



JAIPUR ENGINEERING COLLEGE
AND RESEARCH CENTRE

JAIPUR ENGINEERING COLLEGE AND RESEARCH CENTRE

JECRC Campus, Shri Ram ki Nangal, Via-Vatika , Tonk Road, Jaipur

Department of Mechanical Engineering

Name of Subject: Engineering Mechanics

Subject Code: 3ME3-04

Year: 2nd Year, 3rd Semester



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Department of Mechanical Engineering

Vision and Mission of Institute:

Vision: To become a renowned center of outcome based learning, and work towards academic, professional, cultural and social enrichment of the lives of individuals and communities.

Mission:

M1: Focus on evaluation of learning outcomes and motivate students to inculcate research aptitude by project based learning.

M2: Identify, based on informed perception of Indian, regional and global needs, areas of focus and provide platform to gain knowledge and solutions.

M3: Offer opportunities for interaction between academia and industry.

M4: Develop human potential to its fullest extent so that intellectually capable and imaginatively gifted leaders can emerge in a range of professions.

Vision and Mission of Department:

Vision: The Mechanical Engineering Department strives to be recognized globally for outcome based technical knowledge and to produce quality human resource, who can manage the advance technologies and contribute to society.

Mission:

M1: To impart quality technical knowledge to the learners to make them globally competitive mechanical engineers.

M2: To provide the learners ethical guidelines along with excellent academic environment for a long productive career.

M3: To promote industry-institute relationship.



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Department of Mechanical Engineering

PROGRAM EDUCATIONAL OBJECTIVES (PEOS)

PEO1: To equip graduates with a strong foundation in engineering sciences, with an emphasis on mechanical engineering principles, enabling them to analyze, design, and solve real-world engineering challenges.

PEO2: To prepare graduates with sound scientific and engineering fundamentals to innovate and deliver effective solutions addressing practical challenges in mechanical engineering

PEO3: To inculcate in graduates a professional and ethical attitude, effective communication and teamwork skills, a multidisciplinary approach, entrepreneurial mindset, and the ability to connect engineering solutions with societal and environmental concerns.

PEO4: To provide students with an academic environment that fosters excellence, leadership, adherence to ethical standards, and encourages self-motivated lifelong learning essential for a successful professional career in mechanical

PEO5: To prepare students to excel in industry and higher education by providing quality education grounded in strong technical knowledge and high moral values

Program Specific Outcomes (PSOs)

PSO1: Graduates will be able to design, analyze, and fabricate electric and hybrid vehicles using modern engineering tools and sustainable practices.

PSO2: Graduates will be able to apply design principles and computational techniques, including programming and data structures, to analyze and solve mechanical engineering problems.



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Program Outcomes (POs)

- PO1: Engineering Knowledge:** Apply knowledge of mathematics, natural science, computing, engineering fundamentals and an engineering specialization as specified in WK1 to WK4 respectively to develop to the solution of complex engineering problems.
- PO2: Problem Analysis:** Identify, formulate, review research literature and analyze complex engineering problems reaching substantiated conclusions with consideration for sustainable development. (WK1 to WK4)
- PO3: Design/Development of Solutions:** Design creative solutions for complex engineering problems and design/develop systems/components/processes to meet identified needs with consideration for the public health and safety, whole-life cost, net zero carbon, culture, society and environment as required. (WK5)
- PO4: Conduct Investigations of Complex Problems:** Conduct investigations of complex engineering problems using research-based knowledge including design of experiments, modelling, analysis & interpretation of data to provide valid conclusions. (WK8).
- PO5: Engineering Tool Usage:** Create, select and apply appropriate techniques, resources and modern engineering & IT tools, including prediction and modelling recognizing their limitations to solve complex engineering problems. (WK2 and WK6)
- PO6: The Engineer and The World:** Analyze and evaluate societal and environmental aspects while solving complex engineering problems for its impact on sustainability with reference to economy, health, safety, legal framework, culture and environment. (WK1, WK5, and WK7).
- PO7: Ethics:** Apply ethical principles and commit to professional ethics, human values, diversity and inclusion; adhere to national & international laws. (WK9)
- PO8: Individual and Collaborative Team work:** Function effectively as an individual, and as a member or leader in diverse/multi-disciplinary teams.
- PO9: Communication:** Communicate effectively and inclusively within the engineering community and society at large, such as being able to comprehend and write effective reports and design documentation, make effective presentations considering cultural, language, and learning differences
- PO10: Project Management and Finance:** Apply knowledge and understanding of engineering management principles and economic decision-making and apply these to one's own work, as a member and leader in a team, and to manage projects and in multidisciplinary environments.
- PO11: Life-Long Learning:** Recognize the need for, and have the preparation and ability for i) independent and life-long learning ii) adaptability to new and emerging technologies and iii) critical thinking in the broadest context of technological change. (WK8)
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SYLLABUS

Credit: 2
2L+0T+0P

Max. Marks: 100 (IA:30, ETE:70)
End Term Exam: 2 Hours

Applicable to the students admitted from 2018-19 onwards		
SN	Contents	Hours
1	Statics of particles and rigid bodies: Fundamental laws of mechanics, Principle of transmissibility, System of forces, Resultant force, Resolution of force, Moment and Couples, Varignon's theorem, Resolution of a force into a force and a couple, Free body diagram, Equilibrium, Conditions for equilibrium, Lami's theorem. Plane trusses: Types of structures, Trusses, Support Conditions, Types of Loadings, Classification of trusses, Determinacy of trusses, Basic assumptions of truss analysis, Method of joints, Method of sections. Virtual work: Principle of Virtual Work, Active forces and active force diagram, Stability of equilibrium.	5
2	Centroid & Moment of inertia: Location of centroid and center of gravity, Moment of inertia, Parallel axis and perpendicular axis theorem, Radius of gyration, M.I of composite section, Polar moment of inertia, M.I of solid bodies. Lifting machines: Mechanical advantage, Velocity Ratio, Efficiency of machine, Ideal machine, Ideal effort and ideal load, Reversibility of machine, Law of machine, Lifting machines; System of pulleys, Simple wheel and axle, Wheel and differential axle, Weston's differential pulley block, Worm and worm wheel, Single purchase winch crab, Double purchase winch crab, Screw jack, Differential screw jack.	5
3	Friction: Types of Friction, Laws of friction, Angle of friction, Angle of repose, Ladder, Wedge, Belt Friction. Belt and Rope drive: Types of belts, Types of belt drives, Velocity ratio, Effect of slip on Velocity ratio, Crowding of pulleys, Length of belt, Ratio of tensions in flat belt drive, Power transmission by belt drives, Advantage and disadvantages of V-Belt over Flat Belt.	5
4	Kinematics of particles and rigid bodies: Velocity, Acceleration, Types of Motion, Equations of Motion, Rectangular components of velocity and acceleration, Angular velocity and Angular acceleration, Radial and transverse velocities and accelerations, Projectiles motion on plane and Inclined Plane, Relative Motion. Kinetics of particles and rigid bodies: Newton's second law, Equation of motion in rectangular coordinate, Equation of motion in radial and transverse components, Equation of motion in plane for a rigid body, D'Alembert principle.	5
5	Work, Energy and power: Work of a force, weight, spring force and couple, Power, Efficiency, Energy, Kinetic energy of rigid body, Principle of work and energy, Conservative and Non-conservative Force, Conservation of energy.	6
	Impulse and momentum: Linear and angular momentum, Linear and angular impulse, Principle of momentum for a particle and rigid body, Principle of linear impulse and momentum for a particle and rigid body, Principle of angular momentum and Impulse, Conservation of angular momentum, Angular momentum of rigid body, Principle of impulse and momentum for a rigid body, Central impact, Oblique impact, System of variable mass, Rocket.	
	TOTAL	26



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REFERENCE BOOKS (Engineering Mechanics)

Text Book

- Engineering Mechanics D.S. Kumar S K Kataria & Sons Publishers 5th Edition 2016.

Reference Books

- Engineering Mechanics R.C. Hibbeler Pearson, 15th Edition, 2023.
 - Engineering Mechanics S S Bhavikatti, New Age International Publishers 1st Edition, 2017.
 - Engineering Mechanics Statics and Dynamics Meriam J L Kraige L G, Wiley & Sons, 9th edition 2021.
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COURSE OUTCOME

Subject: Engineering Mechanics

Code: 3ME3-04

CO1. Apply laws of mechanics to analyze equilibrium of particles and rigid bodies.

CO2. Determine centroid, center of gravity, and moment of inertia for simple and composite bodies.

CO3. Analyze the effect of friction in engineering systems and solve related problems.

CO4. Solve problems related to motion of particles and rigid bodies using kinematics and kinetics.

CO5. Evaluate internal forces and reactions in beams, trusses, and frames under various loads.

