 0 & \mp 0.866 & 9 \\ 0 & +1 & 0 & 7 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Similarly for $o_z = -1$

$$T = \begin{bmatrix} \pm 0.866 & 0 & +0.5 & 3 \\ 0.5 & 0 & \mp 0.866 & 9 \\ 0 & -1 & 0 & 7 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Q.1 (c) Solution:

Microprocessor	**Micro Controller**
	Microcontroller | Read only memory | Read write memory Timer | I/O Port | Serial interface
• Microprocessor is heart of computer system.	• Microcontroller is heart of embedded system.
• CPU is stand-alone, RAM, ROM, I/O timer are seperate.	• A CPU, RAM, ROM, I/O and timer are all on a single chip.
• Since memory and I/O has to be connected externally the circuit becomes large.	• Since memory and I/O are present internally, the circuit is small.
• Cannot be used in compact system and hence inefficient.	• Can be used in compact system and hence it is an efficient technique.
• Cost of entire system is high.	• Cost of entire system is low.
• Due to external components, the entire power consumption is high. Hence it is not suitable to used with devices running on stored power like batteries.	• Since external components are low total power consumption is less and can be used with devices running on stored power like batteries.
• Most of the microprocessor do not have power saving features.	• Most of the micro controllers have power saving modes like idle mode and power saving mode. This helps to reduce power consumption even further.
• Speed is slow.	• Speed is fast.
• Microprocessor are based on Von-Neumann model/ architecture where program and data are stored in same memory module.	• It is based on Harvard architecture where program memory and data memory are seperate.
• Mainly used in personal computers.	• Used mainly in washing machine, MP_3 player.

Q.1 (d) Solution:

Equivalent load for complete work cycle:

Element No.	P(N)	Element time	Speed(rpm)	Revolution N in element time
1	$2000-(P_1)$	0.25	500	$125-(N_1)$
2	$3000-(P_2)$	0.5	500	$250-(N_2)$
3	$2500-(P_3)$	0.25	400	$100-(N_3)$

So, equivalent load, $P_e = \sqrt[3]{\dfrac{N_1P_1^3+N_2P_2^3+N_3P_3^3}{N_1+N_2+N_3}}$

$$P_e = 2696.44 \text{ N}$$

L_{10} life corresponding to 90% reliability or R_{90}

$$\left(\frac{L_{15}}{L_{10}}\right) = \left(\frac{\log_e \frac{1}{R_{85}}}{\log_e \frac{1}{R_{90}}}\right)^{1/b}$$

where, L_{15} = Life corresponding to 85% reliability

L_{15} = 5 million rev.

$b = 1.17$

So,
$$\left(\frac{5}{L_{10}}\right) = \left(\frac{\log_e \frac{1}{0.85}}{\log_e \frac{1}{0.90}}\right)^{1/1.17}$$

$$L_{10} = 3.452 \text{ million revolution}$$

So, dynamic load capacity $= C$

$$\left(\frac{C}{P_a}\right)^3 = (L_{10})$$

$$C = 4075.18 \text{ N}$$

Q.1 (e) Solution:

(i)

^2P is the point with respect to moving frame {2}, ^{1}P is the point with respect to fixed frame and $^1R_2$ is rotation of frame with respect to fixed frame {1}.

So, $$^1P = {}^1R_2{}^2P \qquad \text{...(1)}$$

$$^1R_2 = R_z(\theta) = \begin{bmatrix} C\theta & -S\theta & 0 \\ S\theta & C\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

at θ = 90° $$R_z(\theta) = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

equation (1)

$$^1P = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} 2 \\ 3 \\ 5 \end{bmatrix} \qquad \text{given } ^1P = [2\ 3\ 5]$$

$$^1P = \begin{bmatrix} -3 \\ 2 \\ 5 \end{bmatrix} \text{ or } [-3\ 2\ 5]^T$$

or $$^1P = [-3\ 2\ 5\ 1]^T$$

(ii)

As, each rotation is done about an axis of fixed reference frame $\{x\ y\ z\}$. So this is called fixed angle rotations.

So, the final frame orientation is obtained by composition of rotations with respect to fixed frame and the overall rotation matrix $^1R_2$ is computed by pre multiplication of matrices of elementary rotations.

$$R_{zyx}(\theta_1, \theta_2, \theta_3) = {}^1R_2 = R_x(\theta_3)R_y(\theta_2)R_z(\theta_1)$$

where, $\theta_1 = 60°$

$\theta_2 = 120°$

$\theta_3 = 90°$

$$^1R_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C_3 & -S_3 \\ 0 & S_3 & C_3 \end{bmatrix} \times \begin{bmatrix} C_2 & 0 & S_2 \\ 0 & 1 & 0 \\ -S_2 & 0 & C_2 \end{bmatrix} \times \begin{bmatrix} C_1 & -S_1 & 0 \\ S_1 & C_1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$^1R_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix} \times \begin{bmatrix} -0.5 & 0 & 0.866 \\ 0 & 1 & 0 \\ -0.866 & 0 & -0.5 \end{bmatrix} \times \begin{bmatrix} 0.5 & -0.866 & 0 \\ 0.866 & 0.5 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$^1R_2 = \begin{bmatrix} -0.25 & 0.433 & 0.866 \\ 0.433 & -0.75 & 0.5 \\ 0.866 & 0.5 & 0 \end{bmatrix}$$

Q.2 (a) Solution:

Given: $\phi = 20°$, Power, $P = 50$ kW, $N_1 = 300$ rpm, $T_1 = 30$, $T_2 = 60$, $T_3 = 25$ and $T_4 = 50$
$m = 8$ mm, gear 1 is rotating in clockwise direction,
when seen from the left side of page.

We know that,

$$\text{Power, } P = T \times \omega$$

$$P = T_1 \times \omega_1 \qquad \text{(for gear 1)}$$

So,

$$P = T_1 \times \omega_1 = F_{t1} \times r_1 \times \omega_1$$

$$\omega_1 = \frac{2\pi N_1}{60} = \frac{2\pi \times 300}{60} = 31.416 \text{ rad/s}$$

$$P = F_{t1} \times \frac{mT_1}{2} \times \omega_1$$

$$50 \times 10^3 = F_{t1} \times \frac{8}{1000} \times \frac{30}{2} \times 31.416$$

$$F_{t1} = 13262.92 \text{ N}$$

and

$$F_{r1} = F_{t1}\tan\phi = 4827.31 \text{ N}$$

$$F_{t1} = F_{t2} \text{ and } F_{r1} = F_{r2}$$

For gear 3 and gear 4

$$P = T_3 \times \omega_3$$

$$\omega_3 = \omega_2 \qquad \text{[gear 3 and gear 2 are on same shaft]}$$

$$\frac{\omega_2}{\omega_1} = \frac{T_1}{T_2} = \frac{30}{60} = \frac{1}{2}$$

$$\omega_2 = 15.708 \text{ rad/s}$$

$$P = T_3 \times \omega_3$$

$$50 \times 10^3 = F_{t3} \times r_3 \times \omega_3$$

$$50 \times 10^3 = F_{t3} \times \frac{mT_3}{2} \times \omega_3$$

$$F_{t3} = 31830.94 \text{ N}$$

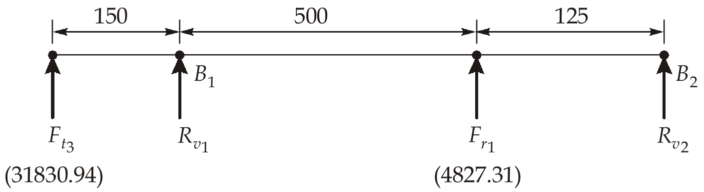
$$F_{r3} = 11585.51 \text{ N}$$

$$F_{t3} = F_{t4} \text{ and } F_{r3} = F_{r4}$$

(ii) For reactions at B_1 and B_2, consider the gear 2 and 3 which are mounted on shaft and, calculate the reactions in vertical and horizontal plane

For vertical plane:

Moment about B_1:



$$F_{t3} + 150 = F_{r1} \times 500 + R_{v2} \times 625$$

$$31830.94 \times 150 = 4827.307 \times 500 + R_{v2} \times 625$$

$$R_{v2} = 3769.856 \text{ N}$$

Moment about B_2:

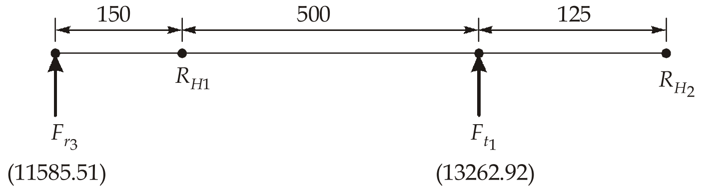
$$F_{t3} \times 775 + R_{v1} \times 625 + F_{r1} \times 125 = 0$$

$$31830.94 \times 775 + R_{V1} \times 625 + 4827.307 \times 125 = 0$$

$$R_{V1} = -40435.827 \text{ N}$$

For horizontal plane:

Moment about B_1:



$$R_{H2} \times 625 \times F_{t1} + 500 = F_{r3} \times 150$$

$$R_{H2} \times 625 + 13262.92 \times 500 = 1158.51$$

$$R_{H2} = -7829.813 \text{ N}$$

Moment about (B_2):

$$R_{H1} \times 625 + 11585.51 \times 775 + F_{t1} \times 125 = 0$$

$$R_{H1} = -17018.6164 \text{ N}$$

Resultant reactions:

at $$(B_1) = \sqrt{(R_{V1})^2 + (R_{H1})^2} = 43871.28 \text{ N}$$

at $$(B_2) = \sqrt{(R_{V2})^2 + (R_{H2})^2} = 8690.097 \text{ N}$$

Q.2 (b) Solution:

$$^{j}T_k = {}^{j}T_i \times {}^{i}T_k \qquad \text{...(1)}$$

$$^{i}T_k = \left[{}^{k}T_i\right]^{-1}$$

We know that

$$^{i}T_k = \left[{}^{k}T_i\right]^{-1} = \left[\begin{array}{c|c} \left[{}^{k}R_i\right]^T & -\left[{}^{k}R_i\right]^T \times \left[{}^{k}D_i\right] \\ \hline 0\ \ 0\ \ 0 & 1 \end{array}\right]$$

$$^{k}R_i = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.866 & -0.5 \\ 0 & 0.5 & 0.866 \end{bmatrix}$$

$$^{k}R_i^{\,T} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.866 & 0.5 \\ 0 & -0.5 & 0.866 \end{bmatrix}$$

$$^{k}D_i = \begin{bmatrix} 0 \\ 10 \\ -20 \end{bmatrix}$$

$$-\left[{}^{k}R_i\right]^T \times \left[{}^{k}D_i\right] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.866 & 0.5 \\ 0 & -0.5 & 0.866 \end{bmatrix}\begin{bmatrix} 0 \\ 10 \\ -20 \end{bmatrix}$$

$$= -\begin{bmatrix} 0 \\ -1.34 \\ -12.32 \end{bmatrix} = \begin{bmatrix} 0 \\ 1.34 \\ 12.32 \end{bmatrix}$$

