ESE

2019

THEORY OF MACHINES

MECHANICAL ENGINEERING

ECG Publications

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CONTENTS

CHAPTER - 1
BASIC CONCEPT

1.1. INTRODUCTION
Theory of machine is a study of relative motion between various parts of Machine and forces acting upon them. It can be further divided into the two parts.

1.1.1 Kinematics
Kinematics is study of motion without considering external force acting on the machine parts.

Velocity, $v = \frac{d\vec{s}}{dt}$

Acceleration, $a = \frac{d\vec{v}}{dt}$

$J = \frac{d\vec{a}}{dt}$

1.1.2 Dynamics
Dynamics is study of motion with effect of some external force acting on the machine parts.
It can further divide into two parts

1. Statics
It is a study of forces and their effects on machine and its parts, when it is at rest.

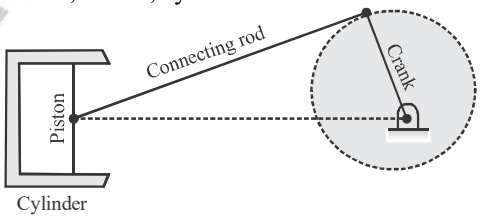
2. Kinematics
It is study of combined effect of mass & motion of Machine and its parts

Momentum $\overrightarrow{F_{ext}} = \frac{d}{dt}(m\vec{v})$

1.2 KINEMATIC LINK OR ELEMENT
It is a part of machine which moves relative with respect to some other part of machine. It should be a resistant body so that it is capable of transmitting the motion from one part to other part of machine with negligible deformation.

1.3 CLASSIFICATION OF LINKS
The detailed classification of links is described below:

1.3.1. Rigid Link
It is a link which transmits required motion & force without any significant deformation.
Example. Connecting rod, Crank, Piston, cylinder etc.



Slider Crank Chain Mechanism

IAS OBJ QUESTIONS

1. For one degree of freedom planar mechanism having 6 links, which one of the following is the possible combination?

[IAS - 2007]

(a) Four binary links and two ternary links
(b) Four ternary links and two binary links
(c) Three ternary links and three binary links
(d) One ternary link and five binary links

2. Consider the following statements in respect of four bar mechanism:
1. It is possible to have the length of one link greater than the sum of length of the other three links.
2. If the sum of the lengths of the shortest and the longest links is less than the sum of lengths of the other two, it is known as the Grashoff's linkage.
3. It is possible to have the sum of the lengths of the shortest and the longest links greater than that of the remaining two links.
Which of these statements is/are correct?

[IAS - 2003]

(a) 1, 2 and 3 (b) 2 and 3
(c) 2 only (d) 3 only

3. Assertion (A): The kinematic mechanism shown in figure 1 and figure 2 below are the kinematic inversion of the same kinematic chain.

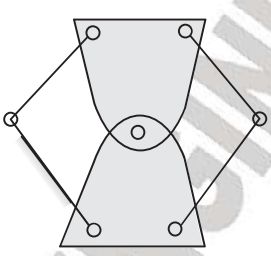


Figure 1

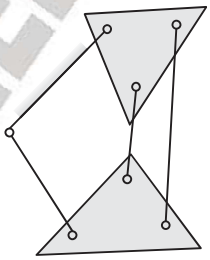


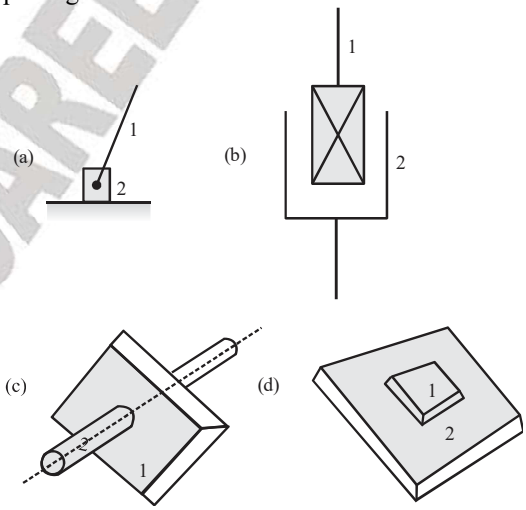
Figure 2

Reason (R): Both the kinematic mechanisms have equal number of links and revolute joints, but different fixed links.

