Unit - IV

Flywheel

~~Wo or Wi is taken w.r.t to the load torque if~~

→ A Flywheel is a heavy rotating body that acts a reservoir of energy.

→ Energy is stored in form of K.E.

→ Flywheel ~~is~~ acts like energy bank

→ Depending upon source of power & type of driven machinery there are two applications of flywheel.

– when power is supplied at uniform rate & demand is variable	– Power – Variable, demand – Uniform
– Punch press machine	– I.C. Engine
– Max^m power required during punching or shearing only.	– Flywheel absorbs excess energy during expansion stroke.
– Rest of time require no power.	– stored energy in flywheel is supplied back to engine during suction, compression and exhaust stroke.
– we can't use electric motor of constt ~~too~~ power as most of energy will get waste.	

→ Functions of Flywheel:-

1. To store and release energy when needed during the working cycle.
2. To reduce power capacity of electric motor or engine.
3. To reduce amplitude of fluctuations

material → Grey cast iron.

- It may be solid one piece.
- arms – elliptical
- Small Flywheel: solid webs arms

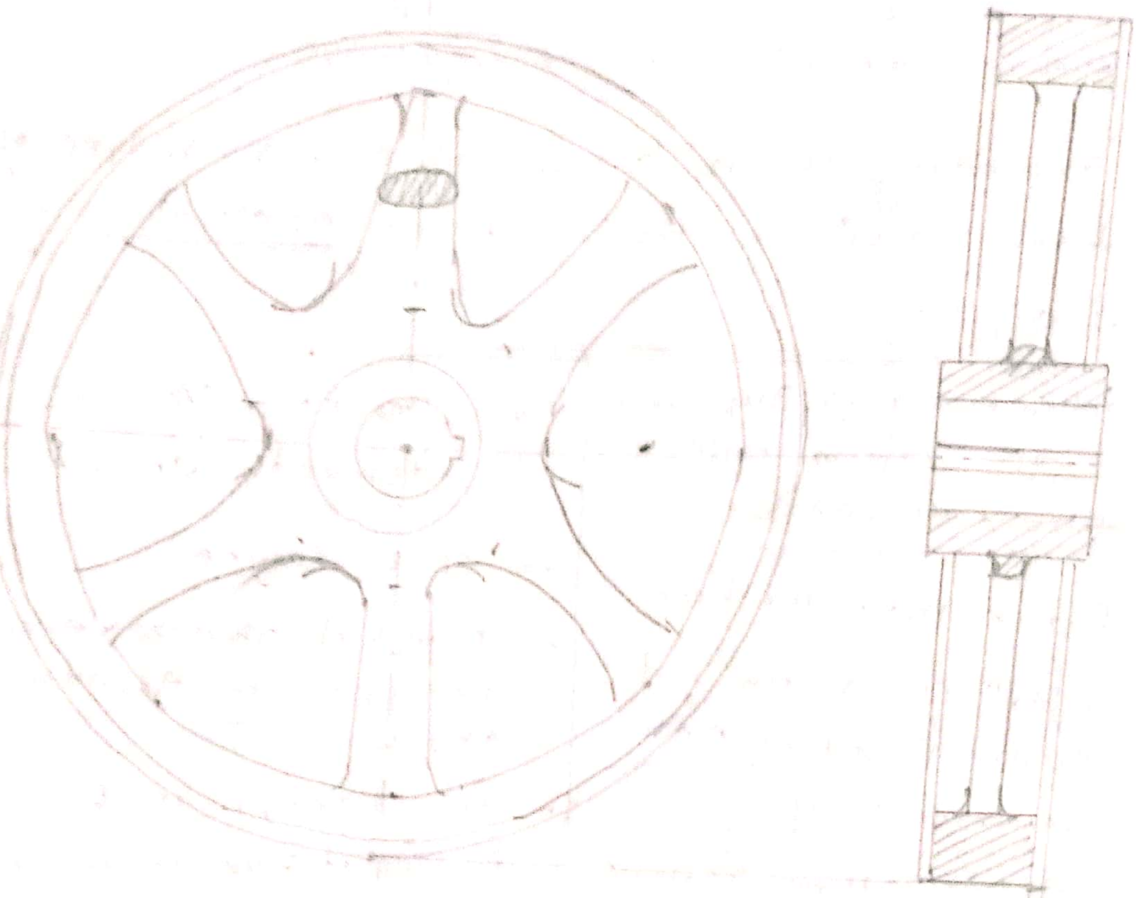

Fig:- Solid one piece Flywheel.

- In large Flywheel, stresses called cooling stresses are induced during casting. Cooling stresses occur at hub due to more concentration of mass at that portion.

Due to more ~~that~~ mass there is unequal cooling at hub, rib, and arms. This may result in breakage of arms. hence split type Flywheel is used, therefore arms are free to contract during cooling.

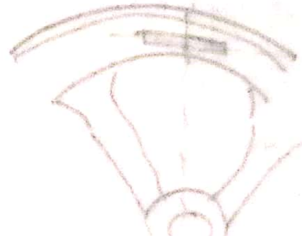

Fig:- split flywheel

Flywheel and Governor

Both Flywheel and Governor are used in engines to control the speed.

Governer controls the mean speed of engine as the load on engine varies. Governer adjust the fuel supply of engine and restores the speed as load varies.

① Engine load (↑) ⇒ Engine speed (↓) ⇒ Fuel supply (↑) by opening throttle valve

② Engine load (↓) ⇒ Engine speed (↑) ⇒ Fuel supply (↓) by reducing the opening of throttle valve.

Petrol Engine → governer adjust throttle valve

diesel Engine → governer adjust opening of fuel pump.

Differences :-

Flywheel.	Governer.
① Flywheel limits the fluctuation of speed in each cycle.	① Governer ~~limits~~ controls the mean speed of Engine by varying fuel supply.
② Flywheel has no influence on mean speed. It doesn't maintain constant speed.	② Governer has no influence on cyclic speed fluctuation
③ The operation of flywheel is continous. ~~doesnt~~ ~~wasting~~ whether the load increase or decrease or constant.	③ Governer is more or less intermittent, i.e if mean speed is constant, Governer will not operate.
④ Flywheel may not be used if cyclic fluctuations of energy output are small or negligible.	④ Governer is essential for all type of engines to adjust fuel supply as per demand.

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⑤ Energy stored in Flywheel is K.E. K.E is all available 100% Convertible to work without friction.	⑤ The governer mechanism involves friction looses.

* Flywheel Materials :-

Tradiation Materials :- Cast Iron

→ **Advantages of C.I flywheel :-**

1. Cheapest
2. Complex shapes can be made without involving machining operations.
3. C.I flywheel have excellent ability to damp vibrations.