So,

$$^{i}T_k = \left[{}^{k}T_i\right]^{-1} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0.866 & 0.5 & 1.34 \\ 0 & -0.5 & 0.866 & 22.32 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

eq. (i):

$$^{j}T_{k} = {}^{j}T_{i} \times {}^{i}T_{k}$$

$$^{j}T_{k} = \begin{bmatrix} 0.866 & -0.5 & 0 & 11 \\ 0.5 & 0.866 & 0 & -1 \\ 0 & 0 & 1 & 8 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0.866 & 0.5 & 1.34 \\ 0 & -0.5 & 0.866 & 22.32 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 0.866 & -0.5\times0.866 & -0.5\times0.5 & -0.5\times1.34+11 \\ 0.5 & 0.866\times0.866 & 0.5\times0.866 & 0.866\times1.34-1 \\ 0 & -0.5 & 0.866 & 22.32+8 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{j}T_{k} = \begin{bmatrix} 0.866 & -0.433 & -0.25 & 10.33 \\ 0.5 & 0.7499 & 0.433 & 0.16044 \\ 0 & -0.5 & 0.866 & 30.32 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

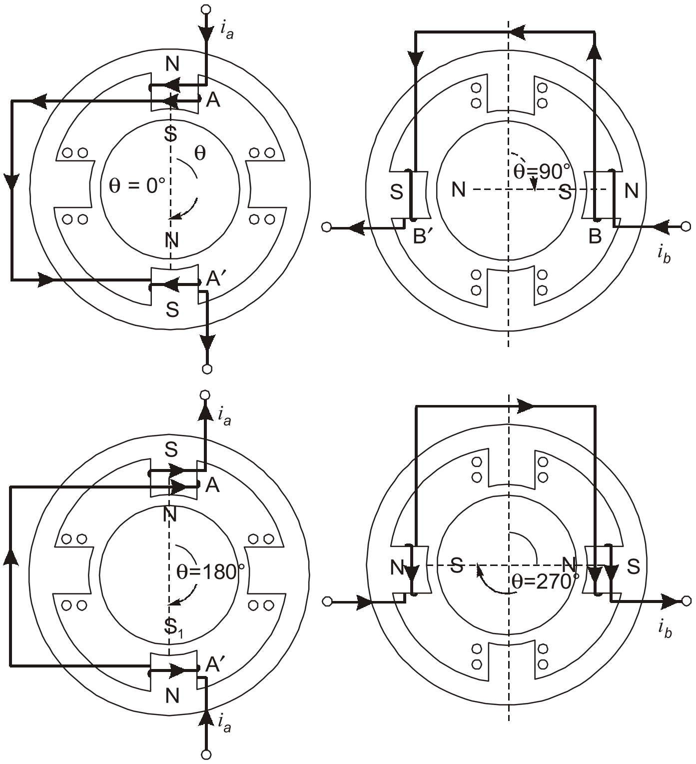
Q.2 (c) Solution:

A stepper motor is a pulse-driven motor that changes the angular position of the rotor in steps. Due to this nature of a stepper motor it is widely used in low cost, open loop position control systems. A stepper motor is basically a brushless DC- motor whose rotor rotates in discrete angular movements when its winding is energized in a programmed manner. In stepper motor a full rotation is divided into a number of equal steps.

Permanent magnet (PM) stepper motor: The stator of permanent magnet stepper motor consists of salient poles with concentrated windings. The rotor as the name of this motor suggest, consists of permanent magnet poles. For the illustration of the working principle of PMSM an elementary form of 2-phase 4/2 pole stepper motor is considered here. The concentrated winding on diametrically opposite poles are connected in series so as to result in 2-phase winding on the stator. The rotor is magnetized to give two permanent magnets.

Working: Two coils AA' connected in series constitute phase A winding. When this winding is excited with current i_a, the stator produced poles attract the rotor permanent magnet poles so that their magnetic axis coincides. Let this exciting of phase A winding be denoted by $+A$.

Now the current in phase *A* winding is reduced to zero while phase *B* winding is excited with current i_b. Stator produced poles now attract the rotor poles, causing a CW step rotation through θ = 90°. Let the exciting of phase *B* winding be denoted by +*B*.



Internal structure of Permanent Magnet (PM) Stepper Motor

Now the phase winding *A* is again excited but with current opposite to i_a that is $-i_a$ this time. Now rotor poles further move through a step of 90° CW so that θ =180°. This step of exciting phase winding be denoted by –*A*.

Now the phase winding *B* is made to carry exciting current opposite to that of i_b that is $-i_b$ this time. The rotor again executes further step of 90° CW so that θ = 270°. This method of exciting phase *B* winding be designated as –*B*.

For further 90° CW step phase winding *B* is de-energized and phase winding *A* is energized. This shows that four steps complete one revolution of the rotor movement.

So here by the application of each current pulse to the stator winding in proper sequence, the rotor can be made to execute discrete angular steps of 90°. Sequence of exciting the stator phase winding is +*A*, +*B*, –*A*, –*B*, +*A* for CW rotor movement. For CCW rotor rotation, sequence of exciting stator phase winding is +*A*, –*B*, –*A*, +*B*, –*B*.

If both the stator windings are excited in the sequence +*A* together with +*B*, then the resultant stator field is along the interpolar axis, the rotor therefore moves a step of

45° CW. This shows for obtaining the angular step of 45° CW the switching sequence should be as +*A*, (+*A* +*B*), +*B*, (+*B* –*A*), –*A*, (–*A* – *B*), –*B*, (–*B* +*A*), +*A*.

This method of reducing step angle to half the normal step is called half step mode of excitation.

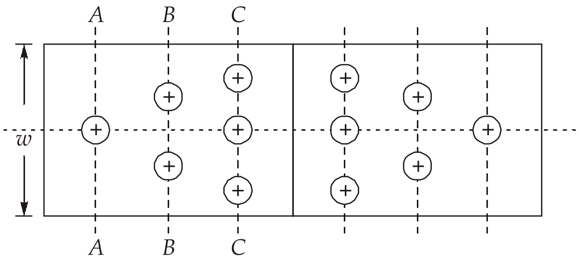
Advantages of stepper motors:

- Low cost
- Ruggedness
- Simplicity of construction
- Low maintenance
- Less likely to stall or slip
- Will work in any environment
- Excellent start stop and reversing responses

Disadvantages of stepper motor:

- Low torque capacity compared to DC motors.
- Limited speed.
- During overloading, the synchronization will be broken. Vibration and noise occur when running at high speed.

Q.3 (a) Solution:



Given, $P_{\text{total}} = P = 450$ kN, $t = 25$ mm, $\sigma_t = 80$ N/mm^2

$\tau = 60$ N/mm^2, $\sigma_c = 110$ N/mm^2

(i) Diameter of rivet

$$d = 6\sqrt{t} = 6\sqrt{25} = 30 \text{ mm}$$

$$d = 30 \text{ mm}$$

(ii) No of rivets:

Shear resistance of one rivet

$$P_{s1} = 1.875 \times \frac{\pi}{4} \times d^2 \times \tau = 79521.56 \text{ N}$$

Crushing reistance of one rivet,

$$P_{c1} = d \times t \times \sigma_c = 30 \times 25 \times 110$$
$$P_{c1} = 82500 \text{ N}$$

$$\text{Number of rivets, } n = \frac{P}{\min\left(P_{s1} \text{ and } \mathrm{P}_{c1}\right)}$$

$$n = \frac{450 \times 10^3}{79521.56} = 5.65$$
$$n \simeq 6$$

Strength of the rivet = Minimum (P_{s1} and P_{c1}) = 79521.56 N

Arrangement of rivets in rows: There are 3 rows, so one rivet in 1st row, two rivets in 2nd row and three rivets in 3rd row.

(iii) Efficiency of joints: To calculate the efficiency of the joint, find out the weakest cross-section of the joint. It may fail from the sections denoted by AA, BB or CC.

Assuming same diameter for rivet and rivet hole.

Width of the plate:

$$P_{\text{total}} \leq (w - d)t\,\sigma_t \qquad (\text{where, } P_{\text{total}} = P)$$
$$450 \times 10^3 \leq (w - d) \times 25 \times 80$$
$$w \geq 255 \text{ mm}$$

or $w = 255$ mm

1. The joint can fracture along section AA without affecting rivets in middle and inner rows.
2. The joint cannot fracture along section BB without shearing one rivet in double shear. This is the rivet in outer row.
3. The joint cannot fracture along section CC without shearing three rivets in double shear. These are rivets in outer and middle rows.