[IAS - 2002]

(a) Both A and R are true and R is the correct explanation of A
(b) Both A and R are true but R is not a correct explanation of A
(c) A is true but R is false
(d) A is false but R is true

4. Which one of the following "Kinematic pairs" has 3 degrees of freedom between the pairing elements?



[IAS - 2002]

5. In a four-link kinematic chain, the relation between the number of links (L) and number of pairs (j) is

[IAS - 2000]

(a) $L = 2j + 4$ (b) $L = 2j - 4$
(c) $L = 4j + 2$ (d) $L = 4j - 2$

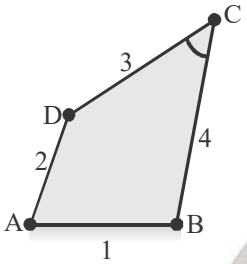
6. The given figure shows a/an

CHAPTER - 2
INVERSION OF KINEMATIC CHAINS

2.1 INTRODUCTION

The method of obtaining different mechanism by fixing different links in a kinematic chain is known as in version of mechanism. Through process of inversion the relative motion between various link is not changed in any manner.

2.2 FOUR BAR CHAIN OR QUADRIC CYCLE CHAIN

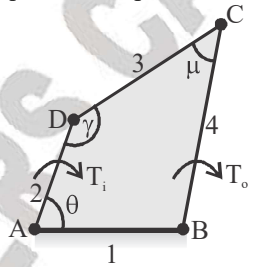


As name suggested that, the chain is combination of four kinematic pairs i.e. four Revolute Pair such that the relative motion between the links is completely constrained.

The link AD which is adjacent to the link AB or frame (which is usually fixed) is called as driver (crank) and link BC to which motion is transferred is known as follower (rocker) and link DC which transmits motion from link AD to link BC is known as coupler (connecting rod).

2.2.1 Mechanical Advantage (M.A)

It is the ratio of the output force or torque to the input force or torque at any instant.



From Principle of conservation of energy, we know that:

Power Input = Power output

If T_i is torque applied by input link 2 with angular speed ω_i and T_o is torque obtained by the output link 4 with angular speed ω_o respectively.

Then, $T_i\omega_i = T_o\,\omega_o$ $\quad (\therefore P = T\,\omega)$

$$M.A = \frac{T_o}{T_l} = \frac{\omega_i}{\omega_o}$$

To achieve M.A. to be infinite, the angular velocity ω_0 of the output link 4 becomes zero at extreme positions.

Two extreme condition can be obtained at $\gamma = 0°$ or $\gamma = 180°$. In both conditions the link 2 and link 3 will be in the same line.

ESE OBJ QUESTIONS

1. Consider the following motions :
1. Piston reciprocating inside an engine cylinder
2. Motion of a shaft between foot-step bearings
Which of the above can rightly be considered as successfully constrained motion?

[ESE - 2016]

(a) 1 only (b) 2 only
(c) Both 1 and 2 (d) Neither 1 nor 2

2. In a crank and slotted lever type quick return mechanism, the link moves with an angular velocity of 20 rad/s, while the slider moves with a linear velocity of 1.5 m/s. The magnitude and direction of Coriolis component of acceleration with respect to angular velocity are

[ESE - 2015]

(a) 30 m/s^2 and direction is such as to rotate slider velocity in the same sense as the angular velocity

(b) 30 m/s^2 and direction is such as to rotate slider velocity in the opposite sense as the angular velocity

(c) 60 m/s^2 and direction is such as to rotate slider velocity in the same sense as the angular velocity

(d) 60 m/s^2 and direction is such as to rotate slider velocity in the opposite sense as the angular velocity.