CO6. Formulate innovative mechanical models for complex real-world systems

CO-PO MAPPING

CO	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PSO1	PSO2
CO1	2	3	1	1	2	2	1	2	2	1	2	3	2
CO2	2	2	1	2	1	1	1	1	1	1	3	3	2
CO3	3	2	2	2	2	1	2	2	2	2	2	2	3
CO4	3	3	2	3	3	1	1	1	1	1	2	3	3
CO5	3	2	3	2	3	1	1	1	1	1	2	3	3
CO6	3	2	2	2	2	1	1	1	1	1	3	2	2



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Course Plan

Name of the Course: **Engineering Mechanics**

Code of the course: **3ME3-04**

Name of Faculty: **Dr. Manoj Gupta**

Course Outcome

CO1. Apply laws of mechanics to analyze equilibrium of particles and rigid bodies.

CO2. Determine centroid, center of gravity, and moment of inertia for simple and composite bodies.

CO3. Analyze the effect of friction in engineering systems and solve related problems.

CO4. Solve problems related to motion of particles and rigid bodies using kinematics and kinetics.

CO5. Evaluate internal forces and reactions in beams, trusses, and frames under various loads.

CO6. Formulate innovative mechanical models for complex real-world systems

Unit	Topic	Lecture	CO	Specific Objectives	Expected Outcomes	Reference (DS Kumar)
Intro	Introduction, Objectives, Scope and Applications of Engineering Mechanics	1	NA	Explain the scope and importance of Engineering Mechanics	Understand course objectives and engineering applications	Ch.1
1	Fundamental Laws of Mechanics, SI Units	2	CO1	Explain fundamental laws	Apply basic principles of mechanics	Ch.1
1	Force Systems, Resultant and Resolution of Forces	3	CO1	Explain force systems	Determine resultant forces	Ch.2
1	Moments, Couples and Varignon's Theorem	4	CO1	Explain moment concepts	Solve moment problems	Ch.2
1	Free Body Diagram and Equilibrium	5	CO1	Construct free body diagrams	Analyze equilibrium of rigid bodies	Ch.3
1	Lami's Theorem and Applications	6	CO1	Apply equilibrium conditions	Solve concurrent force problems	Ch.3



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	Types, Assumptions and Support Conditions			truss behavior	members and supports	
1	Method of Joints	8	CO5	Analyze trusses	Determine internal member forces	Ch.5
1	Method of Sections	9	CO5	Apply section method	Evaluate member forces efficiently	Ch.5
1	Principle of Virtual Work and Stability	10	CO5	Explain virtual work	Analyze equilibrium using virtual work	Ch.6
2	Centroid and Centre of Gravity	11	CO2	Explain centroid concepts	Determine centroid locations	Ch.7
2	Composite Sections	12	CO2	Apply centroid principles	Calculate centroid of composite bodies	Ch.7
2	Moment of Inertia and Radius of Gyration	13	CO2	Explain moment of inertia	Calculate MOI of sections	Ch.8
2	Parallel & Perpendicular Axis Theorems	14	CO2	Apply axis theorems	Evaluate MOI efficiently	Ch.8
2	Polar MOI and MOI of Solid Bodies	15	CO2	Explain polar MOI	Calculate MOI of solids	Ch.8
2	Mechanical Advantage, Velocity Ratio & Efficiency of Lifting Machines	16	CO2	Explain lifting machine concepts	Analyze lifting machine performance	Ch.9
2	Screw Jack, Pulley Block, Wheel & Axle, Winch Crab	17	CO2	Analyze lifting mechanisms	Solve lifting machine problems	Ch.9
3	Types of Friction, Laws of Friction, Angle of Friction & Repose	18	CO3	Explain frictional behavior	Solve dry friction problems	Ch.10
3	Ladder and Wedge Friction	19	CO3	Apply friction concepts	Analyze ladder and wedge systems	Ch.10
3	Belt Friction and	20	CO3	Explain belt	Determine belt	Ch.11



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3	Rope Drives, Velocity Ratio, Slip and Power Transmission	21	CO3	Explain rope drives	Analyze power transmission systems	Ch.11
3	Engineering Applications of Friction (Brakes, Clutches & Bearings)	22	CO3	Apply friction principles	Select suitable engineering systems	Activity
3	Numerical Problem Solving on Friction and Belt Drives	23	CO3	Integrate friction concepts	Solve comprehensive engineering problems	Tutorial
4	Kinematics of Particles: Velocity and Acceleration	24	CO4	Explain particle motion	Solve kinematic problems	Ch.12
4	Relative Motion and Projectile Motion	25	CO4	Analyze relative motion	Solve projectile problems	Ch.12
4	Rigid Body Motion, Angular Velocity & Acceleration	26	CO4	Explain rigid body motion	Analyze rotational motion	Ch.13
4	Newton's Second Law and Equations of Motion	27	CO4	Apply Newton's laws	Solve kinetics problems	Ch.13
5	D'Alembert Principle, Work, Energy and Power	28	CO4	Explain dynamic equilibrium	Solve work- energy problems	Ch.14
5	Conservation of Energy	29	CO4	Apply energy principles	Analyze engineering systems	Ch.14
5	Linear & Angular Momentum	30	CO5	Explain momentum principles	Calculate momentum	Ch.15
5	Impulse- Momentum Principle and Impact	31	CO5	Apply impulse concepts	Analyze impact problems	Ch.15
5	Variable Mass Systems and Rocket Motion	32	CO5	Explain variable- mass systems	Analyze rocket motion	Ch.15
Application	Engineering Mechanics in	33	CO6	Integrate mechanics	Apply mechanics to	Case Study



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	(Brakes, Hoists, Cranes, Lifting Systems)			machine design	design	
Application	Mechanical Modeling of Truss Bridges, Robot Arms, Vehicle Suspension and Bicycle Frames	34	CO6	Develop analytical mechanical models	Formulate real-world engineering models	Activity
Review	Integrated Design Challenge, Numerical Problem Solving and Course Review	35	CO6	Integrate concepts from all units	Formulate innovative mechanical models for complex real-world systems	All Chapters

Reference Books

- Engineering Mechanics R.C. Hibbeler Pearson, 15th Edition, 2023.
- Engineering Mechanics S S Bhavikatti, New Age International Publishers 1st Edition, 2017.
- Engineering Mechanics Statics and Dynamics Meriam J L Kraige L G, Wiley & Sons, 9th edition 2021.



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UNIT CONVERSION	
1 m = 100 cm = 1000 mm 1 km = 1000 m 1 cm ² = 100 mm ² 1 m ² = 10 ⁶ mm ² 1 kgf = 9.81 N = 10 N 1 kN = 10 ³ N	1 Mpa = 1 N/mm ² 1 Gpa = 10 ³ N/mm ² 1 Pascal = 1 N/m ² 1 degree = $\frac{\pi}{180}$ radians

QUANTITY					
Scalar Quantity: “A Scalar Quantity is one which can be completely specified by its magnitude only”			Vector Quantity: “A vector Quantity is one which requires magnitude and direction both to completely specified it”		
Length	Mass	Distance	Displacement	Force	Weight
Density	Area	Temperature	Velocity	Angular displacement	Acceleration
Volume	Speed	Time	Angular velocity	Momentum	Angular acceleration
Energy	Work	Moment of inertia	Moment	impulse	

Space: It is a region in all directions encompassing the universe. It is a geometric position occupied by bodies. These positions are describe by linear or angular measurements with reference to a defined system of co-ordinates.

Time: Time is a measurement to measure a duration between successive events. In the study of statics time does not play important role. In dynamics time is very important parameter. In all system of units, unit of time is second.

Particle: A particle is ideally dimensionless. But it has a very small mass.

Rigid body: No body is perfectly rigid, however rigid body is defined as a body in which particles do not change their relative positions under the action of any force or torque. Rigid body is ideal body. When the body does not deform under the action of A force or A torque, body is said rigid.

Deformable body: When a body deforms due to A force or A torque it is said deformable body. Material generates stresses against deformation.

Force: Force is an agent, which generates or tends to generate and destroy or tends to destroy the motion in a body.

Characteristics of a force:

- It has a magnitude
- It has a direction
- It is a vector quantity
- It has a point of application
- It has a nature
 - Tensile force
 - Compressive force
 - Pull force
 - Push force

SYSTEM OF FORCES

When two or more forces act on a body, they are called to for a system of forces.

Coplanar forces: The forces, whose lines of action lie on the same plane, are known as coplanar forces.

Collinear forces: The forces, whose lines of action lie on the same line, are known as collinear forces.