Based on these assumptions, the strength of the joint is:

$$\text{Along section-AA: } (P_{t1}) = (w - d)t\,\sigma_t = (255 - 30)\,25 \times 80 = 45000 = 450 \text{ kN}$$

$$\begin{aligned}\text{Along section-BB: } (P_{t2}) &= (w - 2d)t\,\sigma_t + N_1(\text{strength of each joint}) \\ &= (255 - 2 \times 30) \times 25 \times 80 + 1 \times 79521.56 \\ &= 469521.56 \text{ N} = 469.521 \text{ kN}\end{aligned}$$

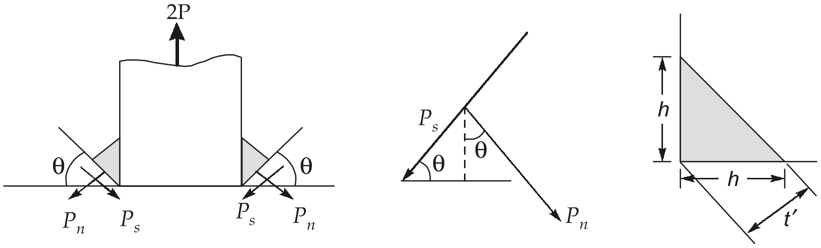
$$\begin{aligned}\text{Along section-CC: } (P_{t3}) &= (w - 3d)t\sigma_t + (N_1 + N_2)(\text{strength of each joint}) \\ &= (w - 3 \times 30) \times 25 \times 80 + (1 + 2)\,(79521.56) \\ &= 568564.68 \text{ N} = 568.56 \text{ kN}\end{aligned}$$

Shear resistance of all rivets, $P_s = n \times P_{s1} = 6 \times 79521.56$

$$P_s = 477129.36 \text{ N} = 477.13 \text{ kN}$$

$$\begin{aligned}\text{Crushing resistance of all rivets, } P_c &= n \times P_{c1} = 6 \times 82500\\ &= 495000 \text{ N} = 495 \text{ kN}\\ \text{Strength of riveted joint} &= \text{Minimum}(P_s, P_c, P_{t1}, P_{t2}, P_{t3}) = 450 \text{ kN}\\ \text{Strength of solid plate} &= w \times t \times \sigma_t\\ &= 255 \times 25 \times 80 = 510000 \text{ kN} = 510 \text{ kN}\\ \text{Efficiency, } \eta &= \frac{\text{Strength of riveted joint}}{\text{Strength of solid plate}} = \frac{450}{510} = 0.8823 = 88.23\%\end{aligned}$$

Q.3 (b) Solution:



Finding the inclination (θ) of the plane in the weld where the maximum shear stress is induced. The effect of bending is neglected.

P_s and P_n are the shear force and normal force acting on the section at an angle θ.

Considering equilibrium of vertical force,

$$2P = 2P_s\sin\theta + 2P_n\cos\theta$$

$$P = P_s\sin\theta + P_n\cos\theta \qquad \text{...(1)}$$

Equilibrium of horizontal component.

$$P_s\cos\theta = P_n\sin\theta \quad \text{or} \quad P_n = \frac{P_s\cos\theta}{\sin\theta}$$

Substituting in equation (1)

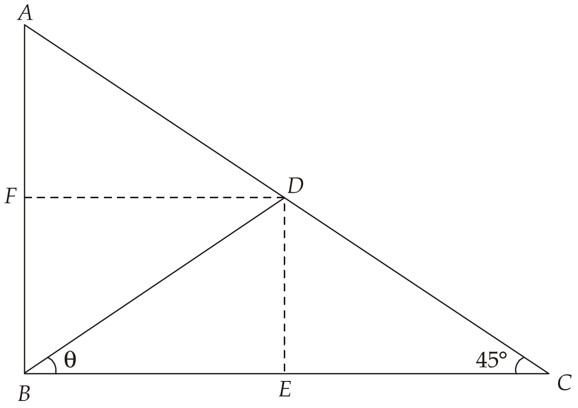
$$P = P_s\sin\theta + \frac{P_s\cos\theta\cos\theta}{\sin\theta} \qquad \text{...(2)}$$

Multiplying both side of equation (2) by sinθ

$$P\sin\theta = P_s\sin^2\theta + P_s\cos^2\theta = P_s(\sin^2\theta + \cos^2\theta) = P_s$$

or $$P_s = P\sin\theta$$

In triangle *ABC*,



$$AB = BC = h$$

$$BC = BE + EC$$

$$BC = BD\cos\theta + BD\sin\theta \quad (DE = EC) \text{ and } (BD = t')$$

$$h = t'(\sin\theta + \cos\theta) \text{ or } t' = \frac{h}{\sin\theta+\cos\theta}$$

Area of the weld in a plane that is inclined at angle θ is ($t'l$).

Shear stress in this plane, $\tau = \dfrac{P_s}{t'l}$

$$\tau = \frac{P\sin\theta(\sin\theta+\cos\theta)}{hl} \qquad \text{[putting value of } P_s \text{ and } t'\text{]}$$

For finding maximum shear stress, differentiae τ with respect to θ and equate to zero.

$$\frac{d\tau}{d\theta} = 0$$

$$\frac{P}{hl}\frac{\partial}{\partial\theta}[\sin\theta(\sin\theta+\cos\theta)] = 0$$

or $$\frac{\partial}{\partial\theta}[\sin\theta(\sin\theta+\cos\theta)] = 0$$

$$\sin\theta(\cos\theta - \sin\theta) + \cos\theta(\sin\theta + \cos\theta) = 0$$

$$2\sin\theta\cos\theta + \cos^2\theta - \sin^2\theta = 0$$

$$\sin2\theta + \cos2\theta = 0$$

$$\tan2\theta = -1$$

$$2\theta = 135$$

$$\theta = 67.5°$$

So, $$\tau_{max}(\text{at } \theta = 67.5°) = \frac{P\sin(67.5)(\sin(67.5)+\cos(67.5))}{hl}$$

$$\tau_{max} = \frac{1.21P}{hl}$$

Hence proved

Q.3 (c) Solution:

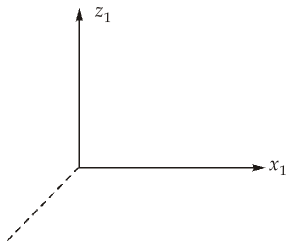
In cylindrical manipular, it has 3 joints, one revolute and two prismatic.

Algorithm for assigning frames and axis.

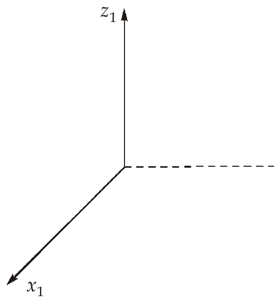
Step 0: The three joints are numbered as 1 2 and 3 starting with immobile base as 0.

Step 1: We know frame {0} location is arbitrary, its choice is made based on simplification of the model and some convenient reference in workspace. Its axis is made in such a way that it should not add unnecessary variables (θ_i, d_i). Assign all joint z axis. Start with frame {1} to last frame. Frame {0} can be made in last and it will be same as joint 1 axis.

Step 2: The x_1- axis is set in the direction of perpendicular to plane containing z_1 and z_o axis. As z_o and z_1 coincide it can be placed in 2 ways:

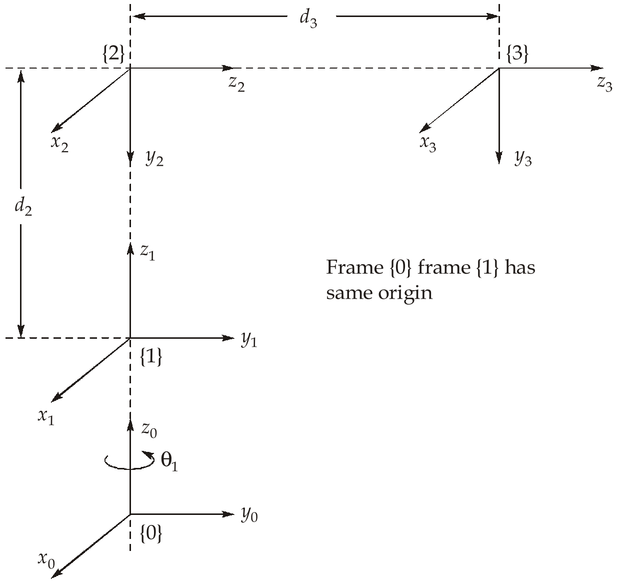


or



To remove this ambiguity, start with x_2. Similarly x_2 will be perpendicular to plane assigned. x_1 should be parallel to x_2 because it should not add extra joint angle (θ_i) (angle between x_{i-1} and x_i axis). x_3 can be made similar to x_2 because frame {3} is at the face plate for attaching wrist i.e. can be chosen arbitrary. Frame {0} and frame {n} containing x_2 and z_2. So, x_2 can be asigned. (last frame) is assigned in same way.

Step 3: The y-axis for all frame is fixed by right hand rule.



Frame {0} frame {1} has same origin

Joint-Link parameter table:

Link(i)	a_i	α_i	d_i	θ_i	q_i	$C\theta_i$	$S\theta_i$	$C\alpha_i$	$S\alpha_i$
1	0	0	0	θ_1	θ_1	C_1	S_1	1	0
2	0	–90	d_2	0	d_2	1	0	0	–1
3	0	0	d_3	0	d_3	1	0	1	0

Transformation matrices:

We know that

$$^{i-1}T_i = \begin{bmatrix} C\theta_i & -S\theta_i C\alpha_i & S\theta_i S\alpha_i & a_i C\alpha_i \\ S\theta_i & C\theta_i C\alpha_i & -C\theta_i S\alpha_i & a_i S\theta_i \\ 0 & S\alpha_i & C\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^0T_1 = \begin{bmatrix} C_1 & -S_1 & 0 & 0 \\ S_1 & C_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^1T_2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^2T_3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^0T_3 = {^0T_1}\,{^1T_2}\,{^2T_3} = \begin{bmatrix} C_1 & 0 & -S_1 & -d_3 S_1 \\ S_1 & 0 & C_1 & d_3 C_1 \\ 0 & -1 & 0 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

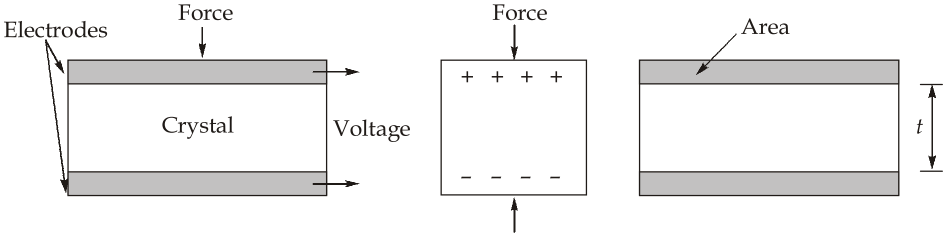
Q.4 (a) Solution:

(i)

Piezoelectric materials when stretched or compressed generate electric charges with one face of the material becoming positively charged and the opposite face negatively charged. As a result a voltage is produced. Piezoelectric material are ionic crystal, which when stretched or compressed result in charge distribution in the crystal. The net charge q on a surface is proportional to amount x by which the charges have been displaced and since the displacement is proportional to the applied force.

$$q = kx = SF$$

k is a constant and S is a constant termed as charge sensitivity.