3. In a crank and slotted lever quick-return motion, the distance between the fixed centres is 150 mm and the length of the driving crank is 75 mm. The ratio of the time taken on the cutting and return strokes is

[ESE - 2014]

(a) 1.5 (b) 2.0
(c) 2.2 (d) 2.93

4. Which one of the following mechanisms is an inversion of double slider-crank chain?

[ESE - 2014]

(a) Elliptic trammels
(b) Beam engine
(c) Oscillating cylinder engine
(d) Coupling rod of a locomotive

5. In a crank and slotted lever quick return motion mechanism, the distance between the fixed centres is 160 mm and the driving crank is 80 mm long. The ratio of the taken by cutting and return strokes is

[ESE - 2012]

(a) 0.5 (b) 1
(c) 1.5 (d) 2

6. In an elliptic trammel, the length of the link connecting the two sliders is 100mm. the tracing pen is placed on 150 mm extension of this link. The major and minor axes of the ellipse traced by the mechanism would be

[ESE - 2012]

(a) 250 mm and 150 mm
(b) 250 mm and 100 mm
(c) 500 mm and 300 mm
(d) 500 mm and 200 mm

7. Statement (I): Method of obtaining different mechanisms by fixing in turn diffident links in a kinematic chain is known as inversion.
Statement (II): Scotch Yoke mechanism is an inversion of a double slider crank mechanism.

[ESE - 2012]

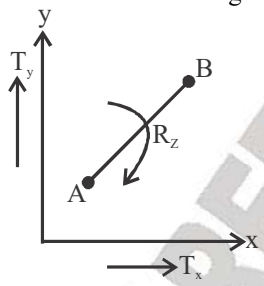
(a) Both Statements (I) and Statement (II) are individually true and Statement (II) is the correct explanation of Statement (I)
(b) Both Statement (I) and Statement (II) are individually true but Statement (II) is not the correct explanation of Statement (I)
(c) Statement (I) is true but Statement (II) is false
(d) Statement (I) is false but Statement (II) is true.

CHAPTER - 3
KINEMATICS OF MACHINE

3.1 INTRODUCTION
Kinematics deals with study of relative motion between the various parts of machine. The motion leads to concept of displacement, velocity and acceleration.

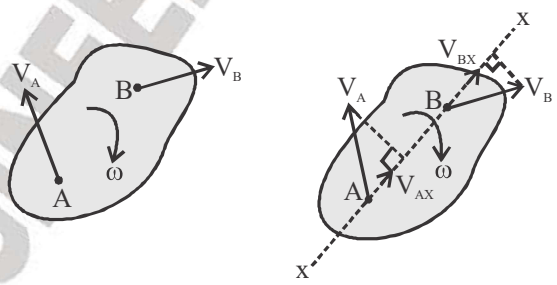
3.2 VELOCITY IN MECHANISM
Velocity analysis of a mechanism can be carried out by following methods:
(i) Relative velocity method
(ii) Instantaneous centre method

3.2.1 Relative Velocity Method
In the planar motion, rigid body has two motion like sliding an rotation as shown in figure



Consider a rigid link AB, which translate in X & Y direction as T_x & T_y respectively. Thus, both end of rigid link translate with same velocity and acceleration along the same path.
Now, consider a link AB, which has rotation along Z direction as R_z. thus, both end of rigid link rotate with same angular velocity and angular acceleration.

1. Direction of Velocity
Consider a rigid body rotating with angular speed (ω) and it has two points A & B on it. The velocity of point A & B are V_A & V_B respectively shown in the figure. Since, the velocity component V_{AX} & V_{BX} parallel to connecting line should be equal if V_{AX} & V_{BX} are if velocity component are different then following conditions may arise as:



(i) If V_B is greater than V_A, then, point B elongate the rigid body along V_A the direction of velocity V_{BX} which is impossible.