→ **Disadvantes of C.I Flywheel :-**

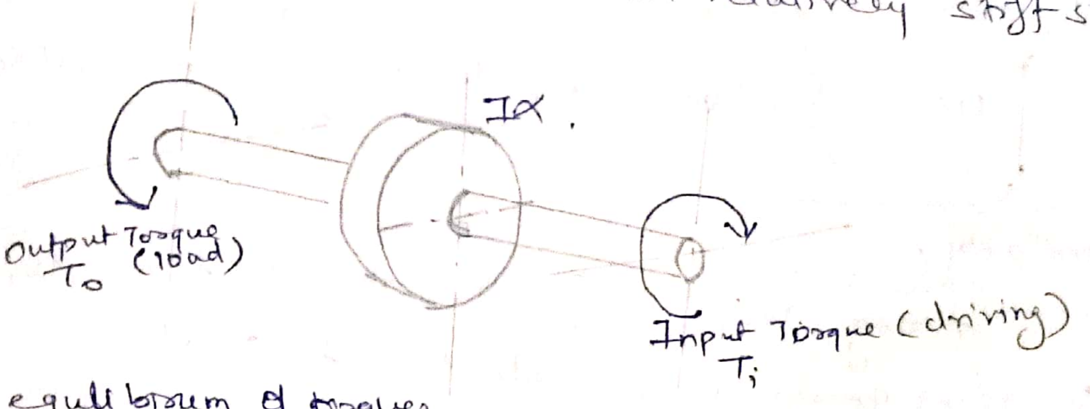
1. Poor Tensile Strength compared to steel.
2. Failure is sudden & total.
3. Poor Machinability compared to steel.

New materials:

1. Flywheels are made of high strength steel & Composites. in vehicle applications
2. Graphite – Fiber Reinforced polymers (GFRP)

* Torque Analysis:-

Flywheel is mounted on relatively stiff shaft.



For equilibrium of torques,

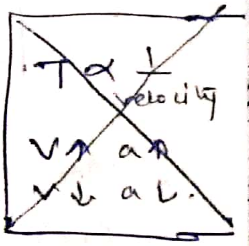
Output Torque − Input torque = Iα.

$$T_o - T_i = I\alpha.$$

where

I = M.M.I of Flywheel (kg-m²)

α = Angular acceleration of shaft rad/s².

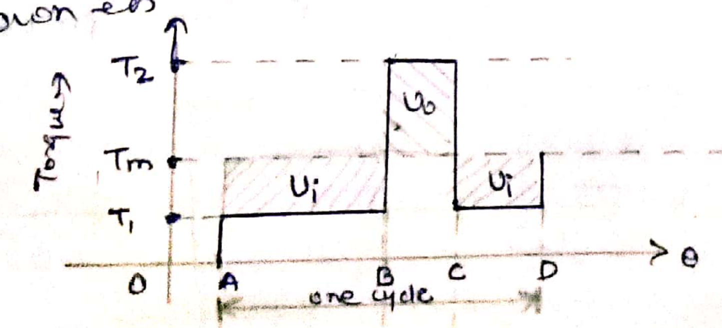


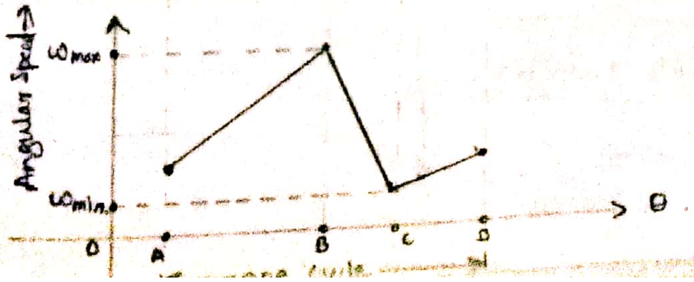
when, $+(T_i - T_o) \Rightarrow$ Flywheel accelerated

$-(T_i - T_o) \Rightarrow$ Flywheel retarded.

let take an example of constant torque motor having mean Torque (T_m)

For particular application the load required for each cycle is as shown in T–θ diagram.





① During element AB, ($T_1 < T_m$) hence Flywheel accelerates

② During element BC, ($T_2 > T_m$), hence flywheel Decelerates.

③ During CD ($T_1 < T_m$) again Flywheel accelerates.

④ $$T_m = \frac{\text{Work done per cycle}}{\text{length of cycle}}$$

During AB and CD energy is supplied to flywheel.
So total Energy input given to Flywheel,

$$U_i = \int_A^B (T_m - T_1).d\theta + \int_C^D (T_m - T_1) d\theta$$

Similarly,
during BC Energy is taken from flywheel
So total Energy output U_o from flywheel.

$$U_o = \int_B^C (T_2 - T_m) \, d\theta$$

Similarly change in K.E of flywheel in BC

$$U_o = \frac{1}{2} I \left(\omega_{max}^2 - \omega_{min}^2 \right)$$

$$U_o = \frac{1}{2} I (\omega_{max} + \omega_{min})(\omega_{max} - \omega_{min}) \quad \text{— (1)}$$

- The difference in maximum & minimum speed i.e ($\omega_{max} - \omega_{min}$) during a cycle is called the "maximum Fluctuation of Speed".

- Coefficient of Fluctuation of Speed (C_s) = (Maximum Fluctuation of Speed) / Mean speed.

$$C_s = \frac{\omega_{max} - \omega_{min}}{\omega} \quad \text{— (2)}$$

where

$$\omega = \frac{\omega_{max} + \omega_{min}}{2} \quad \text{— (3)}$$

Substituting equtn ② & ③ in equtn ①.

$$U_0 = \frac{1}{2} I (2\omega)(C_s \omega)$$

$$\boxed{U_0 = I \omega^2 C_s}$$

Values of C_s

	Type of Equipment	C_s
1	Punching shearing & Forming Process	0.200
2	Compressor (belt driven)	0.120
3	— " — (Gear — ")	0.020
4	Machine Tools	0.025
5	Reciprocating Pumps.	0.040
6	Geared drives	0.020
7	I.C. Engines	0.030
8	D.C. Generators	0.010
9	A.C. Generator.	0.005

$$C_s = \frac{\omega_{max} - \omega_{min}}{\omega}$$

$$C_s = \frac{\omega_{max} - \omega_{min}}{(\omega_{max} + \omega_{min})/2}$$

$$\boxed{C_s = \frac{2(\omega_{max} - \omega_{min})}{(\omega_{max} + \omega_{min})}}$$

Similarly,

$$C_s = \frac{\omega_{max} - \omega_{min}}{\omega}$$

$$= \frac{n_{max} - n_{min}}{n}$$

$$C_s = \frac{2(n_{max} - n_{min})}{(n_{max} + n_{min})}$$

where,

n_{max} & n_{min} are max & min speed in RPM.