Metal electrodes are deposited on opposite faces of the piezoelectric crystal. The capacitance C of the piezoelectric material between the plates.

$$C = \frac{\varepsilon_0 \varepsilon_r \times A}{t}$$

ε_r = relative permittivity

A = area

t = thickness

Charge $\quad q = CV$

So, $$V = \frac{S \times t \times F}{\varepsilon_0 \varepsilon_r \times A}$$

$$V = S_V \times t \times P \qquad \text{where, } S_V = \frac{S}{\varepsilon_0 \varepsilon_r}$$

S_V = Voltage sensitivity

(ii)

$$\text{Pressure, } P = \frac{F}{A} = \frac{6}{6 \times 6 \times 10^{-6}} = 0.167 \text{ MN/m}^2$$

$$\text{Voltage sensitivity, } S_V = \frac{S}{\varepsilon_0 \varepsilon_r} = \frac{S}{\varepsilon}$$

$$S_V = \frac{150\times10^{-12}}{12.5\times10^{-9}} = 0.012 \text{ Vm/N}$$

$$\text{Voltage generated, } E = S_V \times t \times P$$

$$= 0.012 \times 1.5 \times 10^{-3} \times 0.167 \times 10^{6}$$

$$E = 3\text{V}$$

$$\text{Charge, } Q = S \times F = 150 \times 10^{-12} \times 6 = 9 \times 10^{-10}\text{ C}$$

We know that $q = CV$

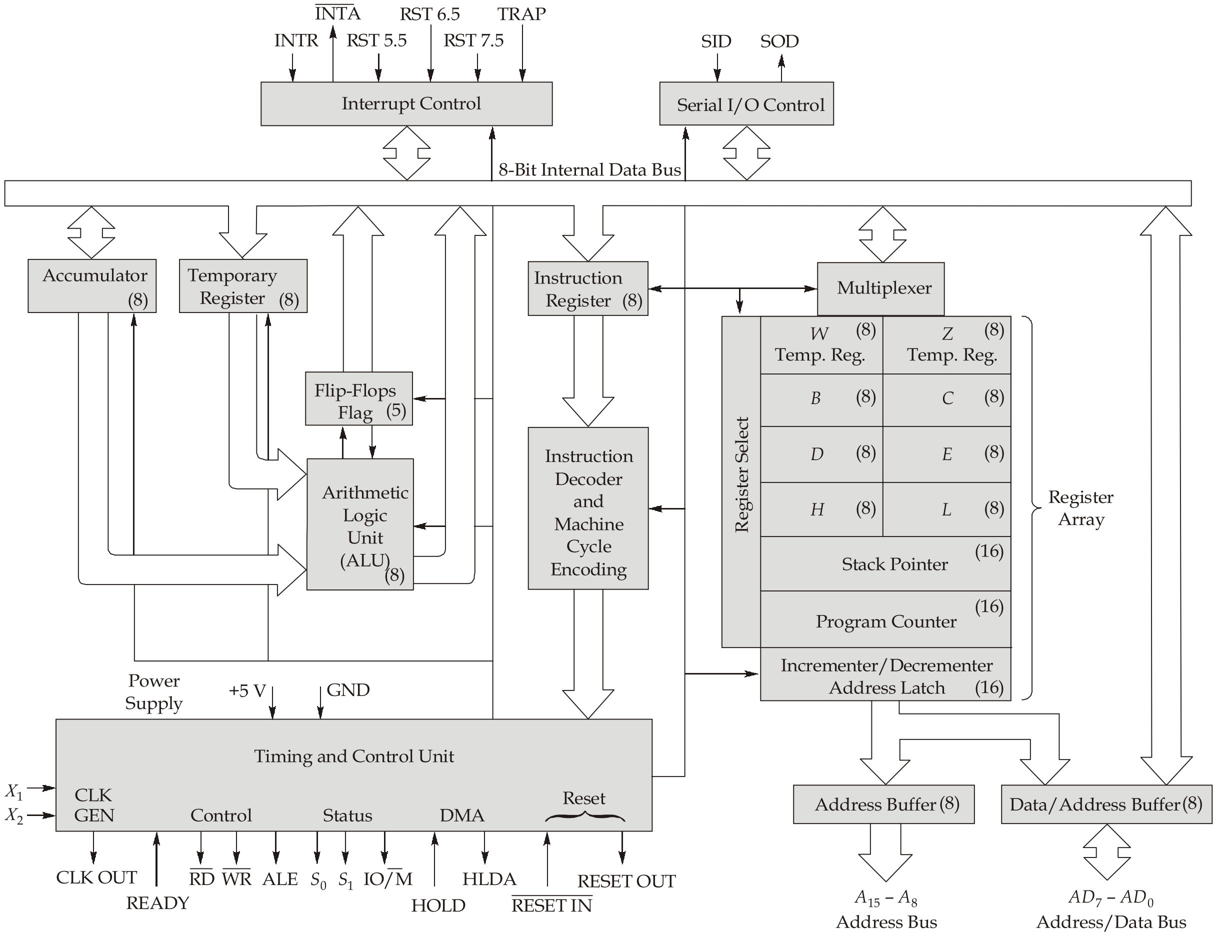
1. $$\text{Capacitance, } C = \frac{900\times10^{-12} F}{3} = 300 \text{ pF}$$

2. $$\text{strain} = \frac{\text{Stress (Pressure)}}{\text{Young modulus}} = \frac{0.167}{12} = 0.0139$$

Q.4 (b) Solution:

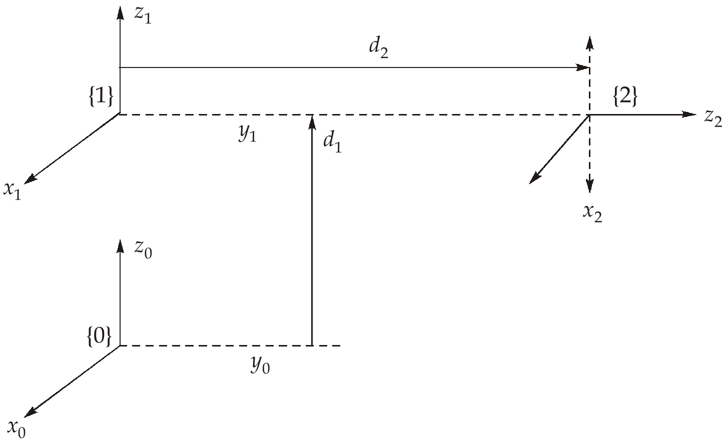
It is an 8 bit microprocessor i.e. It can accept process, or provide 8 bit data simultaneously.

- It operates on a single +5V power supply connected at V_{cc}, power supply ground is connected to V_{ss}.
- It operates on clock cycle with 50% duty cycle.
- It has a chip clock generator.
- It can operate with a 3 MHz clock frequency. The 8085 A-2 version can operate at the maximum frequency of 5 MHz.
- It has 16 address lines, hence it can access (2^{16}) 64 kbytes of memory.
- It provides 8 bit I/O addresses to access (2^8) 256 I/O ports.
- It has 8-bit accumulator, flag register, instruction, six 8 bit general purpose register (*B C D E H* and *L*) and two 16 bit registers. (SP and PC).
- It has serial I/O control which allows serial communication.
- It supports 74 instruction with the following addressing modes.
  (a) Immediate (b) Register (c) Direct (d) Indirect (e) Implied
- It has a mechanism by which it is possible to increase its interrupt handling capacity.



Q.4 (c) Solution:

In this manipulator, there are 2 prismatic joint.



Joint link parameter table:

Link(i)	a_i	α_i	d_i	θ_i	q_i	$C\theta_i$	$S\theta_i$	$C\alpha_i$	$S\alpha_i$
1	0	0	d_1	0	d_1	C_1	0	1	0
2	0	–90	d_2	0	d_2	1	0	0	–1

Transformation matrices:

We know that

$$^{i-1}T_i = \begin{bmatrix} C\theta_i & -S\theta_i C\alpha_i & S\theta_i S\alpha_i & a_i C\alpha_i \\ S\theta_i & C\theta_i C\alpha_i & -C\theta_i S\alpha_i & a_i S\theta_i \\ 0 & S\alpha_i & C\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{0}T_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{1}T_2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{0}T_2 = {}^{0}T_1 \times {}^{1}T_2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & d_1 + d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Section B : IC Engine, Renewable Sources of Energy-2+Industrial & Maintenance Engg.-2

Q.5 (a) Solution:

Let,
V_u = Upstream wind speed
V_d = Downstream wind speed
V = Wind speed passing through the rotor
A = Cross sectional area of rotor
ρ = Density of air
R = Radius of rotor
λ = Tip speed ratio

$$\omega = \text{Rotational speed of rotor}$$

$$\text{Axial thrust, } F_x = \dot{m}V_u - \dot{m}V_d$$

$$= \dot{m}(V_u - V_d) = \rho AV(V_u - V_d) \qquad \left\{\because V = \frac{V_u + V_d}{2}\right\}$$

$$= \frac{1}{2}\rho A(V_u + V_d)(V_u - V_d)$$

$$F_x = \frac{1}{2}\rho A\left(V_u^2 - V_d^2\right)$$

For maximum axial thrust, $V_d = 0$

$$(F_x)_{\max} = \frac{1}{2}\rho AV_u^2$$

We know that, Torque, $T = F_x \times R$

$$T_{\max} = (F_x)_{\max} \times R$$

$$T_{\max} = \frac{1}{2}\rho AV_u^2 \times R$$

$$T_{\max} = \frac{1}{2}\rho AV_u^2 \times \left(\frac{\lambda \times V_u}{\omega}\right) \qquad \left\{\because \lambda = \frac{U_{bt}}{V_u} = \frac{R\omega}{V_u}\right\}$$

$$T_{\max} = \frac{1}{2}\rho AV_u^3 \times \left(\frac{\lambda}{\omega}\right)$$

$$T_{\max} = (P_{\text{total}}) \times \left(\frac{\lambda}{\omega}\right)$$

We know that, Maximum power = $T \times \omega$

$$(C_p) \times P_{\text{total}} = C_T \times T_{\max} \times \omega$$

where C_p is power coefficient C_T is torque coefficient.

$$(C_p) \times P_{\text{total}} = C_T \times T_{\max} \times \omega$$

Where C_p is power coefficient C_T is torque coefficient.

$$(C_p) \times P_{\text{total}} = C_T \times P_{\text{total}} \times \left(\frac{\lambda}{\omega}\right) \times \omega$$

$$C_p = C_T \times \lambda$$

$$\text{Torque coefficient, } C_T = \frac{C_p}{\lambda}$$

$$\text{Maximum torque coefficient, } (C_T)_{\max} = \frac{(C_p)_{\max}}{\lambda}$$

$$(C_T)_{\max} = \frac{0.593}{\lambda}$$

We know that maximum possible value of power coefficient is 0.593 (i.e. Betz limit).