CHAPTER - 4
DYNAMICS OF MACHINE

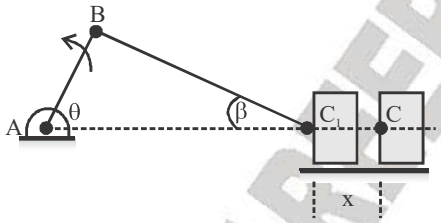
4.1 INTRODUCTION
Dynamic deals with study of forces acting upon the various parts of machine. Dynamic forces are always present when machines working under full or part load condition.

4.1.1 D'Alembert's Principle
It states that, the inertia force and couples, and the external force and torques on a body together gives statically equilibrium.

Thus, $\Sigma F + F_i = 0$

and $\Sigma T + C_i = 0$

4.2 SLIDER-CRANK MECHANISM
Let, the crank AB has turned through angle θ from inner dead centre (IDC) and slider changes its position C to C_1 with displacement X.



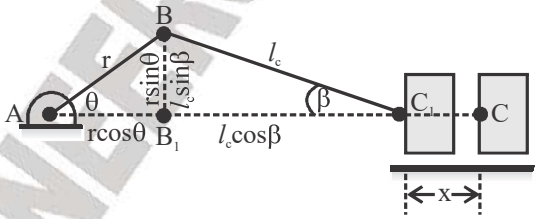
4.2.1 Displacement of Piston
It is a distance travel by piston.

$x = C C_1 = CA - C_1 A$

$x = (l_c + r) - (r\cos\theta + l_c \cos\beta)$

$= (nr + r) - (r\cos\theta + nr\cos\beta)$ $[\therefore n = l_c / r]$

$= r[n + 1 - \cos\theta - n\cos\beta]$



Where,

$\sin^2\beta + \cos^2\beta = 1$

$\cos\beta = \sqrt{1 - \sin^2\beta}$

At BB_1, $r\sin\theta = l_c \sin\beta$

$\sin\beta = \sin\theta \times \frac{r}{l_c} = \frac{\sin\theta}{n}$

CHAPTER - 5
BALANCING

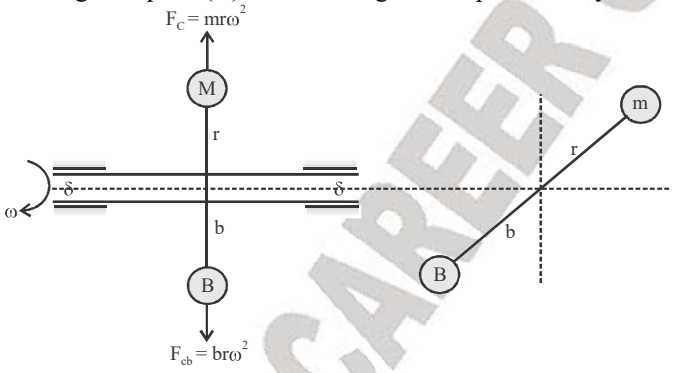
5.1 INTRODUCTION

In an every machine there are two types of parts are commonly used as: rotating part and reciprocating part. It is necessary to balance both types of parts in the machines to avoid unbalance force components. These unbalanced focus case excessive noise, vibrations or and fear of the system.

Meanwhile now days high speed engines and other machines are requirement of each every industry. Thus, it is very essential to balance the machines to reduce or eliminate unbalanced forces.

5.2 BALANCING OF A SINGLE ROTATING MASS

Whenever a certain mass is attached to a rotating shaft, it exists centrifugal force which tends to bend the shaft and produce vibration and also produce lends on bearings. To eliminate the effect of centrifugal force we should attach an another balanced mass in opposite directions in such a way that it eliminate effect of centrifugal force. Let us consider a mass (m) is attached to the shaft which is rotating at an angular speed (w) and centrifugal force produced by this mass is F_C. Thus



$$F_c = F_{cb}$$

$$mr\omega^2 = Bb\omega^2$$

$$mr = Bb$$

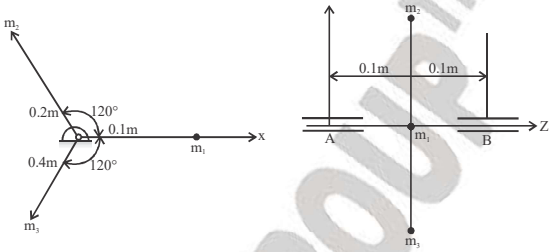
1. Product of mass × radius will be remains same for both original mass and balanced mass respectively.
2. Usually radius of balanced mass is taken larger to reduce the balance mass.
3. Both mass will rotate at same angular speed.