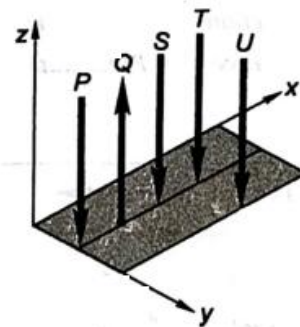
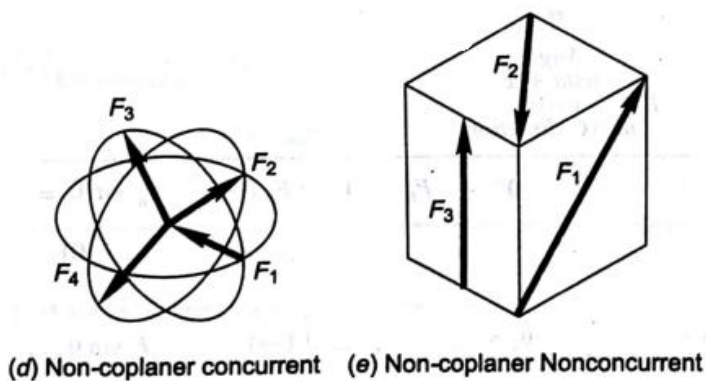
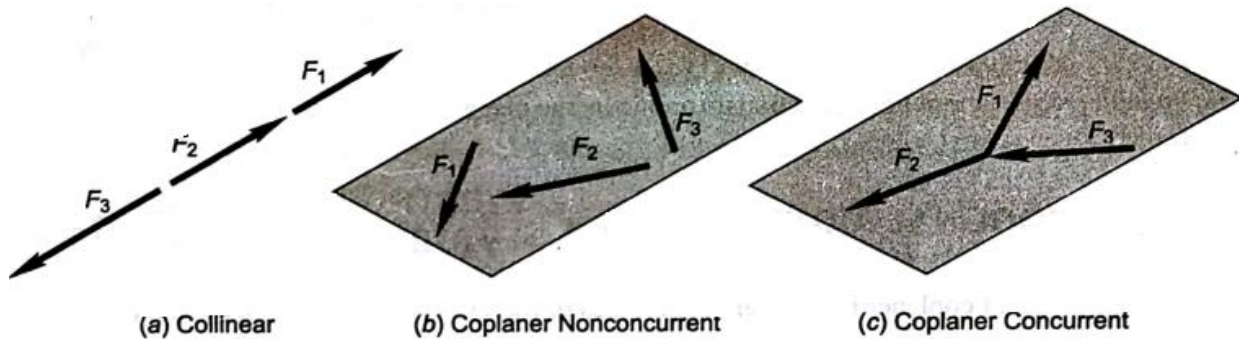
Concurrent forces: The forces, which meet at one point, are known as concurrent forces. The concurrent forces may or may not be collinear.

Coplanar concurrent forces: The forces, which meet at one point and their line of action also lay on the same plane, are known as coplanar concurrent forces.

Coplanar non-concurrent forces: The forces, which do not meet at one point, but their lines of action lie on the same, are known as coplanar non-concurrent forces.

Non-Coplanar concurrent forces: The forces, which meet at one point, but their lines of action do not lie on the same plane, are known as non-coplanar concurrent forces.

Non-Coplanar non-concurrent forces: The forces, which do not meet at one point and their lines of action do not lie on the same plane, are called non-coplanar non-concurrent forces.

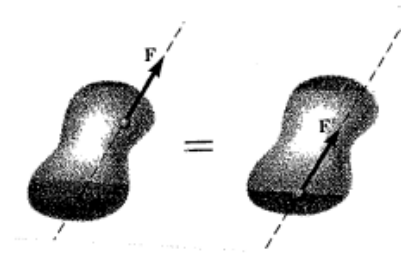
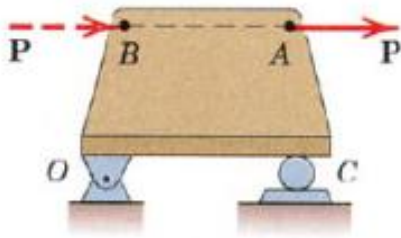


(f) Parallel Forces

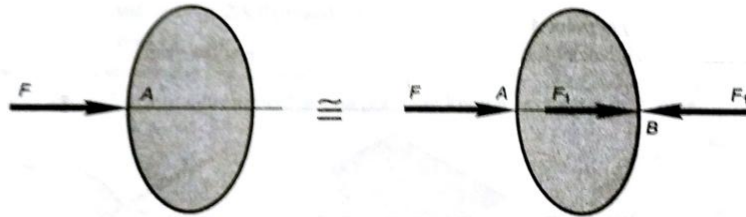
1. Like – $[P - S - T - U]$
2. Unlike $[All]$
3. Coplaner – $[P - Q - S - T]$
4. Non-Coplaner $[All]$

Principle of transmissibility:

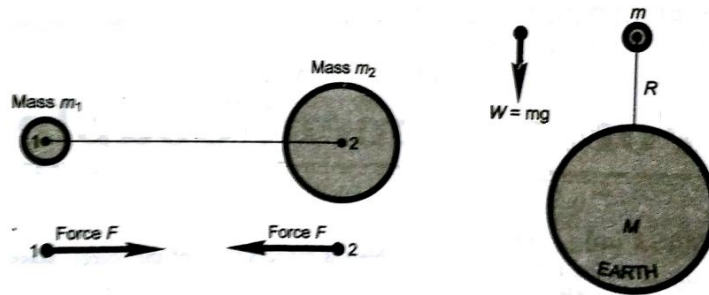
The principle of transmissibility states that a force may be applied at any point on its given line of action without altering the resultant effects of the force external to the rigid body on which it acts. Thus, whenever we are interested in only the resultant external effects of a force, the force may be treated as a sliding vector, and we need specify only the magnitude, direction, and line of

**Principle of superposition:**

The effect of a force on a body remains same or remains unaltered if a force system, which is in equilibrium, is added to or subtracted from it.

**Law of Gravitation:**

Magnitude of gravitational force of attraction between two particles is proportional to the product of their masses and inversely proportional to the square of the distance between their centers.

**Law of parallelogram of force:**

“Two force acting simultaneously on a body. If represented in magnitude and direction by the two adjacent side of a parallelogram then the diagonal of the parallelogram, from the point of intersection of above two forces, represents the resultant force in magnitude and direction”

As shown in fig P and Q are the forces acting on a body are taken as two adjacent sides of a parallelogram ABCD as shown in Fig. so diagonal AC gives the resultant ”R”.

The resultant can be determine by drawing the force with magnitude direction or mathematically is given as following:

$$R = \sqrt{P^2 + Q^2 + 2PQ\cos\theta}$$

$$\tan\alpha = \frac{Q \sin \theta}{P + Q \cos \theta}$$

➤ **Force:**

“An agent which produces or tends to produce, destroys or tends to destroy motion of body is called force”

Unit: N, kN, Kg etc.

Quantity : Vector

Characteristics of Force:

- 1) **Magnitude:** Magnitude of force indicates the amount of force (expressed as N or kN) that will be exerted on another body
- 2) **Direction:** The direction in which it acts
- 3) **Nature:** The nature of force may be tensile or compressive
- 4) **Point of Application:** The point at which the force acts on the body is called point of application

Types of Forces:

- Contact Force
- Body force
- Point force and distributed force
- External force and internal force
- Action and Reaction
- Friction force
- Wind force
- Hydrostatic force
- Cohesion and Adhesion
- Thermal force

System of Forces:

- Coplanar Forces
- Concurrent forces
- Collinear forces
- Coplanar concurrent forces
- Coplanar non-concurrent forces
- Non-coplanar concurrent forces
- Non-coplanar non-concurrent forces
- Like parallel forces
- Unlike parallel forces
- Spatial forces

➤ **Principle of Individual Forces**

1) Principle of transmissibility:

“If a force acts at a point on a rigid body, it may also be considered to act at any other point on its line of action, provided the point is rigidly connected with the body.”

2) Principle of Superposition of forces:

“If two equal, opposite and collinear forces are added to or removed from the system of forces, there will be no change in the position of the body. This is known as principle of superposition of forces.”