* **Coefficient of Steadiness (m) :-**

It is defined as the reciprocal of the Coefficient of fluctuation of speed.

$$m = \frac{1}{C_s}$$

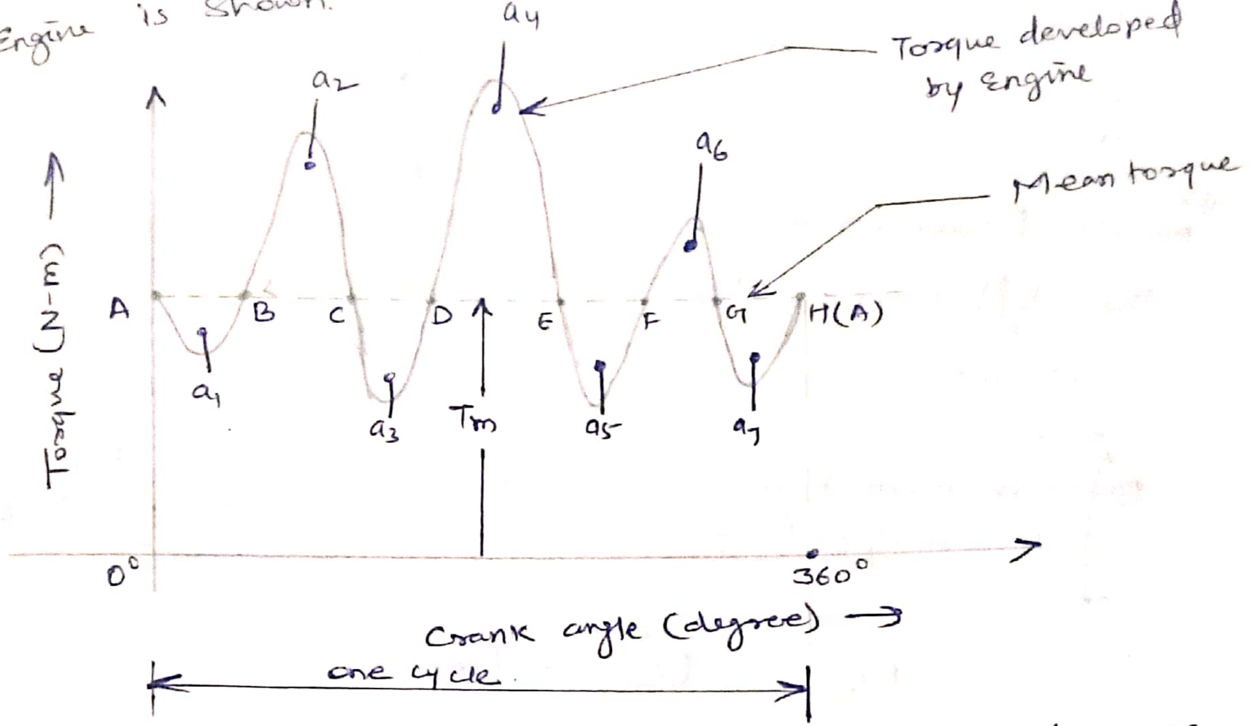
$$m = \frac{\omega}{\omega_{max} - \omega_{min}}$$

or

$$m = \frac{n}{n_{max} - n_{min}}$$

* Coefficient of Fluctuation of Energy (Ce) :-

Turning moment diagram for a multicylinder Engine is shown.



The Intercept areas between engine and mean torques are taken in $-a_1$, $+a_2$, $-a_3$, $+a_4$, $-a_5$, $+a_6$, $-a_7$.

Assuming Energy stored in Flywheel at A as U.

Energy at A = U

Energy at B = $U - a_1$

Energy at C = $U - a_1 + a_2$

Energy at D = $U - a_1 + a_2 - a_3$

Energy at E = $U - a_1 + a_2 - a_3 + a_4$

Energy at F = $U - a_1 + a_2 - a_3 + a_4 - a_5$

Energy at G = $U - a_1 + a_2 - a_3 + a_4 - a_5 + a_6$

Energy at H or A = $U - a_1 + a_2 - a_3 + a_4 - a_5 + a_6 - a_7$
$\doteq U$.

let say, Maximum Energy at E

Maximum Energy	$= U - a_1 + a_2 - a_3 + a_4$.

Similarly let say,

minimum energy at B.

Minimum Energy = $U - a_1$.

So,

"Maxm Fluctuations in Energy" is defined as the difference between maximum K.E & minimum K.E in one cycle.

$$\text{Maximum Fluctuations in Energy } (U_0) = \left[\text{Maximum K.E}\right] - \left[\text{Minimum K.E}\right]$$

$$U_0 = U_E - U_B$$

$$= (U - a_1 + a_2 - a_3 + a_4) - (U - a_1)$$

$$= \cancel{U} - \cancel{a_1} + a_2 - a_3 + a_4 - \cancel{U} + \cancel{a_1}$$

$$\boxed{U_0 = a_2 - a_3 + a_4}$$

"Coefficient of Fluctuation of energy" (C_e) is defined as the ratio of maximum Fluctuation of energy to the work done per cycle.

$$C_e = \frac{\text{Maximum Fluctuation of Energy}}{\text{work done per cycle}}$$

$$C_e = \frac{U_0}{\text{Work done per cycle}}$$

work done per cycle = Area below mean torque line in one cycle ($0°$ to $360°$)

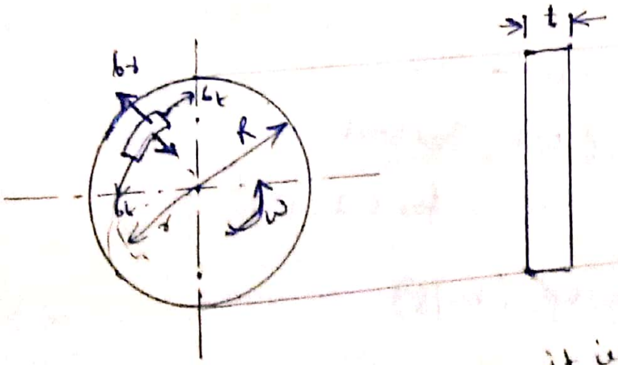
| work done per cycle = $(2\pi)\,T_m$ | — For 2 stroke engine

| work done / Cycle = $(4\pi)\,T_m$ | — For 4-stroke Engine.

values of coeff. of fluctuations of energy.