Numerical: Given, $R = \frac{50}{2} = 25$ m, $N = 40$ rpm

$$\omega = \frac{2\pi N}{60} = \frac{2\pi \times 40}{60} = 4.1888 \text{ rad/s}$$

$$V_u = 30 \text{ m/s}$$

$$\text{Tip speed ratio, } \lambda = \frac{R\omega}{V_u} = \frac{25 \times 4.1888}{30} = 3.49$$

$$\text{Maximum torque coefficient, } (C_T)_{\max} = \frac{0.593}{\lambda} = \frac{0.593}{3.49} = 0.17$$

$$(C_T)_{\max} = 0.17$$

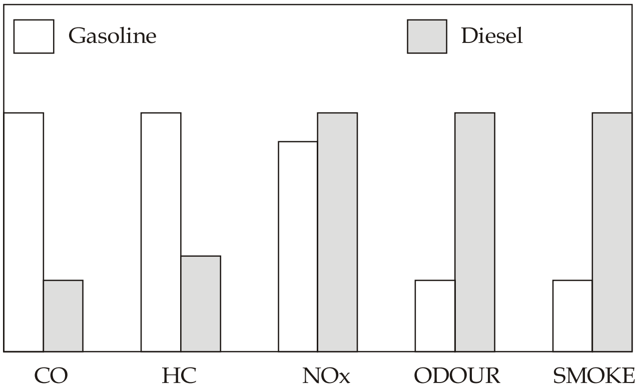
Q.5 (b) Solution:

Comparison of diesel and gasoline emissions: There is a marked difference between the products of combustion of diesel and petrol engines. Although the exhaust emission is the result of incomplete combustion in both, the nature of combustion, fuel and the design are markedly different.

Differences in combustion chamber designs and fuel control systems of petrol engines are generally smaller than those found in diesel engines. Thus petrol engines are generally smaller than those found in diesel engines. Thus petrol engines have a somewhat similar emission pattern; they react in the same manner to changes in operating variables, while the wide variation in diesel engine combustion system designs preclude any possibility of a representative emission pattern. So all diesel engines have different emission characteristics. The combustion in a diesel engine occurs over a wide range of fuel-air ratios ranging from very lean mixture to very rich mixture while the gasoline combustion is of a relatively homogeneous mixture. These variations are further increased by the different control system of the two types of engines. Petrol engines are controlled by throttling and it keeps fairly constant fuel-air ratio while the diesel engines have large amount of excess air most of the time as it is controlled by changing fuel quantity. This results in considerable dilution of products of combustion. All these differences in design and operating principles make it quite difficult to compare the two types of engine. A correction factor given by

$$\text{Correction factor} = \frac{15}{\%CO_2 + \%CO + \%C}$$

is applied to enable comparison of the two engine types. The diesel engines, if properly maintained, have very little CO in their exhaust and a small amount of smoke, while the petrol engine exhausts significant amount of CO and UBHC. So diesel engine is cleaner as compared to petrol engine and pollutes less. However, this fact is generally not noted because a small increase in smoke becomes highly visible while CO and UBHC cannot be noticed so easily.



Comparison of emissions and odour from petrol and diesel engine

Q.5 (c) Solution:

Fuel cells on the basis of electrolyte:

1. Phosphoric acid fuel cell (PAFC)
2. Alkaline fuel cell (AFC)
3. Proton exchange membrane fuel cell or polymer electrolytic membrane fuel cell or solid polymer fuel cell.
4. Molten carbonate fuel cell (MCFC)
5. Solid oxide fuel cell (SOFC)

Molten carbonate fuel cell (MCFC): In MCFC, carbonates of alkali metals (Na, K or Li) in molten (liquid) phase is used as electrolyte. This requires the cell operation at a temperature above melting points (i.e., about 600°C – 700°C) of the respective carbonates. Because of high temperature of operation, a catalyst is not necessary. Porous nickel is used for electrodes and the electrolyte is held in sponge-like ceramic matrix.

A special feature of these cells is that during operation they oxidize hydrogen to water and carbon monoxide (present in fuel) to carbon dioxide. Hence gaseous mixtures of hydrogen and carbon monoxide (synthesis gas), which are relatively inexpensive to manufacture can also be used. This feature offers the prospects for use of a variety of fossil fuels including coal (gasified). These fuels are first converted to get H_2 and CO and desulfurized to prevent poisoning of electrodes. The theoretical value of emf at no load is approximately 1 volt at 700°C. However, actual voltage at load is lower (about 0.8 Volt).

The discharge mainly consisting of steam, CO_2 and N_2 from spent oxidant (air) are at a temperature exceeding 540°C. These hot gases can be used to supply industrial process heat or to generate additional power employing waste heat boilers and steam turbines. Because of this fuel overall efficiency increases.

The working of MCFC is explained with the help of a diagram shown in figure. At the fuel electrode H_2 and CO react with CO_3^{--} ions present in the electrolyte and release two electrons each to the electrode as given below:

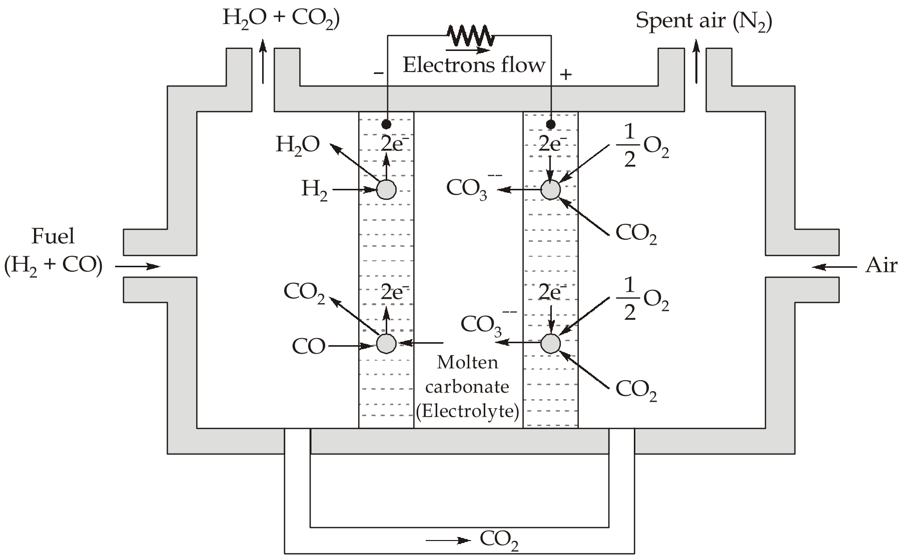
$$H_2 + CO_3^{--} \rightarrow H_2O + CO_2 + 2e^-$$
$$CO + CO_3^{--} \rightarrow 2CO_2 + 2e^-$$

These electrons circulate through external resistance, forming load current, and reach the oxidant electrode. The CO_2 produced at the fuel electrode is circulated through an external path to the oxidant electrode, where it combines with O_2 and the returning electron through the external path to produce CO_3^{--}.

$$O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^{--}$$

The CO_3^{--} ions thus produced are responsible for transposition of charge from positive to negative electrode within the electrolyte. The overall reaction may be written as:

$$H_2 + CO + O_2 \rightarrow H_2O + CO_2$$



Molten carbonate fuel cell

Q.5 (d) Solution:

$$p_{im} = \frac{\text{Area of the diagram}}{\text{Lenght of the diagram}} \times \text{Spring const.}$$

$$= \frac{8.5}{8.5} \times 5.5 = 5.5 \text{ bar}$$

$$ip = \frac{p_{im}LAn}{60000} = \frac{5.5\times10^5\times0.45\times\frac{\pi}{4}\times0.3^2\times\frac{200}{2}}{60000}$$

$$= 29.16 \text{ kW}$$

$$bp = \frac{2\pi NWR}{60000} = \frac{\pi NWd}{60000}$$

$$= \frac{\pi\times200\times(150-20)\times9.81\times1.5}{60000} = 20.03 \text{ kW}$$

$$\eta_m = \frac{20.03}{29.16}\times100 = 68.75$$

$$\dot{m}_f = \frac{4}{30}\times60\times10^{-3}\times800 = 6.4 \text{ kg/h}$$

$$bsfc = \frac{6.4}{20.03} = 0.3195 \text{ kg/kWh}$$

$$\eta_{ith} = \frac{ip}{\dot{m}_f\times CV} = \frac{29.16\times3600}{6.4\times43000}\times100 = 38.14\%$$

Q.5 (e) Solution:

Given (1): Time, $t = 5000$ hour

Reliability, $R = 0.9$

Availability, $A = 0.97$

We know that, Reliability is exponential function of time.