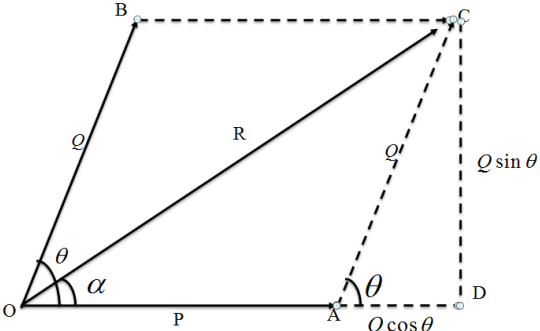
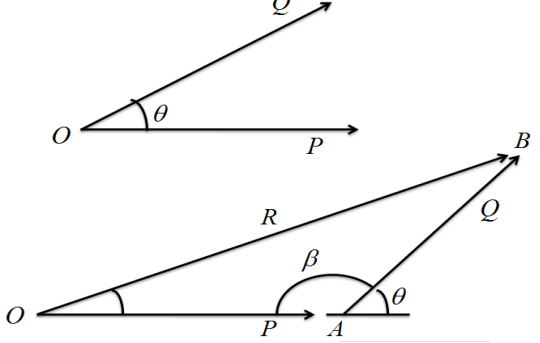
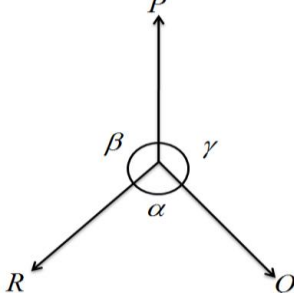
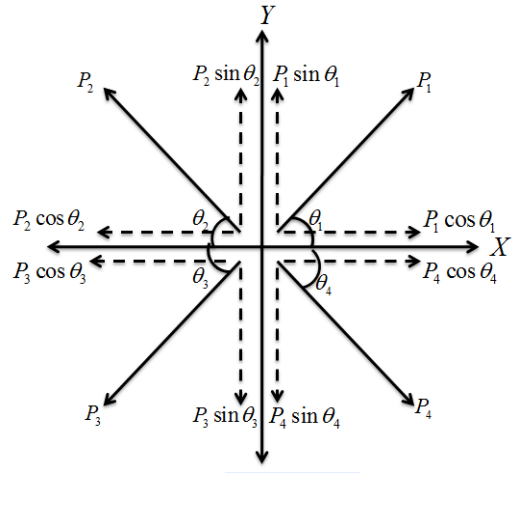
COPLANAR CONCURRENT FORCES

Resultant Force:

If number of Forces acting simultaneously on a particle, it is possible to find out a single force which could replace them or produce the same effect as of all the given forces is called resultant force.

Methods of Finding Resultant:-

- 1) Parallelogram Law of Forces (For 2 Forces)
- 2) Triangle Law (For 2 Forces)
- 3) Lami's theorem (For 3 forces)
- 4) Method of resolution (For more than 2 Forces)

[1]	Parallelogram law of forces $R = \sqrt{P^2 + Q^2 + 2PQ \cos \theta}$ $\tan \alpha = \frac{Q \sin \theta}{P + Q \cos \theta}$ Where, R = Resultant force θ = angle between P and Q α = angle between P and R	
[2]	Triangle law of forces $R = \sqrt{P^2 + Q^2 - 2PQ \cos \beta}$ Where, $\beta = 180^\circ - \theta$ R = Resultant force θ = angle between P and Q α = angle between P and R $\alpha = \sin^{-1} \left(\frac{Q}{R} \sin \beta \right)$	
[3]	Lami's theorem $\frac{P}{\sin \alpha} = \frac{Q}{\sin \beta} = \frac{R}{\sin \gamma}$ Where, P, Q, R are given forces α = angle between Q and R β = angle between P and R γ = angle between P and Q	
[4]	Resolution of concurrent forces $\sum H = P_1 \cos \theta_1 + P_2 \cos \theta_2 + P_3 \cos \theta_3 + P_4 \cos \theta_4$ $\sum V = P_1 \sin \theta_1 + P_2 \sin \theta_2 + P_3 \sin \theta_3 + P_4 \sin \theta_4$ $R = \sqrt{(\sum H)^2 + (\sum V)^2}$ $\tan \theta = \left \frac{\sum V}{\sum H} \right $ Where, P_1, P_2, P_3, P_4 are given forces $\theta_1, \theta_2, \theta_3, \theta_4$ are angle of accordingly P_1, P_2, P_3, P_4 forces from X-axes R = Resultant of all forces θ = angle of resultant with horizontal	

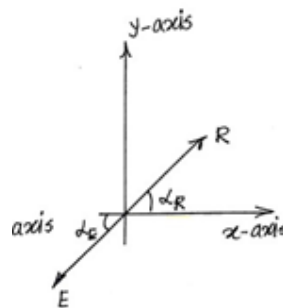
➤ **Equilibrium:**

Equilibrium is the status of the body when it is subjected to a system of forces. We know that for a system of forces acting on a body the resultant can be determined. By Newton's 2nd Law of Motion the body then should move in the direction of the resultant with some acceleration. If the resultant force is equal to zero it implies that the net effect of the system of forces is zero this represents the state of equilibrium. For a system of coplanar concurrent forces for the resultant to be zero hence

$$\begin{aligned}\sum f_x &= 0 \\ \sum f_y &= 0\end{aligned}$$

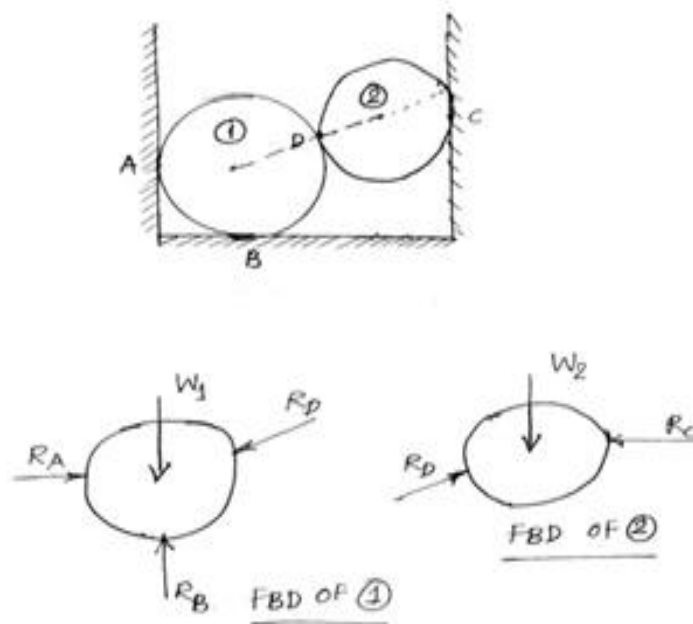
➤ **Equilibrant:**

Equilibrant is a single force which when added to a system of forces brings the status of equilibrium. Hence this force is of the same magnitude as the resultant but opposite in sense. This is depicted in figure.



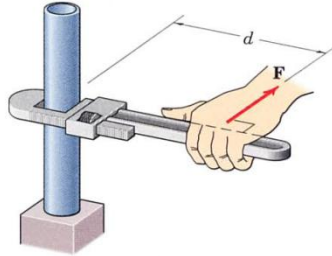
➤ **Free Body Diagram:**

Free body diagram is nothing but a sketch which shows the various forces acting on the body. The forces acting on the body could be in form of weight, reactive forces contact forces etc. An example for Free Body Diagram is shown below.



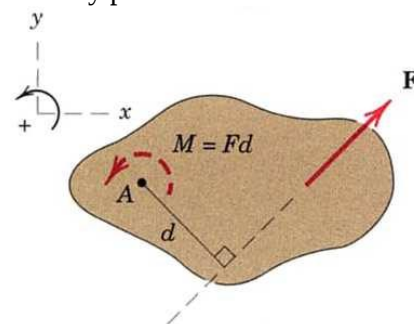
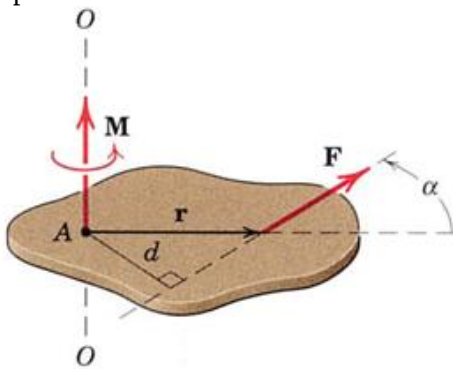
Moment

A force can tend to rotate a body about an axis which neither intersects nor is parallel to the line of action of the force. This rotational tendency is known as the moment M of a force.



The moment M of a force F about a point A is defined using cross product as $\mathbf{M}_A = \mathbf{r} \times \mathbf{F}$

Where $\mathbf{r}$ is a position vector which runs from the moment reference point A to any point on the line of action of F .



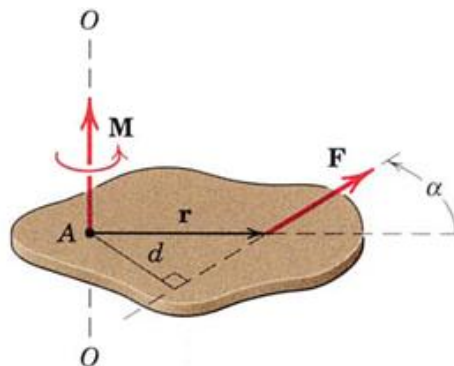
Note $\mathbf{r} \times \mathbf{F} = \mathbf{F} \times \mathbf{r}$.

Moment about a point A means here : Moment with respect to an axis normal to the plane and passing through the point A .

The magnitude M of the moment is defined as:

$$M_{(A)} = F \times r \sin \alpha = F \times d$$

Where d is the moment arm and is defined as the perpendicular distance between the line of action of the force and the moment center.