	Type of Engine	Ce
(1)	Single cylinder, double acting Steam Engine	0.21
(2)	Cross compound steam Engine	0.096
(3)	Single Cylinder 4-stroke petrol Engine	1.93
(4)	4-Cylinder, 4-Stroke petrol Engine	0.066
(5)	6-Cylinder, 4-Stroke petrol Engine	0.031

Solid disk Flywheel:-



The solid disk as it is rotating element it is subjected to tangential stress (σ_t) & radial stress (σ_r).

The M.M.I of solid disk,

$$I = \frac{1}{2}(mR^2)$$

where m = mass of flywheel

m = (volume) × density

$m = (\pi R^2).t \times \rho$

$$m = \pi R^2 t.\rho$$

So M.M.I becomes

$$I = \frac{1}{2}\pi R^4 t.\rho$$

t = thickness in m , ρ = kg/m3.

Similarly there are two principal stress in the rotating disk - tangential stress (σ_t) and radial stress (σ_r)

$$\sigma_t = \frac{\rho v^2}{10^6}\left(\frac{\mu+3}{8}\right)\left[1 - \frac{(3\mu+1)}{(\mu+3)}\left(\frac{r}{R}\right)^3\right]$$

$$\sigma_r = \frac{\rho v^2}{10^6}\left(\frac{\mu+3}{8}\right)\left[1 - \left(\frac{r}{R}\right)^2\right]$$

where,

σ_t = tangential stress in N/mm²

σ_r = radial —"—"—"—

μ = poisson ratio (0.3 for steel.
0.27 for C.I)

v = peripheral velocity (m/s)

The maximum tangential stress $(\sigma_t)_{max}$ and maximum radial stress $(\sigma_r)_{max}$ are equal and occur at (r=0)

$$(\sigma_t)_{max} = (\sigma_r)_{max} = \frac{\rho v^2}{10^6}\left(\frac{\mu+3}{8}\right)$$

Q1.1

Torque = 500 Nm to 1500 N-m through 360°
& sudden drop at 360°, to 500 N-m

ω_m = 30 rad/sec

C_s = 0.2

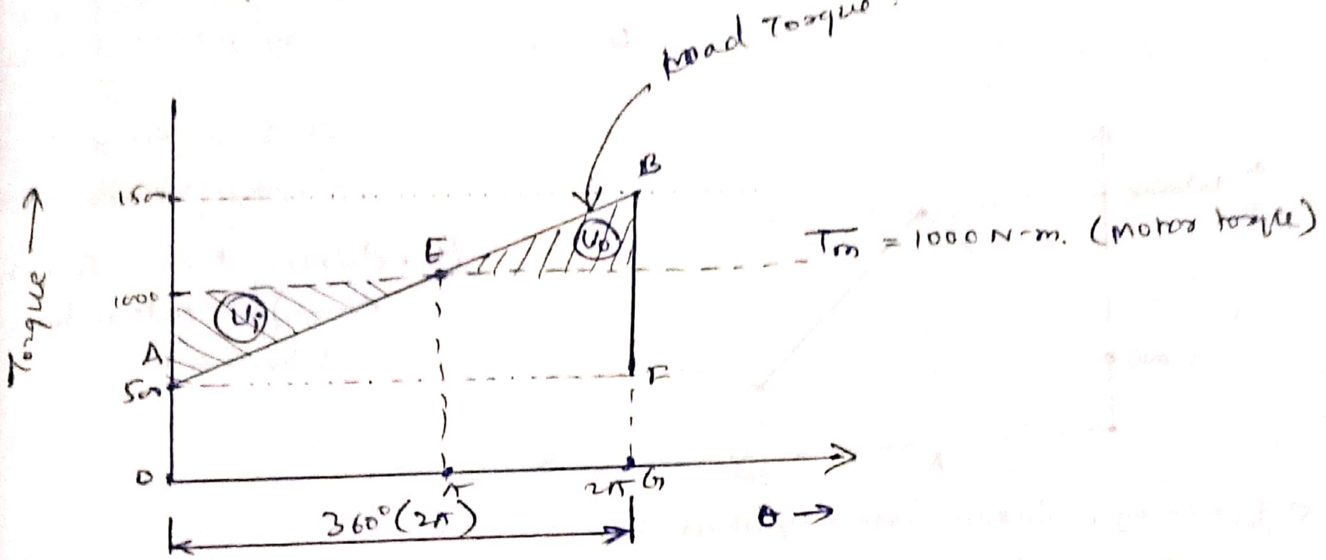
t = 25 mm

ρ = 7800 kg/m³

μ = 0.3

R = ?

σ_t = ?, σ_r = ?



~~$T_m = \frac{500 + 1500}{2} = \frac{2000}{2} = 1000$ N-m~~

$T_m = \frac{\text{Work done per cycle}}{\text{length of cycle}}$

$$T_m = \frac{\text{Area of OABG}}{\text{length of OG}}$$

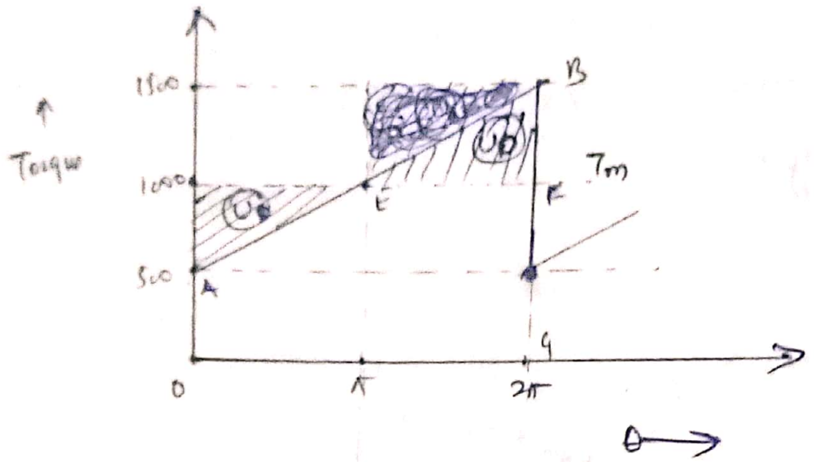
$$= \frac{\left[\frac{1}{2}(2\pi)(1000) + 500 \times 2\pi\right]}{2\pi}$$

$$= \frac{2000\pi}{2\pi}$$

$$\boxed{T_m = 1000 \text{ N-m}}$$

The M.M.I of solid disk,

maximum & minimum angular velocities occur at points E & B respectively.