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

$$0.9 = e^{-\lambda\times500}$$

$$0.9 = e^{-5000\lambda}$$

$$\ln 0.9 = -5000\lambda$$

Failure rate, $\lambda = 2.1072\times10^{-5}$ per hour

Mean time between failure, $\text{MTBF} = \frac{1}{\lambda} = \frac{1}{2.1072\times10^{-5}} = 47456.34$ hour

We know that, Availability, $A = \frac{MTBF}{MTBF+MTTR}$

$$0.97 = \frac{47456.34}{47456.34+MTTR}$$

$$0.97(\text{MTTR}) = 47456.34 - 0.97 \times 47456.34$$

$$\text{MTTR} = 1467.722 \text{ hour}$$

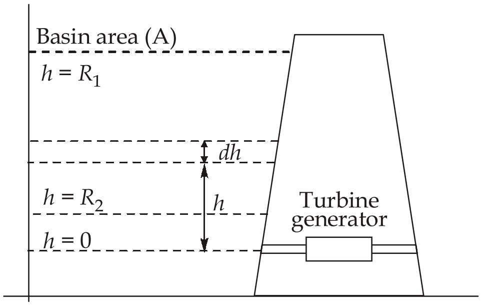
2. Reliability that machine will run for 9000 hour,

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

$$R(9000) = e^{-2.1072 \times 10^{-5} \times 9000} = 0.82725 = 82.725\%$$

Q.6 (a) Solution:

Tidal range (amplitude) 'R_1' and certain head 'h' at given-time during the flow from ocean to basin, the differential work done (dW) is equal to change in potential energy.



$$dW = (dm)gh$$

$$dm = -\rho A dh$$

$$dW = (-\rho A dh)gh$$

$$W_{\text{emp.}} = -\int_{R_1}^{R_2} (\rho A g h)\, dh = -\rho A g \left[\frac{h^2}{2}\right]_{R_1}^{R_2} = \rho A g \left[\frac{R_1^2 - R_2^2}{2}\right]$$

$$W_{\text{emp.}} = \frac{1}{2}\rho A g \left(R_1^2 - R_2^2\right) \text{Joule}$$

The duration of time for emptying the basin is 6 hours and 12.5 minutes (i.e. 22350 second), this is the time between consecutive high and low tides which is to be utilised during power generation.

$$\text{Average power, } P = \frac{\rho A g\left(R_1^2 - R_2^2\right)}{2 \times 22350}$$

Basin area, $A = 3 \text{ km}^2 = 3 \times 10^6 \text{ m}^2$

Density of sea water, $\rho = 1025 \text{ kg/m}^3$

$R_1 = 13$ m

$R_2 = 3$ m

Efficiency of turbine generator, $\eta = 0.7$

$g = 9.81 \text{ m/s}^2$

$$\text{Average power potential} = \frac{1 \times 3 \times 10^6}{2 \times 22350} \times 1025 \times 9.81\left(13^2 - 3^2\right)$$

$$= 107.976 \times 10^6 \text{ Watt} = 107.976 \text{ MW}$$

Average power generated in single emptying process, $P_{gen} = 107.976 \times 0.7$

$= 75.5832$ MW

$$\text{Energy available in single emptying} = \frac{1}{2}\rho Ag\left(R_1^2 - R_2^2\right) = \frac{1}{2}\times 1025\times 3\times 10^6\times 9.81\times\left(13^2 - 3^2\right)$$

$= 2413260 \times 10^6$ Joule

$= 2413.260 \times 10^9$ Joule

One ebb cycle duration = 12 hour 25 minutes

$$\text{Number of ebb cycles in a year} = \frac{365\times 24\times 3600}{(12\times 3600 + 25\times 60)}$$

$= 705.50 \simeq 706$ Cycles per year

Annual energy generation $= (2413.260 \times 10^9 \times 706) \times \eta$

$= (2413.260 \times 706 \times 0.7) \times 10^9$ Joule

$= (1192633.092)$ GJ $\qquad \left(\because 1\,\text{kWh} = \left(\frac{1}{3600}\right)\text{kJ}\right)$

$= 1192633.092 \times 10^6$ kJ

$$\text{Annual energy generation} = \left(\frac{1192633.092\times 10^6}{3600}\right)\text{kWh} = 3.31287 \times 10^8 \text{ kWh}$$

Q.6 (b) Solution:

FMECA: FMECA stands for "Failure Modes, Effects and Criticality Analysis". It is a methodology used for indentifying and analysing:

1. All potential failure modes of the various parts of the system.
2. The effect these failures may have on the system.
3. How to avoid these failures, and /or mitigate the effects of these failures on the system.

FMECA can be used for:

1. Assistance in selection of design alternatives with high reliability.
2. To ensure that all conceivable failure modes and their effects on operational success of the system have been considered.
3. List the potential failures and identify the severity of their effects.
4. To develop early criteria for test planning and test equipment requirement.
5. Provide historical documentation for future reference.
6. Provide a basis for maintenance planning. (Preventive, predictive, breakdown).
7. Provide a basis for quantitative reliability and availability analysis.

When to perform FMECA: The FMECA should be initiated early in the design process, where we are able to have the greatest impact on the equipment reliability.

Types of FMECA:

1. **Design FMECA**: It is carried out to eliminate failures during equipment design, taking into account all type of failures during the whole life span of the equipment.
2. **Process FMECA**: It is focused on problems stemming from how the equipment is manufactured, maintained or operated.
3. **System FMECA**: It looks for potential problems and bottlenecks in bigger processes, such as entire production lines.

Main steps of FMECA:

1. **Step I**: FMECA pre-requisites.
2. **Step II**: System structure analysis.
3. **Step III**: Failure analysis and preparation of FMECA worksheets.
4. **Step IV**: Team review.
5. **Step V**: Corrective actions.

Q.6 (c) Solution:

The stoichiometric equation can be written as

$$C_8H_{18} + x\left(O_2 + \frac{79}{21}N_2\right) \to aCO_2 + bH_2O + cN_2$$

Balancing moles both sides, we get

$$a = 8, b = 9$$

and $$2a + b = 2x$$

$\Rightarrow$ $$x = 12.5$$

and $$c = x \times \frac{79}{21} = 47$$

$$C_8H_{18} + 12.5\left(O_2 + \frac{79}{21}N_2\right) \to 8CO_2 + 9H_2O + 47N_2$$

$$\text{Stoichiometric A/f ratio} = \frac{12.5\left\{32 + \frac{79}{21} \times 28\right\}}{12 \times 8 + 1 \times 18} = 15.06$$

With the given air/fuel ratio as 14.5 : 1, the mixture is rich in fuel. The combustion will be incomplete.

The chemical equation becomes:

$$C_8H_{18} + Y\left(O_2 + \frac{79}{21}N_2\right) \rightarrow xCO + (8 - x)CO_2 + 9H_2O + Y \times \frac{79}{21}N_2$$

$$\frac{\text{air}}{\text{fuel}} = \frac{Y\left(O_2 + \frac{79}{21} \times 28\right)}{12 \times 8 + 1 \times 18} = 14.5$$

$$Y = 12.04$$

By oxygen balance: $Y = \frac{x}{2} + (8 - x) + \frac{9}{2}$

$$x = 0.92$$

The chemical equation now becomes:

$$C_8H_{18} + 12.04\left(O_2 + \frac{79}{21}N_2\right) \rightarrow 0.92CO + 7.08CO_2 + 9H_2O + 45.29\ N_2$$

Number of moles before combustion = $1 + 12.04\left(1 + \frac{79}{21}\right) = 58.33$

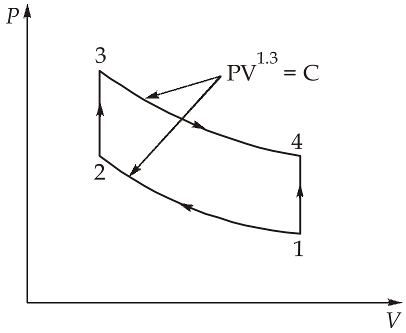
Number of moles after combustion = 0.92 + 7.0 + 9 + 45.29 = 62.29

$$\text{Molecular expansion} = \frac{62.29 - 58.33}{58.33} \times 100 = 6.789\%$$

1. Without considering molecular expansion

$$P_1 = 1 \text{ bar}, T_1 = 333 \text{ K}, n = 1.3$$

$$\frac{T_2}{T_1} = (r)^{n-1}$$



$$T_2 = 333 \times (8)^{0.3} = 621.4K$$

$$q_{2-3} = mc_v(T_3 - T_2)$$

$$m_f(CV) = (m_f + m_a)\, c_v(T_3 - T_2)$$

$$CV = \left(1+\frac{m_a}{m_f}\right)c_v(T_3-T_2)$$

$$44000 = (15.5) \times 0.71 \times (T_3 - 621.4)$$

$$T_3 = 4619.58\,\text{K}$$

$$\frac{P_1V_1}{T_1} = \frac{P_3V_3}{T_3}$$

$$P_3 = \frac{P_1V_1}{T_1}\times\frac{T_3}{V_3} = 8\times\frac{4619.58}{333} = 110.98\text{ bar}$$

Since the mass of reactants and products is the same and specific heats are assumed same, the temperature of the products with molecular expansion will remain the same as without molecular expansion,
only the pressure will change.

$\therefore$ $$T_3 = 4619.58\text{ K}$$

$$PV = n\bar{R}T$$

$$P \propto n$$

$$\frac{P_3'}{P_3} = \frac{n'}{n}$$

where n is the number of moles of product without molecular expansion and n' is the number of moles of products with molecular expansion.

$\therefore$ $$P_3' = P_3\times\frac{n'}{n} = 110.98\times\frac{62.29}{58.33} = 118.51\text{ bar}$$

Q.7 (a) Solution:

The word gasification (or thermal gasification) implies converting solid fuel into a gaseous fuel by thermochemical method without leaving any solid carbonaceous residue.

Gasification involves partial combustion (oxidation in restricted quantity of air/oxidant) and reduction operations of biomass. In a typical combustion process, generally the oxygen is surplus, while in a gasification process, the fuel is surplus. The combustion products, mainly carbon dioxide, water vapour, nitrogen, carbon monoxide and hydrogen pass through the glowing layer of charcoal for the reduction process to occur. During this stage, both carbon dioxide and water vapour, oxidize the char to form CO, H_2 and CH_4. The following are the typical reactions, which occur during gasification.