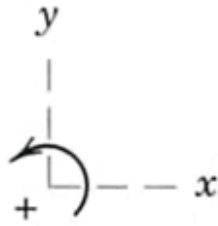


The moment M is a vector quantity. Its direction is perpendicular to the $\mathbf{r}$ - $\mathbf{F}$ -plane.

The sense of M depends on the direction in which F tends to rotate the body $\rightarrow$ right-hand rule

(+): counter clockwise rotation.

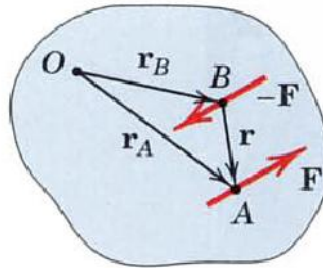
(-): clockwise rotation.



Sign consistency with in a given problem is very important. The moment M may be considered sliding vector with a line of action coinciding with the moment axis.

Couple

The moment produced by two equal, opposite, parallel, and no collinear forces is called a couple. The force resultant of a couple is zero. Its only effect is to produce a tendency of rotation.



The moment M of a couple is defined as

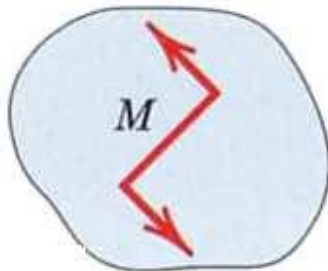
$$\mathbf{M} = \mathbf{r}_A \times \mathbf{F} - \mathbf{r}_B \times \mathbf{F} = (\mathbf{r}_A - \mathbf{r}_B) \times \mathbf{F}$$

$$\mathbf{M} = \mathbf{r} \times \mathbf{F}$$

Where $\mathbf{r}_A$ and $\mathbf{r}_B$ are position vectors which run from point O to Arbitrary points A and B on the lines of action of $\mathbf{F}$ and $-\mathbf{F}$.

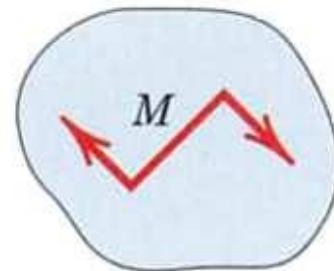
The moment expression contains no reference to the moment center O and, therefore, is the same for all moment centers the moment of a couple is a free vector.

The sense of the moment M is established by the right-hand rule.

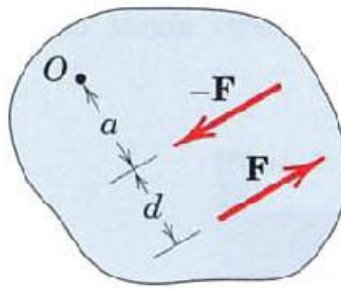


Counter clockwise couple (-)

The magnitude of the couple is independent of the distance.

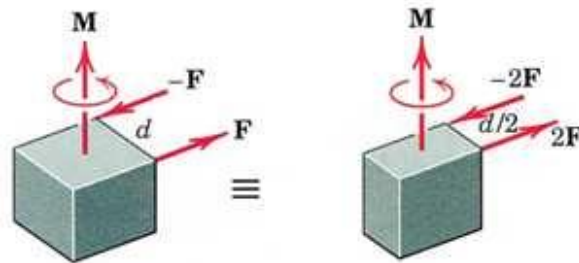


Clock wise couple(+)

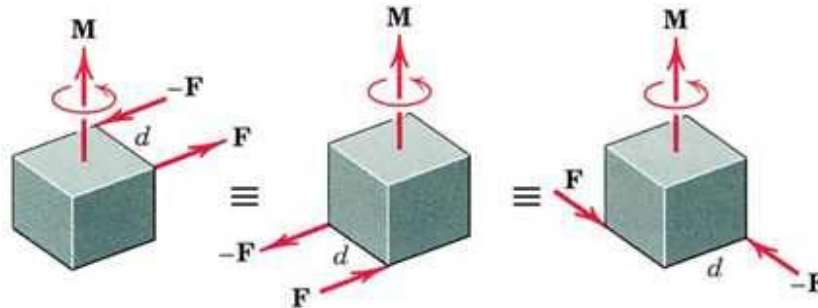


Equivalent Couples

Changing the values of F and d does not change a given couple as long as the product Fd remains the same.



A couple is not affected if the forces act in a different but parallel plane.



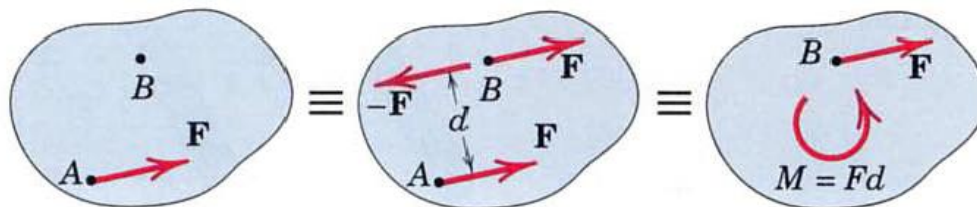
Force-Couple Systems

The effect of a force acting on a body is:

- The tendency to push or pull the body in the direction of the force, and
- To rotate the body about any fixed axis which does not intersect

The line of action of the force (force does not go through the mass center of the body).

We can represent this dual effect more easily by replacing the given force by an equal parallel force and a couple to compensate for the change in the moment of the force.



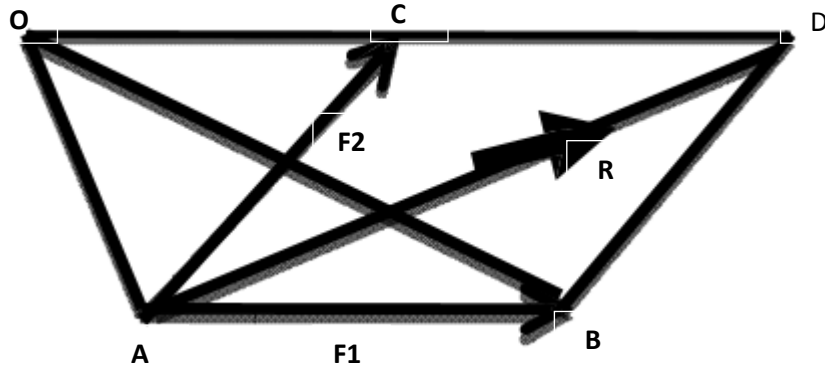
Also we can combine a given couple and a force which lies in the plane of the couple to produce a single, equivalent force.

Varignon's principle of moments:

If a number of coplanar forces are acting simultaneously on a particle, the algebraic sum of the moments of all the forces about any point is equal to the moment of their resultant force about the same point.

Proof:

For example, consider only two forces F_1 and F_2 represented in magnitude and direction by AB and AC as shown in figure below.



Let O be the point, about which the moments are taken. Construct the parallelogram $ABCD$ and complete the construction as shown in fig.

By the parallelogram law of forces, the diagonal AD represents, in magnitude and direction, the resultant of two forces F_1 and F_2 , let R be the resultant force.

By geometrical representation of moments

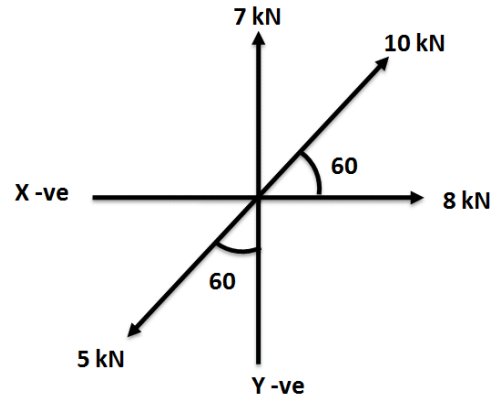
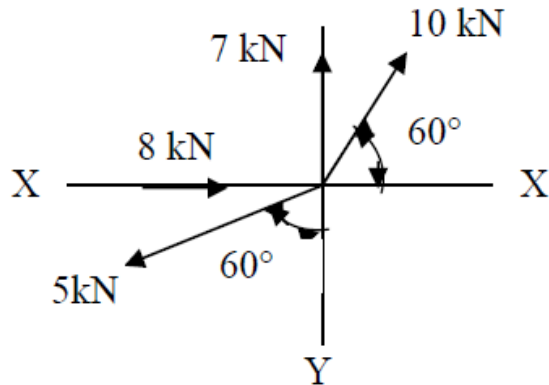
- The moment of force about $O = 2 \times \text{Area of triangle } AOB$
- The moment of force about $O = 2 \times \text{Area of triangle } AOC$
- The moment of force about $O = 2 \times \text{Area of triangle } AOD$ But,
- $\text{Area of triangle } AOD = \text{Area of triangle } AOC + \text{Area of triangle } ACD$
- $\text{Area of triangle } ACD = \text{Area of triangle } ADB = \text{Area of triangle } AOB$
- $\text{Area of triangle } AOD = \text{Area of triangle } AOC + \text{Area of triangle } AOB$