5.3 EXTERNAL BALANCING OF SINGLE ROTATING MASS

If in any case balancing mass cannot possible to place just equal and opposite to original mass then external balancing of mass can be used. In such case, balanced mass to be placed in different plane but the balancing cannot be achieved by single mass because due to difference in planes the

GATE QUESTIONS

1. Three masses are connected to a rotating shaft supported on bearings A and B as shown in the figure. The system is in space where the gravitational effect is absent. Neglect the mass of shaft and rods connecting the masses. For m_1 = 10 kg, m_2 = 5 kg and m_3 = 2.5 kg and for a shaft angular speed of 1000 radian/s, the magnitude of the bearing reaction (in N) at location B is _____



[GATE - 2017]

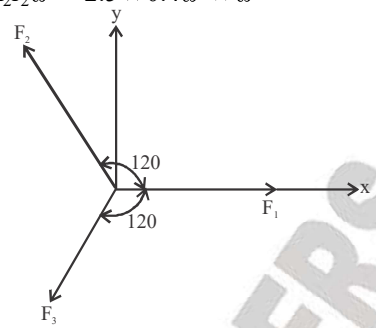
SOLUTIONS

Sol. 1. (0)

$F_1 = m_1r_1\omega^2 = 10 \times 0.1 \times \omega^2 = \omega^2$

$F_2 = m_2r_2\omega^2 = 5 \times 0.2 \times \omega^2 = \omega^2$

$F_2 = m_2r_2\omega^2 = 2.5 \times 0.4\omega^2 \times \omega^2$



$\Sigma F_x = \omega^2[1 + \cos120° + \cos120°] = 0$

$\Sigma F_y = F_2\cos30° - F_3\cos30° = 0$

$\therefore$ Net force = 0

$\therefore$ Bearing reactions = 0 N

CHAPTER - 6
GOVERNORS

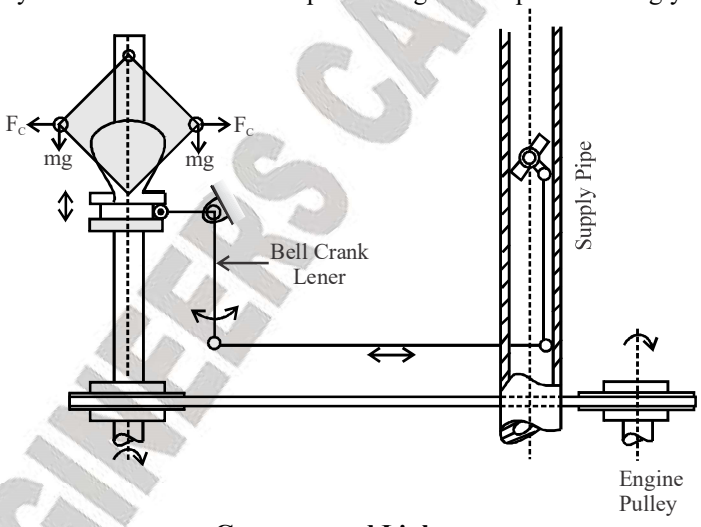
6.1 INTRODUCTION

The flywheel which minimizes fluctuations of speed within the cycle but it cannot minimize fluctuations due to load variation. This means flywheel does not exercise any control over mean speed of the engine. To minimize fluctuations in the mean speed which may occur due to load variation, governor is used. The governor has no influence over cyclic speed fluctuations but it controls the mean speed over a long period during which load on the engine may vary.