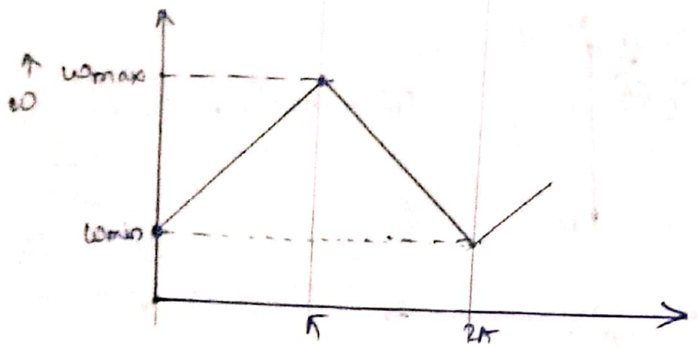


1. In region AE torque required by m/c is less than Tm hence Flywheel accelerates,
2. In region EB the torque required by m/c is more than Tm hence it decelerates
3. During AE Ui (input energy given to Flywheel

at E, ω_{max}

at, B, ω_{min}

4. during EB Uo (output energy) is taken from Flywheel.



Output energy taken from Flywheel,

U_0 = Area of ΔEBF

$= \frac{1}{2}(EF)(BF)$

$= \frac{1}{2}(2\pi - \pi)(1500-1000)$

$= \frac{1}{2}\pi(500)$

$U_0 = (250\pi)$ N-m

we knows

$U_0 = I\omega^2 C_s$

$250\pi = I(30)^2(0.2)$

$I = 4.3633$ kg-m²

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and we know,

$I = \frac{\pi}{2} \rho t R^4$

$4.3633 = \frac{\pi}{2} (7800)(0.025) R^4$

$R = 0.345 m$

$R = 345 mm$

or

$\boxed{R = 350 mm}$

Stresses in Flywheel,

$(\sigma_t)_{max} = (\sigma_r)_{max}$

$= \frac{\rho v^2}{10^6} \left(\frac{\mu + 3}{8}\right)$

$= \frac{(7800)(0.35 \times 30)^2}{10^6} \left[\frac{0.3+3}{8}\right]$

$\boxed{(\sigma_t)_{max} = (\sigma_r)_{max} = 0.35 \ N/mm^2}$

21.2

Torque eqn of Engine

$T = 14250 + 2200 \sin 2\theta - 1800 \cos 2\theta.$

Resisting torque is Constt.

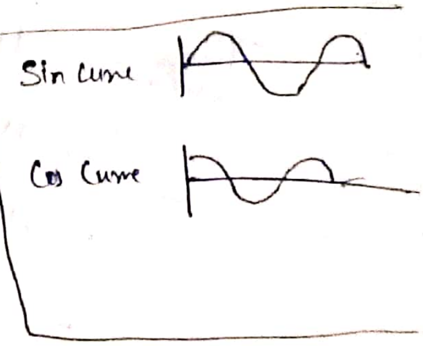
$C_s = 0.01$

$N = 150 rpm$

$t = 50 mm$

$\rho = 7800 \ kg/m^3$

$R = ?$



$T_m = 14250 N\text{-}m$, because the fluctuating terms $\sin 2\theta$ and $\cos 2\theta$ will have 0 value at mean position

So when

$T = T_m$

$14250 = 14250 + 2200 \sin 2\theta - 1800 \cos 2\theta$

$0 = 2200 \sin 2\theta - 1800 \cos 2\theta$

$2200 \sin 2\theta = 1800 \cos 2\theta$

$\tan 2\theta = 0.8181$

$\boxed{2\theta = 39.29}$ or $\boxed{2\theta = 180 + 39.29 = 219.29}$

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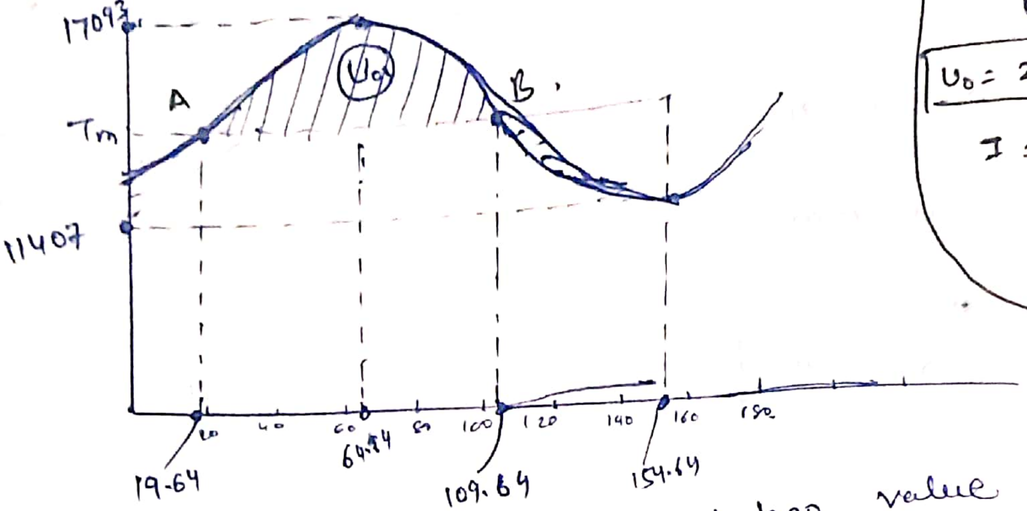
$\boxed{\theta = 19.645^\circ}$ or $\boxed{\theta = 109.64^\circ}$



higher value will be in middle of two value i.e

$$\theta = \frac{19.645^\circ + 109.64}{2} = 64.645^\circ$$

$$T_{64.64} = 14250 + 2200 \sin 2\theta - 1800 \cos 2\theta$$

$$= 14250 + 2200 \sin(2 \times 64.64) - 1800 \cos(2 \times 64.64)$$

$$= 14250 + 2200 (0.774) - 1800 (-0.63)$$

$$= 14250 + 1702.8 + 1134$$

$$\boxed{T_{64.64} = 17093 \text{ Nm}}$$

$$U_0 = \int_A^B (T - T_m)\, d\theta$$

$$U_0 = \int_{19.64}^{109.64} (2200 \sin 2\theta - 1800 \cos 2\theta)$$

$$U_0 = \left[-1100 \cos 2\theta - 900 \sin 2\theta\right]_{19.64}^{109.64}$$

$$\boxed{U_0 = 2842.2 \text{ J.}}$$

$$I = \frac{U_0}{\omega^2 C_s} = \frac{2842.2}{\left[\frac{2\pi \times 150}{60}\right]^2 \times (0.01)}$$

$$\boxed{I = 1151.9 \text{ kg-m}^2}$$

$$I = \frac{\pi}{2} \rho t R^4$$

$\boxed{R = 1171 \text{ mm}}$ or $\boxed{R = 1175 \text{ mm}}$

next θ value will be got be adding (109.64 − 64.64) in term 109.64.

i.e same difference for next extreme end

109.64 − 64.64 = 45°

next maxm θ value is

$$109.64 + 45 = 154.64$$

$$T_{154.64} = 14250 + 2200 \left[\sin(2 \times 154.64)\right] - 1800 \cos(2 \times 154.64)$$

$$= 14250 - 1702.93 - 1139.59$$

$$\boxed{T_{154.64} = 11407 \text{ N-m}}$$

* Rimmed Flywheel :-

- Solid disk Flywheel is rarely used.
- Mostly Rimmed Flywheel is used
- Due to complicated shape its difficult to determine exact Moment of Inertia.