Multiplying throughout by 2, we obtain

$$2 \times \text{Area of triangle } AOD = 2 \times \text{Area of triangle } AOC + 2 \times \text{Area of triangle } AOB$$

$$\text{i.e. Moment of force } R \text{ about } O = \text{Moment of force } F_1 \text{ about } O + \text{Moment of force } F_2 \text{ about } O$$

Example 1: - Find resultant of a force system shown in Figure



Answer:

1) Given Data

$$\begin{aligned}
 P_1 &= 8 \text{ kN} & \theta_1 &= 0 \\
 P_2 &= 10 \text{ kN} & \theta_2 &= 60 \\
 P_3 &= 7 \text{ kN} & \theta_3 &= 90 \\
 P_4 &= 5 \text{ kN} & \theta_4 &= 270 - 60 = 210
 \end{aligned}$$

2) Summation of horizontal force

$$\sum H = P_1 \cos \theta_1 + P_2 \cos \theta_2 + P_3 \cos \theta_3 + P_4 \cos \theta_4 = 8.67 \text{ kN} (\rightarrow)$$

3) Summation of vertical force

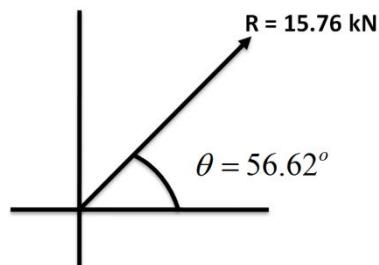
$$\sum V = P_1 \sin \theta_1 + P_2 \sin \theta_2 + P_3 \sin \theta_3 + P_4 \sin \theta_4 = 13.16 \text{ kN} (\uparrow)$$

4) Resultant force

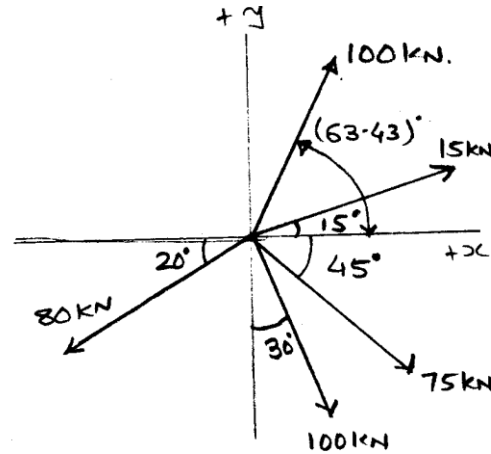
$$R = \sqrt{(\sum H)^2 + (\sum V)^2} = 15.76 \text{ kN}$$

5) Angle of resultant

$$\begin{aligned}
 \tan \theta &= \left| \frac{\sum V}{\sum H} \right| = 1.518 \\
 \theta &= 56.62
 \end{aligned}$$



Example 2 Find magnitude and direction of resultant for a concurrent force system shown in Figure



Answer

1) Summation of horizontal force

→ (+Ve)

← (-Ve)

$$\sum H = +15 \cos 15^\circ + 100 \cos (63.43)^\circ - 80 \cos 20^\circ + 100 \sin 30^\circ + 75 \cos 45^\circ = +87.08 \text{ kN } (\rightarrow)$$

2) Summation of vertical force

↑ (+Ve)

↓ (-Ve)

$$\sum V = +15 \sin 15^\circ + 100 \sin (63.43)^\circ - 80 \sin 20^\circ + 100 \cos 30^\circ + 75 \sin 45^\circ = -73.68 \text{ kN } (\downarrow)$$

3) Resultant force

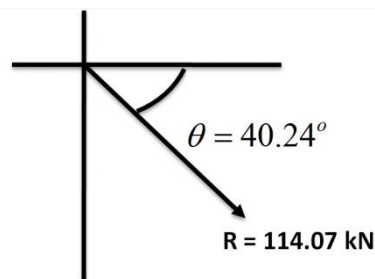
$$R = \sqrt{(\sum H)^2 + (\sum V)^2} = 114.07 \text{ kN}$$

4) Angle of resultant

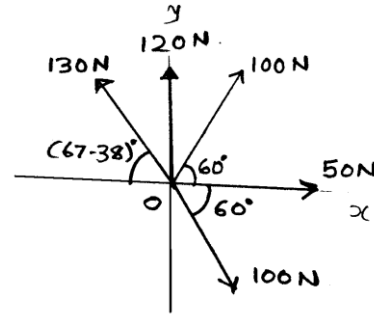
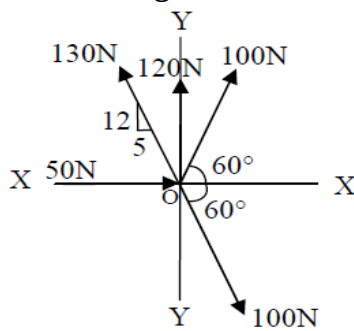
$$\tan \theta = \left| \frac{\sum V}{\sum H} \right| = 0.846$$

$$\theta = 40.24$$

5) Angle of resultant with respect to positive x – axis



Example 3 Determine magnitude and direction of resultant force of the force system shown in fig.



Answer

$$\tan \beta = \frac{12}{5} = 2.4 \quad \therefore \beta = 67.38^\circ$$

1) Summation of horizontal force

$\rightarrow$ (+Ve)

$\leftarrow$ (-Ve)

$$\sum H = +50 + 100 \cos 60^\circ - 130 \cos (67.38)^\circ + 100 \cos 30^\circ + 100 \cos 60^\circ = +100 \text{ N } (\rightarrow)$$

2) Summation of vertical force

$\uparrow$ (+Ve)

$\downarrow$ (-Ve)

$$\sum V = +100 \sin 60^\circ + 120 + 130 \sin (67.38)^\circ - 100 \sin 60^\circ - 100 \sin 60^\circ = +240 \text{ N } (\uparrow)$$

3) Resultant force

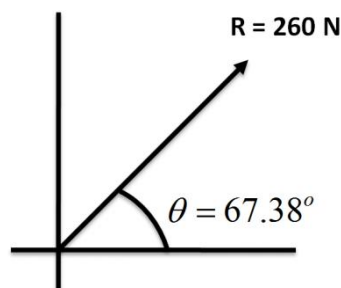
$$R = \sqrt{(\sum H)^2 + (\sum V)^2} = 260 \text{ N}$$

4) Angle of resultant

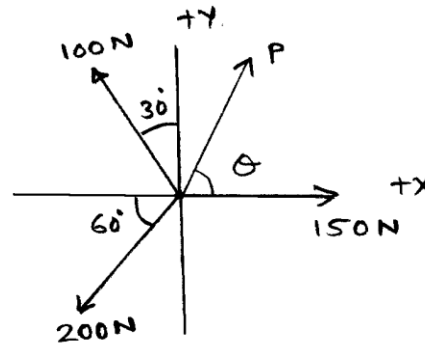
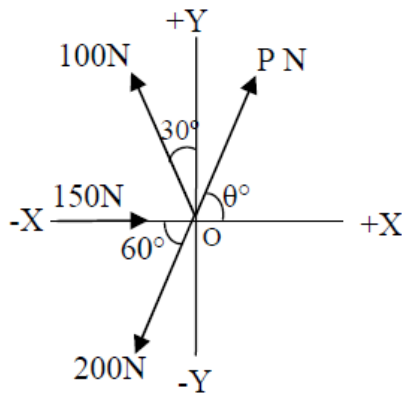
$$\tan \theta = \left| \frac{\sum V}{\sum H} \right| = 2.4$$

$$\theta = 67.38^\circ$$

5) Angle of resultant with respect to positive x – axis



Example: 4 A system of four forces shown in Fig. has resultant 50 kN along + X - axis. Determine magnitude and inclination of unknown force P.



Answer

As the $R = 50\text{N}$ & directed along + X - axis.

$$\sum H = +50\text{N} \text{ and } \sum V = 0\text{N}$$

$$\text{Now, } \sum H = +150 + P \cos \theta - 100 \sin 30^\circ - 200 \cos 60^\circ = 50\text{ N}$$

$$\therefore P \cos \theta = 50 \text{ ----- (1)}$$

$$\text{Now, } \sum V = +P \sin \theta - 100 \cos 30^\circ - 200 \sin 60^\circ = 0$$

$$\therefore P \sin \theta = 86.60 \text{ ----- (2)}$$

From Equation (1) & (2).