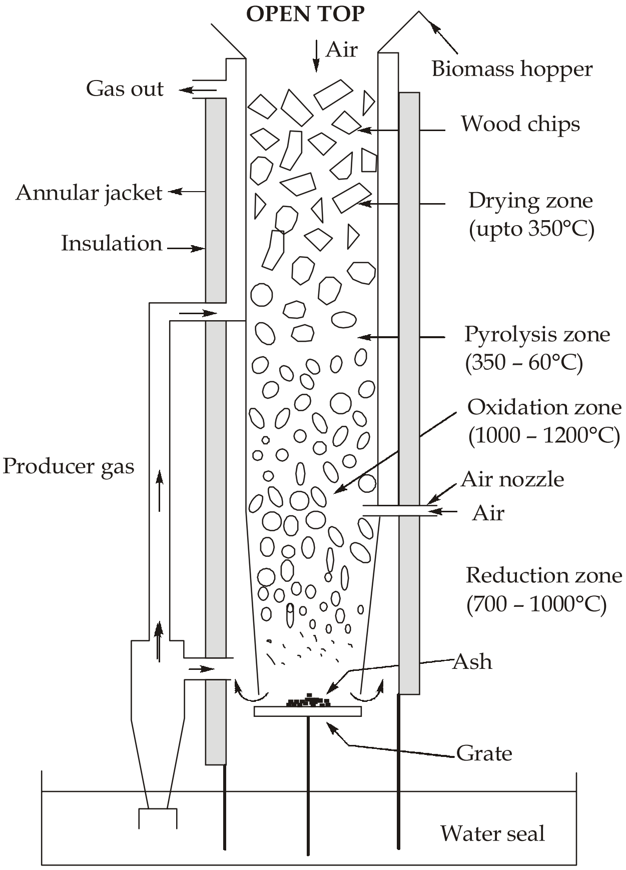
$$C + O_2 \rightarrow CO_2 \qquad \text{(Combustion, 240 kJ/mole)}$$

The moisture available in the biomass is converted to steam and generally no extra moisture is required. Thus the product of combustion of pyrolysis gases results in CO_2 and H_2O and H_2O (steam), which further react with char:

$$C + O_2 \rightarrow 2CO \quad \text{(Boudouard reaction, – 164.9 kJ/mole)}$$
$$C + H_2O \rightarrow CO + H_2 \quad \text{(Water gas reaction – 122.6 kJ/mole)}$$
$$CO + H_2O \rightarrow CO_2 + H_2 \quad \text{(Water shift reaction, 40.2 kJ/mole)}$$
$$C + 2H_2 \rightarrow CH_4 \quad \text{(Methane reaction, 83.3 kJ/mole)}$$

The output gas is known as producer gas, a mixture of H_2(15 – 20%), CO(10 – 20%), CH_4(1 – 5%), CO_2(9 – 12%) and N_2(45 – 55%).

Downdraft type gasifier : The downdraft type is best suited for a variety of biomass. Its design forces the raw products to pass through a high-temperature zone so that most of the unburnt pyrolysis products (especially tars) can be cracked into gaseous hydrocarbons, thus producing a relatively clean gas.



Downdraft biomass gasification plant

In steady-state operation, heat from the combustion zone, near the air nozzle is transferred upwards by radiation, conduction and convection causing wood chips to pyrolyse and lose 70-80% of their weight. These pyrolysed gases burn with air to form CO, CO_2, H_2 and H_2O, thereby raising the temperature to 1000-1200°C. The product gases from the combustion zone further undergo reduction reaction with char to generate combustible products like CO, H_2 and CH_4. Generally about 40-70% air is drawn through the open top depending on the pressure drop conditions due to the size of wood chips and gas-flow rate. This flow of air opposite to the flame front helps in maintaining homogeneous air/gas flow across the bed. Combining the open top with the air nozzle towards the bottom of the reactor helps in stabilizing the combustion zone by consuming the uncovered char left and also by preventing the movement of the flame front to the top.

As a consequence, the high-temperature zone spreads above the air nozzle by radiation and conduction, aided by air flow from the top. The tar thus is eliminated in the best possible way by creating a high-temperature oxidizing atmosphere in the reactor itself. The gas produced is withdrawn from an exit at the bottom and reintroduced in the annular jacket for heat recovery. The hot gas which enters the annular jacket around 500°C, transfers some heat to the wood chips inside, improving the thermal efficiency of the system in addition to drying the wood in this zone. The inner wall temperature reaches more than 350°C after a few hours of operation. This aspect enables the use of wood chips with moisture content as high as 25%. The regenerative heating due to the transfer of heat from hot gas to the biomass moving downwards also increases its residence time in the high temperature zone. This leads to better tar cracking.

Q.7 (b) Solution:

Condition based maintenance: It is also known as predictive maintenance. It is a philosophy that uses the actual operating condition of plant equipment and systems to optimize total plant operation. When the machine is running, it gives us certain signal, which convey the present condition of the machine. Signals are analyzed using real time data to prioritize and optimize maintenance resources. In this way, we take care of system's health and maintenance is carried out only when need arises.

A signal may be in any form such as visual, tactile, electrical, vibration and sound etc.

Classification of CBM:

1. On-load monitoring techniques: It refers to monitoring techniques performed during operation of a system.

i. Visual inspection of accessible component.

ii. Vibration monitoring.

iii. Noise monitoring.

iv. Motor current signature analysis.

2. Off-load Monitoring techniques: It refers to monitoring techniques performed during non-operational period of a system.

i. Wear Debris analysis

ii. Visual inspection of inaccessible or moving parts.

iii. Crack detection.

iv. Leak detection.

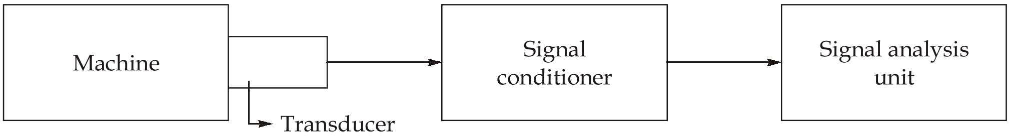
Techniques used for CBM:

1. Vibration monitoring
2. Noise monitoring
3. Wear Debris Analysis
4. Oil analysis
5. Motor current signature analysis
6. Thermography
7. NDT techniques

Benefits of CBM:

1. Reduced maintenance cost
2. Improved system reliability
3. Intervention based on forewarning
4. Continuous availability of machine
5. Maintenance can be planned on holidays (Undisturbed production)
6. Longer machine life
7. Reduced small part inventory
8. Improved operator safety

Essential elements of CBM:



Good CBM system should have:

1. User friendly hardware and software
2. Automated data acquisition
3. Automated data management and trading
4. Flexibility
5. Reliability
6. Accuracy

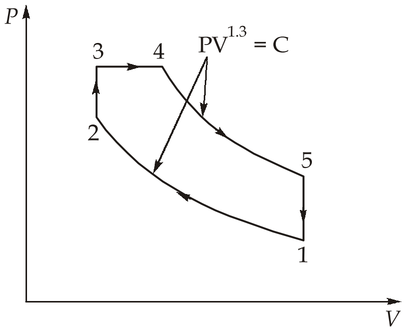
Q.7 (c) Solution:

$$\frac{V_s}{V_c} = r - 1 = 7$$

$$V_s = 7\,V_c$$

We know $$r = \alpha(r_{\text{exp}})$$

So explosion ratio, $$\alpha = \frac{r}{r_{\text{exp}}} = \frac{8}{5.3} = 1.509$$



$$V_2 = V_3 = V_c$$

$$V_1 = V_5 = rV_c = 8\,V_c$$

$$V_4 = \alpha V_3 = 1.509\,V_c$$

$$\frac{T_2}{T_1} = (r)^{n-1} = 8^{0.3} = 1.866$$

$$T_2 = 1.866 \times 300 = 559.82\text{K}$$

$$\frac{P_2}{P_1} = r^n = 8^{1.3} = 14.93$$

$$P_2 = 14.93 \times P_1 = 14.93 \text{ bar}$$

Heat released during constant pressure combustion = 2 × heat released during constant volume combustion.

$$c_p(T_4 - T_3) = 2c_v(T_3 - T_2)$$

$$1.004(T_4 - T_3) = 2 \times 0.717 \times (T_3 - T_2)$$

$$\frac{T_4}{T_3} = \frac{V_4}{V_3} = \alpha = 1.509$$

$$T_4 = 1.509T_3$$

$$1.509T_3 - T_3 = 1.428 \times (T_3 - 559.82)$$

$$T_3 = 869.88\,\text{K}$$

$$T_4 = 1312.65\,\text{K}$$

$$\frac{P_3}{P_2} = \frac{T_3}{T_2} = \frac{869.88}{559.82} = 1.554$$

$$P_3 = 1.554 \times 14.93 = 23.2\text{ bar}$$

$$\frac{T_4}{T_5} = (r_{\text{exp}})^{(n-1)} = (5.3)^{0.3} = 1.649$$

$$T_5 = \frac{1312.65}{1.649} - 796.03\,\text{K}$$

$$\frac{P_4}{P_5} = (r_{\text{exp}})^{n} = (5.3)^{1.3} = 8.741$$

$$P_5 = \frac{P_4}{8.741} = \frac{23.2}{8.741} = 2.654\text{ bar}$$

$$\text{Mean effective pressure} = \frac{\text{Area (12345)}}{V_s}$$

Area(12345) = Area under 3-4 + Area under 4-5 – Area under 1-2

$$= P_3(V_4 - V_3) + \frac{P_4V_4 - P_5V_5}{n-1} - \frac{P_2V_2 - P_1V_1}{n-1}$$

$$= \left[23.2\times(1.509V_c - V_c) + \frac{23.2\times1.509V_c - 2.654\times8V_c}{0.3} - \frac{14.93V_c - 1\times8V_c}{0.3}\right]\times10^5$$

$$= 34.63\,V_c \times 10^5\text{ N/m}^2$$

$$V_c = \frac{V_1}{8}$$

$$\text{Area (12345)} = P_m \times V_s = P_m \times 7 \times V_c$$

$$P_m = \frac{34.63\times V_c\times10^5}{7V_c} = 4.95\times10^5\text{ N/m}^2 = 4.95\text{ bar}$$

Efficiency, $$\eta = \frac{\text{Work}}{\text{Heat supplied}}$$

$$V_1 = \frac{mRT_1}{P_1} = \frac{1\times287\times300}{1\times10^5} = 0.861\text{ m}^3$$

$$w = 34.63 \times 10^5 \times V_c = 34.63 \times 10^5 \times \frac{0.861}{8}$$

$$w = 3.727 \times 10^5 \text{ J/kg} = 372.7 \text{ kJ/kg}$$

$$\text{Heat supplied} = c_v(T_3 - T_2) + c_p(T_4 - T_3)$$

$$= 0.717(869.88 - 559.82) + 1.004(1312.65 - 869.88) = 667 \text{ kJ/kg}$$

$$\eta = \frac{372.7}{667} \times 100 = 55.877\%$$

Q.8 (a) Solution:

Wear debris analysis is the analysis of two things.