• Assumption for Analysis

① Spoke, hub, shaft do not contribute M.I.
Rim only contribute M.I.

② Spoke, hub, shaft contribute 10% M.I
Rim contribute 90% M.I.

Moment of Inertia of Rim,

$$I_r = K \cdot I \quad \text{— ①}$$

where,
I_r = Moment of Inertia of rim (kg-m²)
I = required Moment of Inertia. (kg-m²)

The value of $K = 1$ when entire moment of inertia is due to rim only.

$$K = 0.9$$

generally taken.
we assume 90% is taken by Rim.

$$I = \frac{U_0}{\omega^2 C_s} \quad \text{— ②}$$

from ① & ②.

$$I_r = \frac{K U_0}{\omega^2 C_s}$$

The thickness of rim is very small, hence.

K_G = mean Radius.

$$I_r = m_r R^2 \quad \text{--- (3)}$$

where

m_r = mass of rim (kg)

R = Mean radius of rim (m)

Generally it is required to design mean radius of rim.

From Eqtn (3) we known

if $R \uparrow$ then $m_r \downarrow$ for same I_r..

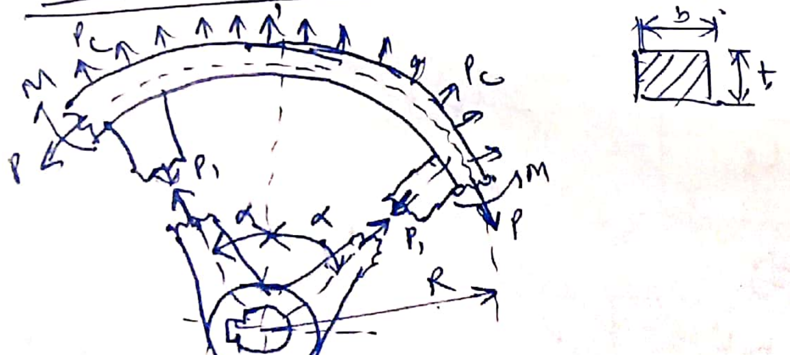
- So always radius should be largest possible to reduce the weight.
- space availability is also a concern.
- Flywheel made of grey C.I, the limiting mean velocity is 30 m/s.

$V = R\omega$

$$R < \frac{30}{\omega}$$

- For high speed application cast steel is used

* **Stresses in Rimmed Flywheel:-**



- rim is subjected to uniformly distributed centrifugal force (P_c)

- Hence a tensile force P induces in rim. tangential direction. & B.M of M.

- tensile load P_1 acting in spoke prevents outward movement of Rim.

→ tensile load in spoke,

$$\boxed{\sigma_t = \frac{P_1}{A_1}} \quad \text{——— (1)}$$

P_1 = tensile force in each spoke.

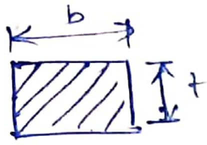
A_1 = C/S of spoke

σ_t = Tensile stress in spoke.

→ Stress in Rim,

due to centrifugal force there are two stress.

Stresses, tensile (tangential) & B.M stress.



$$\sigma_t = \frac{P}{A} \pm \frac{M.y}{I}$$

$$\sigma_t = \frac{P}{bt} \pm \frac{M.\left(\frac{t}{2}\right)}{\frac{1}{12}(b)(t)^3}$$

$$\boxed{\sigma_t = \frac{P}{bt} \pm \frac{6M}{bt^2}} \quad \text{——— (2)}$$

$P_1 \rightarrow$ tensile Force in each spoke.

$P \rightarrow$ — " — " — " — Rim.

$M \rightarrow$ Bending moment in Rim.

The values of above are taken S Timoshenko Book.

He has assumed,

(1) thickness of rim << Mean radius

B.M stresses and tensile stresses taken in account

(2) length of spoke = Mean radius

(In practice length of spoke < mean radius)

$$P_1 = \frac{2}{3}\left[\frac{(1000)\, mv^2}{C}\right]$$

where,

$$C = 12 \times 10^6 \left(\frac{R^2}{t^2}\right) f_2(\alpha) + f_1(\alpha) + \frac{A}{A_1}$$

$$f_1(\alpha) = \frac{1}{2\sin^2\alpha}\left[\frac{\sin 2\alpha}{4} + \frac{\alpha}{2}\right]$$

$$f_2(\alpha) = \frac{1}{2\sin^2\alpha}\left[\frac{\sin 2\alpha}{4} + \frac{\alpha}{2}\right] - \frac{1}{2\alpha}$$

$$M \text{ at } \phi = \frac{1000 P_1 R}{2}\left[\frac{\cos\phi}{\sin\alpha} - \frac{1}{\alpha}\right]$$

$$P \text{ at } \phi = 1000\, mv^2 - \frac{P_1}{2}\frac{\cos\alpha}{\sin\alpha}$$

where,

m = mass of rim per mm of circumference (Kg/mm)

v = velocity at mean radius

R = Mean radius of rim.

b = Width of rim.

A = C/s area of rim (bt)

A_1 = " " " spoke

2α = Angle between consecutive spokes

C = Constt.