When there is change in load, variation in speed also takes place then governor operates a regulatory control and adjusts the fuel supply to maintain the mean speed nearly constant. Therefore, the governor automatically regulates through linkages, the energy supply to the engine as demanded by variation of load so that the engine speed is maintained nearly constant.

The sketch of a governor along with linkages which regulates the supply to the engine. The governor shaft is rotated by the engine shown in the figure. If load on the engine increases the engine speed tends to reduce, as a result of which governor balls move inwards. This causes sleeve to move downwards and this movement is transmitted to the valve through linkages to increase the opening and, thereby, to increase the supply.

On the other hand, reduction in the load increases engine speed. As a result of which the governor balls try to fly outwards. This causes an upward movement of the sleeve and it reduces the supply. Thus, the energy input (fuel supply in IC engines, steam in steam turbines, water in hydraulic turbines) is adjusted to the new load on the engine. Thus the governor senses the change in speed and then regulates the supply. Due to this type of action it is simple example of a mechanical feedback control system which senses the output and regulates input accordingly.



Governor and Linkages

6.2 CLASSIFICATION OF GOVERNORS

The broad classification of governor can be made depending on their operation.

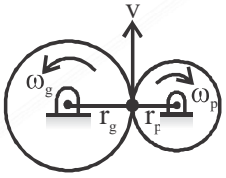
1. Centrifugal governors
2. Inertia and flywheel governors
3. Pickering governors

CHAPTER - 7
GEARS & GEAR TRAINS

7.1 INTRODUCTION

Gears are used to transmit rolling and a sliding motion along the tangent at the point of contract. It can be successfully possible by the engagement of teeth.

The concept of gears has been derived from the rolling of two cylinders or disc. If there is no slip to be assumed in such case, that can definitely transit motion of one to another and vice-versa. The rotating discs are known as friction wheels.



At a point of contact, the same linear velocity can be obtained as

$$v = \omega_g . r_g = \omega_p . r_p$$

$$v = 2\pi N_g r_g = 2\pi N_p r_p$$

or $$\frac{N_g}{N_p} = \frac{r_p}{r_g}$$

or $$\frac{\omega_g}{\omega_p} = \frac{r_p}{r_g}$$

It gives that, the speed of the two rolling discs without slipping is always proportional to the radii of the discs.

The friction wheels can be used to transmit motion at lower speeds. At high speeds it is not possible to transmit continuous motion without slipping. Thus, the concept of gear has been introduced to transmit motion and power at smaller centre distance. This lead to the formation of teeth on the discs and the motion between the surface changes from rolling to sliding. The disc with teeth are called as gear or gear wheel.

To obtain large reduction in velocity sometimes, two or more pair of gears may be used which is called as gear trains.

7.2 ADVANTAGES OF GEARS

Gear has many advantage over belt & chain drive.

1. It can transmit exact velocity ratio with positive drive.
2. It is capable of transmitting higher power.
3. It require less space, which gives compact layout.
4. It gives reliable service with high efficiency.

7.3 CLASSIFICATION OF GEARS

Gear can be classified according to their relative position of axes of the shaft as:

CHAPTER - 8
VIBRATIONS

8.1 INTRODUCTION

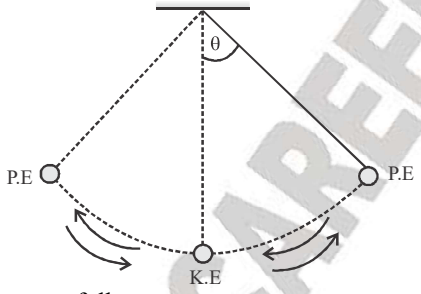
All bodies having mass and elasticity are capable of vibration. The mass is inherent of the body and elasticity can relative motion among its parts.

When body particles are displaced by the application of external force, the internal force in the form of elastic energy are present in the body. These forces try to bring the body to its original position.