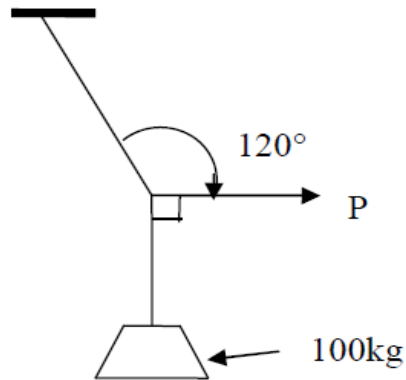
$$\tan \theta = \frac{86.60}{50}$$

$$\tan \theta = 1.732$$

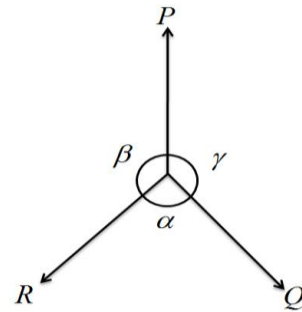
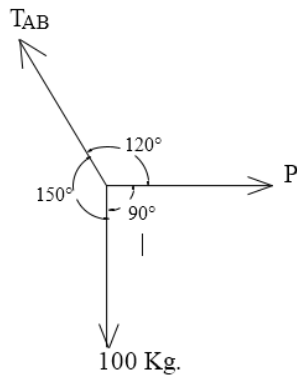
$$\therefore \theta = 60^\circ$$

$$\therefore P = 100\text{ N}$$

Example: 5 Find the magnitude of the force P , required to keep the 100 kg mass in the position by strings as shown in the Figure



Answer:



Free Body Diagram will be as show in fig. and there are three coplanar concurrent forces which are in equilibrium so we can apply the lami's theorem.

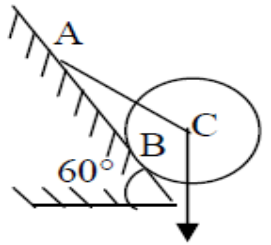
$$\frac{P}{\sin \alpha} = \frac{Q}{\sin \beta} = \frac{R}{\sin \gamma}$$

$$\therefore \frac{P}{\sin 150} = \frac{T_{AB}}{\sin 90} = \frac{100}{\sin 120}$$

$$P = 566.38 \text{ N}$$

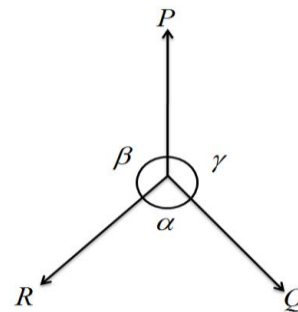
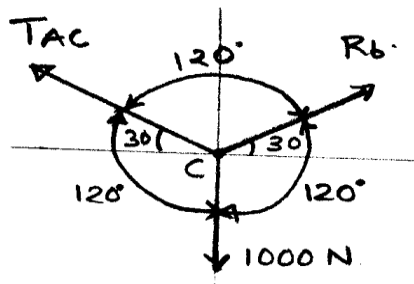
$$T_{AB} = 1132.76 \text{ N}$$

Example: 6 A cylindrical roller 600mm diameter and weighing 1000 N is resting on a smooth inclined surface, tied firmly by a rope AC of length 600mm as shown in fig. Find tension in rope and reaction at B



$W = 1000 \text{ N}$

Answer:



Free Body Diagram will be as show in fig. and there are three coplanar concurrent forces which are in equilibrium so we can apply the lami's theorem.

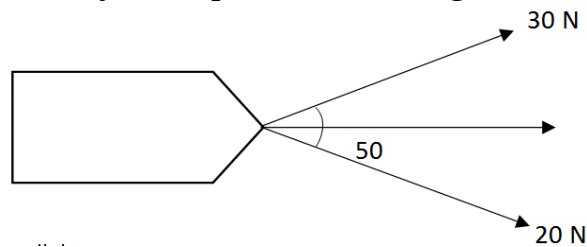
$$\frac{P}{\sin \alpha} = \frac{Q}{\sin \beta} = \frac{R}{\sin \gamma}$$

$$\therefore \frac{T_{ac}}{\sin 120} = \frac{R_b}{\sin 120} = \frac{1000}{\sin 120}$$

$$T_{ac} = 1000 \text{ N}$$

$$R_B = 1000 \text{ N}$$

Example: 7 A boat kept in position by two ropes as shown in figure. Find the drag force on the boat.



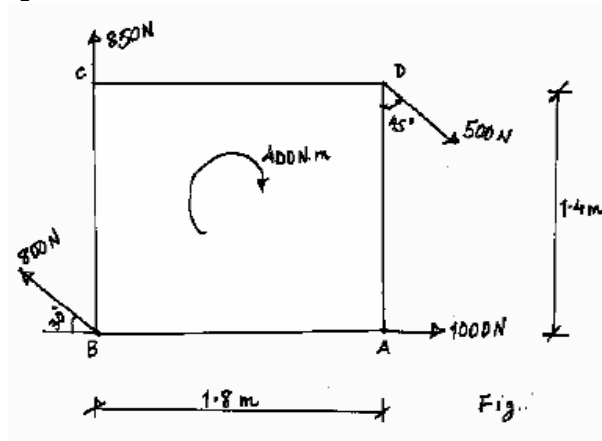
Answer:

According to law of parallelogram

$$R = \sqrt{P^2 + Q^2 + 2PQ \cos \theta} = \sqrt{20^2 + 30^2 + 2 \times 20 \times 30 \cos 50} = 45.51 \text{ N}$$

$$\tan \alpha = \frac{Q \sin \theta}{P + Q \cos \theta} = \frac{30 \sin 50}{20 + 30 \cos 50} \quad \therefore \alpha = 30.32^\circ$$

Example: 8 For a coplanar, non-concurrent force system shown in Fig. determine magnitude, direction and position with reference to point A of resultant force.



Answer

To find out magnitude & direction of R

Summation of horizontal force

$$\Sigma H = +500 \sin 45^\circ - 800 \cos 30^\circ + 1000 = +660.73 \text{ N } (\rightarrow)$$

Summation of vertical force

$$\Sigma V = -500 \cos 45^\circ + 850 + 800 \sin 30^\circ = +896.45 \text{ N } (\uparrow)$$

Resultant force

$$R = \sqrt{(\Sigma H)^2 + (\Sigma V)^2} = \sqrt{(660.73)^2 + (896.45)^2} = 1113.64 \text{ N}$$

Angle of resultant

$$\tan \theta = \frac{896.45}{660.73}$$

$$\therefore \theta = 53.61^\circ$$

Here, we have to also locate the 'R' @ pt. A Let the 'R' is located at a distⁿ x from A in the horizontal direction.

Now this distⁿ 'X' can be achieved by using varignon's principle.

First, Take the moment @ A of all the forces.

$$M_{ALL} = + (500 \sin 45^\circ \times 1.4) + (850 \times 1.8) + (800 \sin 30^\circ \times 1.8) + 400$$

$$= + 3144.97 \text{ N-m } [\downarrow] \text{ ---- (1)}$$

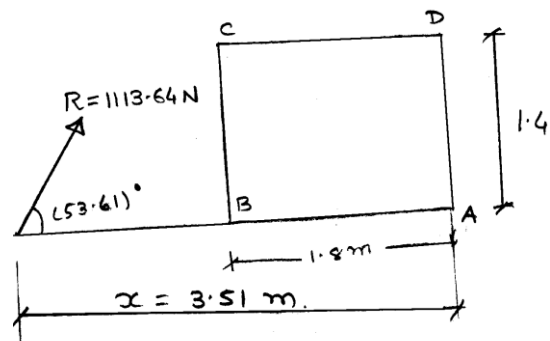
Now moment of 'R' @ point 'A'

$$M_R = + (R \sin \theta \cdot X) = + (\Sigma Fy \cdot x) = 896.45 \cdot x \text{ ---- (2)}$$

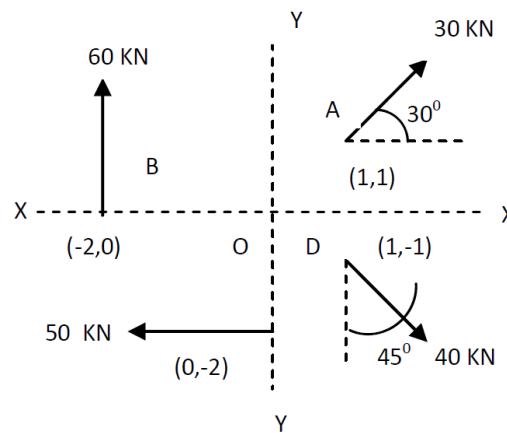
$$(1) = (2)$$

$$896.45 X = 3144.97$$

$$X = 3.51 \text{ m}$$



Example: 9 Find magnitude, direction and location of resultant of force system with respect to point 'O' shown in fig.