So, Substituting value in equation (1)

$$\sigma_t = \frac{P_1}{A_1}$$

$$\boxed{\sigma_t = \frac{2}{3}\left[\frac{(1000)mv^2}{CA_1}\right]}$$

Similarly. substituting in equation (2)

$$\sigma_t = \frac{P}{bt} \pm \frac{6M}{bt^2}$$

$$\boxed{\sigma_t = \frac{(1000)mv^2}{bt}\left[1 - \frac{\cos\phi}{3C\sin\alpha} \pm \frac{2(1000)R}{Ct}\left(\frac{1}{\alpha} - \frac{\cos\phi}{\sin\alpha}\right)\right]}$$

For 4 spokes,

$$2\alpha = \frac{\pi}{2}$$

$$\frac{360}{4} = 90 = \frac{\pi}{2}$$

$$f_1(\alpha) = \frac{1}{2\sin^2(\frac{\pi}{4})}\left[\frac{\sin(\frac{\pi}{2})}{4} + \frac{\pi}{8}\right]$$

$$f_1(\alpha) = 0.643.$$

and $f_2(\alpha) = 0.00169.$

$$C = \left[\frac{72160 R^2}{t^2} + 0.643 + \frac{A}{A_1}\right]$$

For 6 spokes,

$$2\alpha = \frac{\pi}{3}.$$

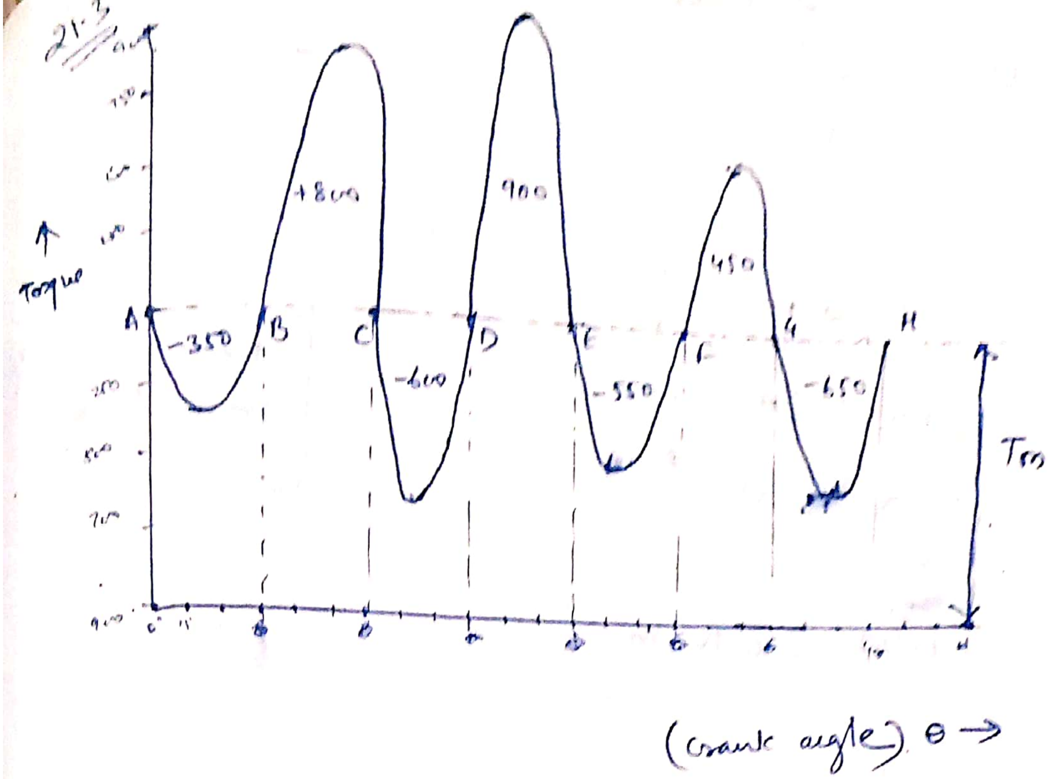
$$f_1(\alpha) = 0.957 \quad , \quad f_2(\alpha) = 0.00169$$

$$C = \left[\frac{20280 R^2}{t^2} + 0.957 + \frac{A}{A_1}\right]$$

$m \Rightarrow$ mass of rim per mm

$$\boxed{m = bt\rho}$$

21.3



<u>Given</u>

$n = 750$ rpm

$C_s = 0.02$

$\rho = 7100$ kg/m³

Rim [rectangular section] $\frac{b}{t} = 1.5$

Scale :-
1 mm² = 250 N-m
1 mm = 1°

Energy at A = U

— " — B = U − 350

Energy at C = U − 350 + 800 = U + 450

Energy at D = U + 450 − 600 = U − 150

Energy at D = U − 150 + 900 = U + 750

— " — E = U + 750 − 550 = U + 200

— " — F = U + 200 + 450 = U + 650

— " — G = U + 650 − 650 = U.

— " — H =

The maxᵐ energy occurs at E

— " — minᵐ — " — — " — B.

The angular velocity of Flywheel will be max at E & min at B.

$U_0 = U_E - U_B$

$= (U+750) - (U-350)$

$= U + 750 - U + 350$

$U_0 = 1100 \; mm^2$

> 1 mm = 250 N-m
> 1 mm = $1° = \frac{\pi}{180}$

$U_0 = (1100)(mm)(mm)$

$U_0 = (1100)(250) \frac{\pi}{180}$

$U_0 = 4799.66 \; N\text{-}m$

II. Dimensions of rim

$\omega = \frac{2\pi n}{60}$

$= \frac{2\pi(750)}{60}$

$\omega = (25\pi) \; rad/sec$

$I_r = \frac{U_0 K}{\omega^2 C_s}$

$= \frac{(4799.66)(0.9)}{(25\pi)(0.02)}$

$I_r = 35 \; kg\text{-}m^2$

Mean radius of Rim is given by,

$R < \frac{30}{\omega}$

$R < \frac{30}{25\pi}$

$R < 0.38 \; m.$

let take.

$R = 0.35\ m$

$\therefore I_r = m_r R^2$

$m_r = \frac{I_r}{R^2}$

$= \frac{35}{(0.35)^2}$

$m_r = 285.71\ kg$

mass of rim is also given as,

$\rho = \frac{m}{V}$, $m = \rho \times V$

$m_r = \rho \times volume$

$= \rho \cdot [b \cdot t \cdot 2\pi R]$

$285.71 = 7100 [1.5t][t] \cdot 2\pi(0.35)$

$t = 0.110\ m$

or

$t = 110.45\ mm$

$\therefore \frac{b}{t} = 1.5$

$b = 1.5 \times t$

$= 1.5 \times 110.45$

$b = 170\ mm$

Q1.4. 3 Single acting cylinder with crank set equally at 120° to each other.