At equilibrium position, the whole of the elastic energy is converted into kinetic energy and body continues to move in the opposite direction because of it. The whole of the K.E. is again converted into elastic or strain energy due to which the body again returns to the equilibrium position. In this way vibratory motion is repeated indefinitely and exchange of energy takes place.

This, any motion which repeats itself after an internal of time is called vibration or oscillation

Example. Simple pendulum, Spring mass system



The main reasons of vibration are as follows

1. Unbalanced centrifugal force in the system. This is caused because of non uniform material distribution in a rotating machine element.
2. Elastic nature of the system
3. External excitation applied on the system
4. Winds may cause vibrations of certain systems such as electricity lines, telephone lines etc.

8.1.1 Advantages of Vibrations

1. Vibration can be used for useful purposes such as vibration testing equipments, vibrations conveyors, hoppers, sieves and compactors.
2. Vibration is found very fruitful in mechanical workshops such as in improving the efficiency of machining, casting, forging and welding techniques, musical instruments and earth quakes for geological research. Etc.
3. It is very useful for propagation of sound.

8.1.2 Disadvantages of Vibration

1. The vibration causes rapid wear of m/c parts such as bearing and gears.
2. Unwanted vibrations may cause loosening of parts from the machine.
3. Many buildings, structures and bridges fall because of vibration.
4. Mechanical failure of the system if the frequency of excitation coincides with one of the natural frequency of the system, a condition of resonance is reached.
5. Sometimes because of heavy vibrations readings of instruments cannot be taken.

ESE OBJ QUESTIONS

1. A simple spring- mass vibrating system has a natural frequency of N. If the spring stiffness is halved and the mass doubled, then the natural frequency will be

[ESE - 2017]

(a) 0.5 N (b) N
(c) 2 N (d) 4 N

2. A car of mass 1450 kg is constructed on a chasis supported by four springs. Each spring has a force constant of 40000 N m. The combined mass of the two people occupying the car is 150 kg. What is the period of execution of two complete vibrations?

[ESE - 2017]

(a) 0.63 s (b) 1.59 s
(c) 4.96 s (d) 1.26 s

3. Consider the following statements:
Artefacts to prevent harmful effects resulting from vibrations of an unbalanced machine fixed on its foundation include
(i)Mounting the machine on springs thereby minimizing the transmission of forces.
(ii)Using vibration isolating materials to prevent or reduce the transmission of forces.
(iii) Moving the foundation so as to have only one degree of freedom towards reducing the transmission of forces.
Which of the above statements are correct?

[ESE -2017]

(a) (i) and (ii) only (b) (i) and (iii) only
(c) (ii) and (iii) only (d) (i), (ii) and (iii)

4. Two heavy rotors are mounted on a single shaft. Considering each of the rotors separately, the transverse natural frequencies are 100 cycles/s and 200 cycles/s, respectively. The lower critical speed will be

[ESE - 2017]

(a) 12000 r.p.m. (b) 9360 r.p.m.
(c) 8465 r.p.m. (d) 5367 r.p.m.

5. The equation of motion of a linear vibratory system with a single degree of freedom is $4\ddot{x}+9\dot{x}+16x=0$
The critical damping coefficient for the system is

[ESE - 2016]

(a) 32 (b) 16
(c) 8 (d) 4

6. A coil-spring of stiffness k is cut exactly at the middle and the two springs thus made are arranged in parallel to take up together a compressive load. The equivalent stiffness of the two springs is

[ESE - 2016]

(a) 0.25 k (b) 0.5 k
(c) 2 k (d) 4 k

7. A helical spring of 10 N/mm rating is mounted on top of another helical spring of 8 N/mm rating. The force required for a total combined deflection of 45 mm through the two springs is

[ESE - 2016]

(a) 100 N (b) 150 N
(c) 200 N (d) 250 N

8. The speed rating for turbine rotors is invariably more than $\sqrt{2}$ times its natural frequency to

[ESE - 2015]

(a) Increase stability under heavy load and huge speed
(b) Isolate vibration of the system from the surrounding
(c) Minimize deflection under dynamic loading as well as to reduce transmissibility of force to the surrounding
(d) None of the above.