1. **Wear particles (contaminants) get deposited in the oil**: Concentration of wear particle, nature of the wear particles and the rate at which it is deposited in the oil gives us some clue about machine condtion.
2. **Oil undergo change in its physical and chemical properties**: The properties of virgin oil will get change when machine is running.

- Unlike in vibration monitoring and noise monitoring, in wear debris analysis, you have to collect the oil in which contaminant is there and given this sample to the lab for analysis. In wear debris analysis In-situ analysis is not possible.
- Quality and quantity of wear metals allows to set alarm level.
- Knowledge of metallurgical composition is helpful in localizing source of wear metal production.

Wear debris characteristics:

1. Quantity (it tells about the severity of machine component).
2. Size of the particle.
3. Morphology (shape/structure).
4. Composition (It tells about the source i.e. parent material from where wear takes place).

If lets of silica/sand grain is found in contaminants, it means that let of foreign dirt has gone into the machine.

Wear Mechanism:

1. Abrasive wear
2. Adhesive wear
3. Diffusion wear
4. Oxidation/corrosion

Wear mode:

1. Running in (during infant mortality zone of bathtub curve).
2. Steady wear (during the useful life of machine).
3. Wear out (towards the end of the life of the machine).
4. Pitting (it is the surface failure of a material as a result of stresses that exceed the endurance limit of the material).
5. Scuffing (due to insufficient lubrication between the mating part).

Wear Debris analysis method:

1. Ferrography:

i. Analytical ferrography

ii. Direct reading ferrography

2. Spectrophotometric technique:

i. Atomic absorption spectroscopy (AAS)

ii. Atomic emission spectroscopy (AES)

iii. X-ray fluorescence (XRF)

iv. Inductively coupled plasma (ICP)

v. Direct current plasma (DCP)

vi. Energy dispersive x-ray analysis(EDX)

Q.8 (b) Solution:

$$BP = 180 \text{ kW}; \; bsfc = 0.2 \text{ kg/kWh}$$

$$\text{mass of fuel supplied} = 0.2 \times 180 = 36 \text{ kg/h}$$

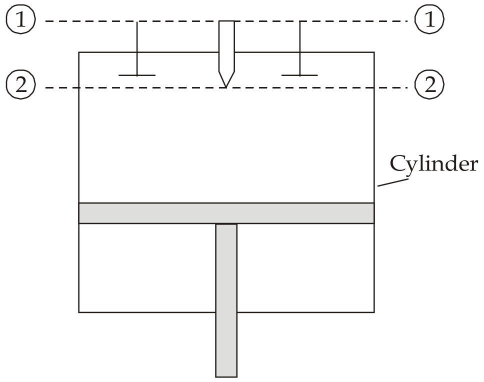
mass of fuel supplied per cylinder and per cycle is,

$$m_f = \frac{\left(\frac{36}{4}\right)\frac{1}{60}\text{kg/min}}{\left(\frac{N}{2}\right)\text{cycles/min}} = \frac{0.3}{N} \text{ kg/cycle}$$

Average injection pressure difference,

$$\Delta P = \frac{(P_{\text{inj}} - P_{\text{cyl}})_{\text{beginning}} + (P_{\text{inj}} - P_{\text{cyl}})_{\text{maximum}}}{2}$$

$$\Delta P = \frac{(200-30)+(500-50)}{2} = 310 \text{ bar}$$



Using Bernoulli's equation between 1 and 2

$$\frac{P_1}{\rho g}+\frac{V_1^2}{2}+z_1 = \frac{P_2}{\rho g}+\frac{V_2^2}{2g}+z_2$$

$$z_1 \simeq z_2$$

V_1 is neglected because V_2 is very high with respect to V_2.

$$\frac{P_1}{\rho g} = \frac{P_2}{\rho g}+\frac{V_2^2}{2g}$$

$$\text{Theoretical velocity, } V_2 = \sqrt{\frac{2(P_1-P_2)}{\rho}} = \sqrt{2\left(\frac{\Delta P}{\rho}\right)}\text{m/s}$$

$$\text{Actual velocity, } V_a = C_d\sqrt{2\frac{\Delta P}{\rho}}\ \text{m/s}$$

$$V_a = 0.75\times\sqrt{\frac{2\times310\times10^5}{900}} = 196.85\ \text{m/s}$$

Given: injection takes place over 15° crank angles.

$$\text{Time for injection, } t = \frac{15^\circ\times\frac{\pi}{180^\circ}}{\frac{2\pi N}{60}} = \frac{2.5}{N}\ \text{sec}$$

From mass balance,

Mass of fuel injected = mass of fuel entering one cylinder in a cycle

$$(\rho AV)\times t = \frac{0.3}{N}$$

$$900 \times A \times 196.85 \times \frac{2.5}{N} = \frac{3.5}{N}$$

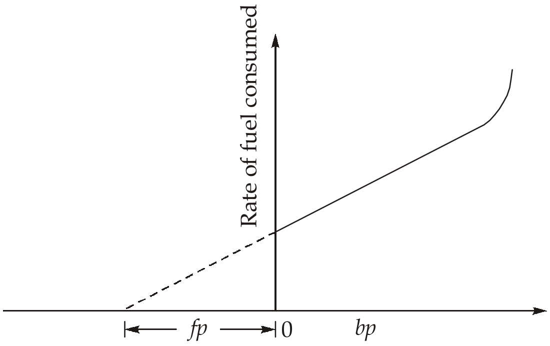
$$A = 6.7733 \times 10^{-7}\ \text{m}^2$$

$$\frac{\pi}{4} d_i^2 = 6.7733 \times 10^{-7}$$

dia. of orifice, $d_i = 0.928$ mm

Q.8 (c) Solution:

Willan's Line Method: This is method of determining the friction power and hence the indicated power ($ip = bp + fp$) of an unthrottled compression ignition engine. This method is not suitable for use with petrol engines. It is based on the fact that at light loads a relatively small amount of fuel is pumped into the air charge. Hence, there is plenty of air available for complete combustion within the engine cylinder. Therefore, at a given engines speed in the light load region, a straight line law exists between the rate at which fuel is consumed and the engine load or brake power. This straight line is Willan's line and is shown in figure. By extrapolation, the fuel flow rate to given zero brake power can be determined. This is the fuel flow rate necessary to overcome friction and consequently, the amount of negative brake power at zero rate of fuel consumption represents the friction power. From this, the indicated power and mechanical efficiency can be evaluated.



The rapid increase in slope of the line at the high load end denotes a progressive reduction in combustion efficiency as more and more fuel is pumped into the given volume of air. It is therefore important that the extrapolation of Willan's line is carried out as accurately as possible and that sufficient readings at light load are taken to define the line.

Since a petrol engine is throttled to maintain a high fuel/air ratio with load, combustion is not complete within the cylinder and a plot of brake power versus the rate of fuel consumption does not yield a straight line. Hence extrapolation is virtually impossible.

The morse test: This method is applicable to reciprocating multi-cylinder engines. The engine is run at a particular speed and the torque is measured by cutting out the firing of each cylinder in turn and noting the fall in the brake power each time, while maintaining the set engine speed by reducing load. The observed difference in brake power between all cylinders firing and with one cylinder cut out is the indicated power of the cut-out cylinder.

If there are *k* cylinders and all are firing.

$$ip = bp + fp$$

or

$$\sum_{i=1}^{k} ip_i = \sum_{i=1}^{k} bp_i + \sum_{i=1}^{k} fp_i \qquad \text{...(i)}$$

With the first cylinder cut out, it will not produce ip and theoretically there will be no contribution to bp from the first cylinder. However, there will be almost the same *fp*.

$$\sum_{i=2}^{k} bp_i = \sum_{i=2}^{k} bp_i + \sum_{i=1}^{k} fp_i \qquad \text{...(ii)}$$

Subtracting eq. (ii) from eq.(i) yields the ip of the first cylinder, i.e.

$$ip_1 = \sum_{i=1}^{k} ip_i - \sum_{i=2}^{k} ip_i = \sum_{i=1}^{k} bp_i - \sum_{i=2}^{k} bp_i \qquad \text{...(iii)}$$

Thus, the ip of each cylinder in turn can be obtained, and hence the sum of these values will give the ip of the engine with all k cylinders firing.

$$ip = ip_1 + ip_2 + ... + ip_k \qquad \text{...(iv)}$$

It is assumed that the friction power remains constant and has the same value in both eq. (i) and (ii). Strictly, this cannot be true. The temperature and pressure of the cut-out cylinder will be low. A reduced temperature will cause an increase in viscous drag on the piston, however a reduced pressure will reduce the frictional force on bearings and piston rings. These two effects tend to cancel out, but cannot do so exactly.

A petrol engine cylinder can be cut out by placed between its or a special high tension switch can be used. With CI engines, it may be possible to hold the fuel pump plunger off its cam with a suitable tool, so as to prevent fuel delivery to a particular cylinder.

Motoring test: In the motoring test the engine is first run at a given speed and load conditions for sufficient time so that the temperature of the engine components, lubricating oil and cooling water reaches a steady state. A swinging field type electric dynamometer is used to absorb the power during this period. The ignition is then switched off and by suitable electric switching devices the dynamometer is converted to run as a motor. The motoring is done to crank the engine at the same speed at which it was operating previously. The test is conducted as rapidly as possible. The torque is measured under firing and under motoring conditions from which the bp and fp are evaluated. Then the ip and mechanical efficiency are determined.

The friction power determined by this method is reasonably good, but not very accurate. Although the coolant temperature will change little during changeover, the piston and cylinder wall temperature of the working parts within the engine is low, and it is temperature of the working parts which affects the viscous drag and hence the friction power. Also in absence of the exhaust blow-down, the pumping losses are not representative.

The motoring method is suitable for assessing the relative contribution to the friction power of the many moving parts within an engine. Components such as piston rings, valve gear, the camshaft and all accessories can be removed in turn and the motor torque measured.

Comparison of methods of measuring fp: The Willan's line method and Morse tests are very cheap and easy to conduct. However, both these tests give only an overall idea of the losses whereas motoring test gives a very good insight into the various causes of losses and is much more power tool. As for as accuracy is concerned the IP-BP method is most accurate if carefully done. Motoring method usually gives a higher value for f.p. as compared to that given by the Willan's line method.

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