Crank angle (°)	0	60	180	180 to 360
Torque (N-m)	0	300	0	0

$n = 240 \, rpm.$

$\omega = \frac{2\pi n}{60} = 8\pi$

$C_s = 0.03$

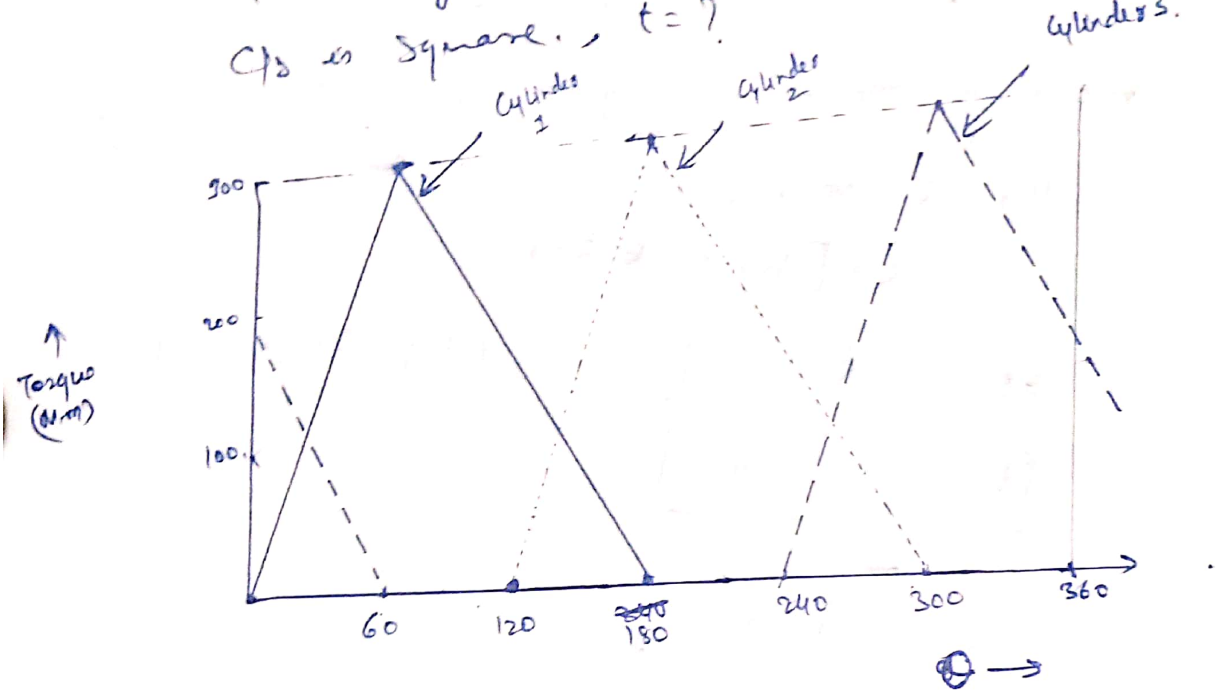
$T_m = $ const.

$R = 0.25 \, m.$

$K = 0.9.$

$\rho = 7150 \, kg/m^3$

C/s is square., $t = ?$



(Work done per cycle) = (Area below below mean torque)

(area below three triangles) $= 2\pi \cdot T_m$

$T_m = \frac{(\text{area below three triangles})}{2\pi}$

$T_m = \frac{3\left[\frac{1}{2} \times \pi \times 300\right]}{2\pi}$

$T_m = \frac{450\pi}{2\pi}$

$\boxed{T_m = 225 \, N\text{-}m}$

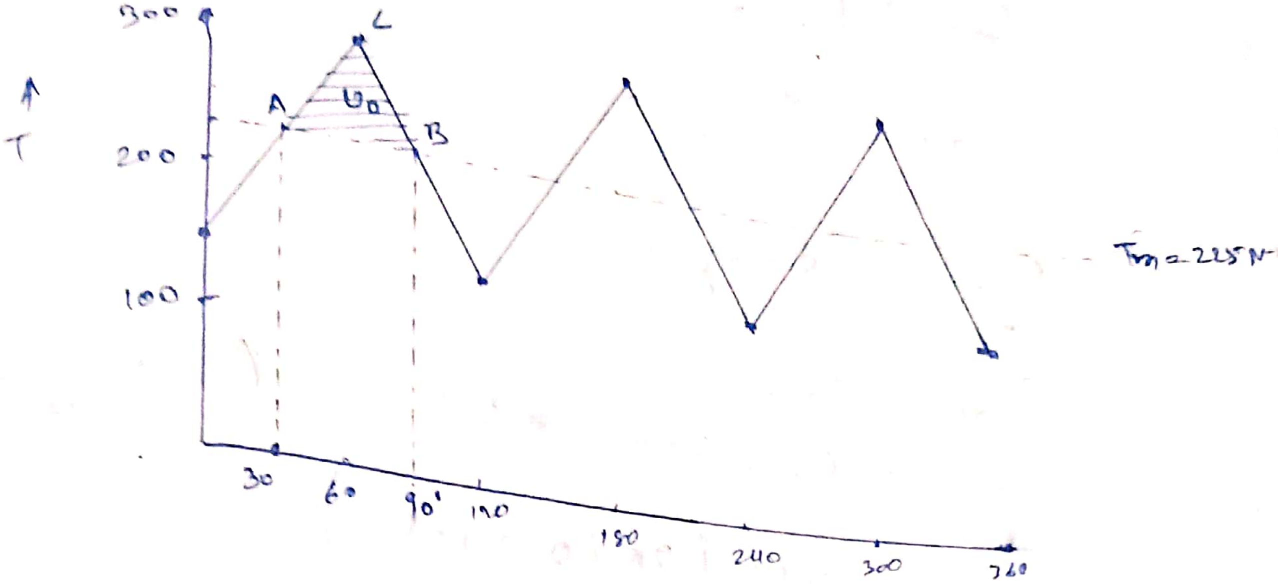


Fig :- Resultant Torque diagram $\theta \rightarrow$

The resultant torque diagram is obtained by taking sum of torque developed by each cylinder at particular angle.

Like at 0° it is. $(0 + 150) = 150$ N-m.

at 60° it is $(0 + 300) = 300$ N-m.

U_0 = area of ΔABC

$= \frac{1}{2}\left[(90° - 30°)\frac{\pi}{180}\right][300 - 225]$

$$\boxed{U_0 = 39.27 \text{ N-m}}$$

$I_r = \frac{U_0 K}{\omega^2 C_s}$

$= \frac{(39.27) \times (0.9)}{(8\pi)^2 (0.03)}$

$$\boxed{I_r = 1.865 \text{ kg-m}^2}$$

$I_r = m_r R^2$

$m_r = \frac{I_r}{R^2}$

$m_r = \frac{1.865}{(0.25)^2}$

$m_r = 29.84$ kg

$m_r = \rho \cdot V$

$m_r = \rho \cdot (2\pi R \cdot t^2)$ (∵ it is square section)

$29.84 = 7150 [2\pi (0.25) \cdot t^2]$

$t = 0.05154$ m

or

$t = 51.54$ mm

or

$t = 55$ mm