9. A block of mass 10 kg is placed at the free and of a cantilever beam of length 1 m and second moment of area 300 mm^4. Taking Young's modulus of the beam material as 200 GPa, the natural frequency of the system is

[ESE - 2015]

(a) $30\sqrt{2}$ rad/s (b) $2\sqrt{3}$ rad/s
(c) $3\sqrt{2}$ rad/s (d) $20\sqrt{3}$ rad/s

GATE QUESTIONS

1. The damping ratio for a viscously damped spring mass system, governed by the relationship

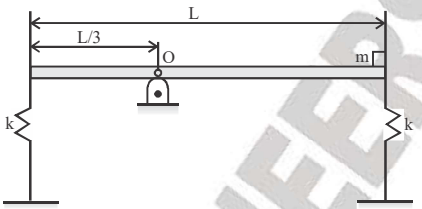
$m\frac{d^2x}{dt^2}+c\frac{dx}{dt}+kx=F(t)$, is given by

[GATE - 2017]

(a) $\sqrt{\frac{c}{mk}}$ (b) $\frac{c}{2\sqrt{km}}$

(c) $\frac{c}{\sqrt{km}}$ (d) $\sqrt{\frac{c}{2mk}}$

2. A thin uniform rigid bar of length L and mass M is hinged at point O, located at a distance of $\frac{L}{3}$ from one of its ends. The bar is further supported using springs, each of stiffness k, located at the two ends. A particle of mass m = $\frac{M}{4}$ is fixed at one end of the bar, as shown in the figure. For small rotations of the bar about O, the natural frequency of the system is

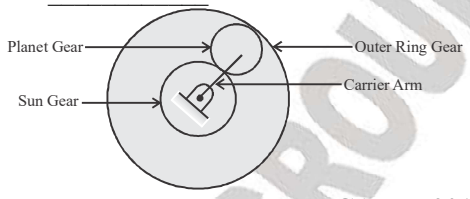


[GATE - 2017]

(a) $\sqrt{\frac{5k}{M}}$ (b) $\sqrt{\frac{5k}{2M}}$

(c) $\sqrt{\frac{3k}{2M}}$ (d) $\sqrt{\frac{3k}{M}}$

3. In an epicyclic gear train, shown in the figure, the outer ring gear is fixed, while the sun gear rotates counterclockwise at 100 rpm. Let the number of teeth on the sun, planet and outer gears to be 50, 25 and 100 respectively. The ratio of magnitudes of angular velocity of the planet gear to the angular velocity of the carrier arm is _____.



[GATE - 2017]

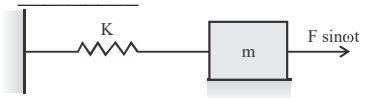
4. The radius of gyration of a compound pendulum about the point of suspension is 100 mm. The distance between the point of suspension and the centre of mass is 250 mm. Considering the acceleration due to gravity as 9.81 m/s^2, the natural frequency (in radian/s) of the compound pendulum is _____

[GATE - 2017]

5. The static deflection of a spring under gravity, when a mass of 1kg is suspended from it, is 1 mm. Assume the acceleration due to gravity g = 10 m/s^2. The natural frequency of this spring-mass system (in rad/s) is _____

[GATE - 2016]

6. A single degree of freedom spring-mass system is subjected to a harmonic force of constant amplitude. For an excitation frequency of $\sqrt{\frac{3k}{m}}$, the ratio of the amplitude of steady state response to the static deflection of the spring is _____



[GATE - 2016]

7. A single degree of freedom mass-spring – viscous damper system with mass m, spring constant k and viscous damping coefficient q is critically damped. The correct relation among m, k and q is

[GATE - 2016]

(a) $q=\sqrt{2km}$ (b) $q=2\sqrt{km}$