Answer

Summation of horizontal forces

$$\Sigma H = +30 \cos 30^\circ - 50 + 40 \sin 45^\circ = +4.265 \text{ KN} \quad (\rightarrow)$$

Summation of vertical forces

$$\Sigma V = +30 \sin 30^\circ + 60 - 40 \cos 45^\circ = +46.72 \text{ KN} \quad (\uparrow)$$

Resultant force

$$R = \sqrt{(\Sigma H)^2 + (\Sigma V)^2} = \sqrt{(4.265)^2 + (46.72)^2} = 46.91 \text{ KN}$$

Angle of resultant

$$\tan \theta = \frac{46.72}{4.265}$$

$$\therefore \theta = 84.78^\circ$$

Now, as we required to find out the position of 'R' with respect to the point 'O'. Take the moment of all the forces @ point 'O' we have,

$$M_0 = +(30 \cos 30^\circ \times 1) - (30 \sin 30^\circ \times 1) + (60 \times 2) + (50 \times 2) - (40 \cos 45^\circ \times 1) + (40 \sin 45^\circ \times 1)$$

$$M_0 = +230.98 \text{ KN-unit} \quad (\downarrow) \quad \text{----- (1)}$$

Now, moment of 'R' @ Pt. 'O'

(considering 'R' lies at a distance x from the point 'O' in the horizontal direction)

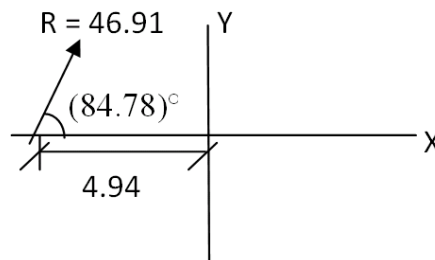
$$M_R = + (R \sin \theta \times X) = (\Sigma F_y \cdot x)$$

$$M_R = +46.72 \cdot X \quad \text{----- (2)}$$

According to varignon's principle

$$\therefore 46.72 X = 230.98$$

$$\therefore X = 4.94 \text{ unit}$$

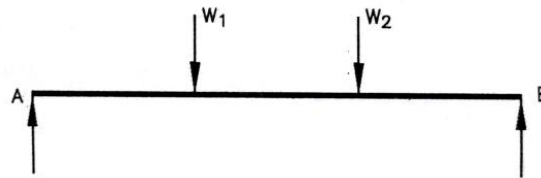


Types of load

- 1) Point load
- 2) Uniformly distributed load
- 3) Uniformly varying load

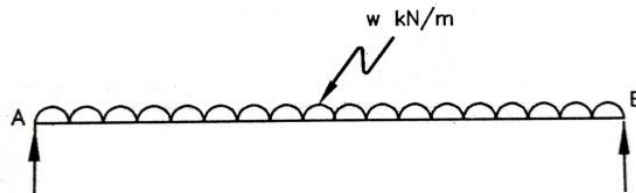
Point load

- Load concentrated on a very small length compare to the length of the beam, is known as point load or concentrated load. Point load may have any direction.
- For example truck transferring entire load of truck at 4 point of contact to the bridge is point load.



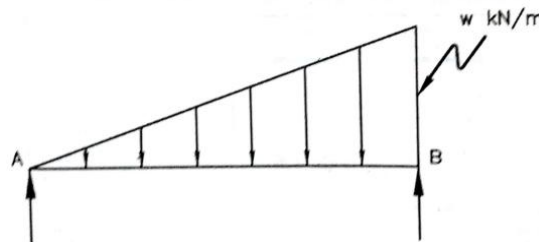
Uniformly distributed load

- Load spread uniformly over the length of the beam is known as uniformly distributed load.
- Water tank resting on the beam length
- Pipe full of water in which weight of the load per unit length is constant.



Uniformly varying load

- Load in which value of the load spread over the length if uniformly increasing or decreasing from one end to the other is known as uniformly varying load. It is also called triangular load.

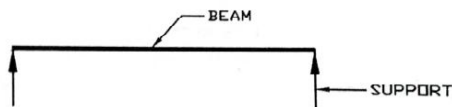


Type of beam

- 1) Simply supported beam
- 2) Cantilever beam
- 3) Fixed beam
- 4) Continuous beam
- 5) Propped cantilever beam

Simply supported beam

- It is the beam which is rest on the support. Here no connection between beam and support.



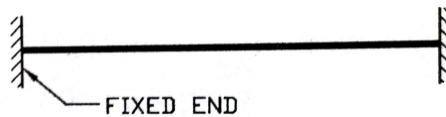
Cantilever beam

- If beam has one end fixed and other end free then it is known as cantilever beam



Fixed beam

- If both end of beam is fixed with support then it is called as fixed beam



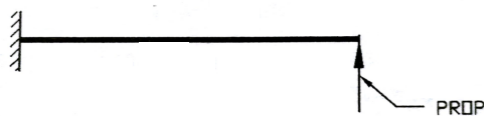
Continuous beam

- If beam has more than two span, it is called as continuous beam



Propped cantilever beam

- If one end of beam is fixed and other is supported with prop then it is known as propped cantilever beam.

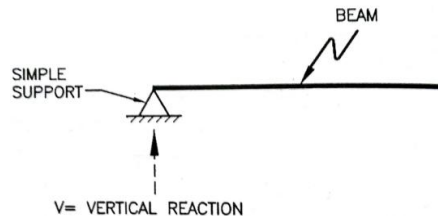


Type of support

- 1) Simple support
- 2) Roller support
- 3) Hinged support
- 4) Fixed support

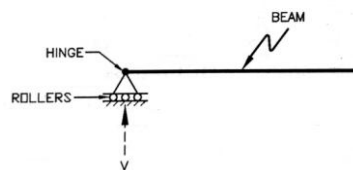
Simple support

- In this type of support beam is simply supported on the support. There is no connection between beam and support. Only vertical reaction will be produced.



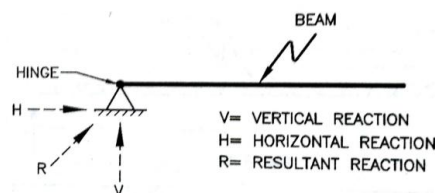
Roller support

- Here rollers are placed below beam and beam can slide over the rollers. Reaction will be perpendicular to the surface on which rollers are supported.
- This type of support is normally provided at the end of a bridge.



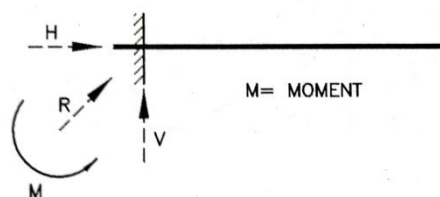
Hinged support

- Beam and support are connected by a hinge. Beam can rotate about the hinge. Reaction may be vertical, horizontal or inclined.

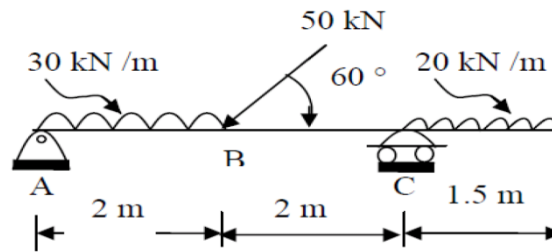


Fixed support

- Beam is completely fixed at end in the wall or support. Beam cannot rotate at end. Reactions may be vertical, horizontal, inclined and moment.



Example 1 Find out the support reactions for the beam.



Answer:

1) Now, Applying $\sum M = 0$ ($\uparrow$ +ve $\downarrow$ -ve)

Now, Taking moment @ pt. A, we have,

$$+ (30 \times 2 \times 1) + (50 \sin 60^\circ \times 2) - (R_C \times 4) = (20 \times 1.5 \times 4.75) = 0$$

$$\mathbf{R_C = 61.45 \text{ kN}}$$

2) Now $\sum F_y = 0$

$$+ R_{AV} - (30 \times 2) - (50 \sin 60^\circ) + R_C - (20 \times 1.5) = 0$$

$$\mathbf{R_{AV} = 71.85 \text{ kN.}}$$

3) Now, $\sum F_x = 0$

$$+ R_{AV} - (50 \cos 60^\circ) = 0$$

$$\mathbf{R_{AV} = 25.0 \text{ KN}}$$

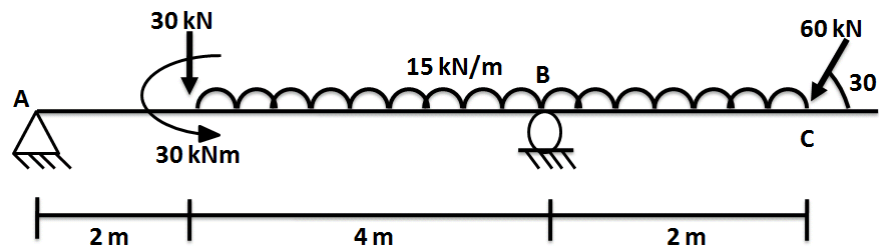
$$\mathbf{R_A = \sqrt{R_{AV}^2 + R_{AH}^2}}$$

$$\mathbf{R_A = 76.08 \text{ kN}}$$

$$\tan \theta = \frac{R_{AV}}{R_{AH}}$$

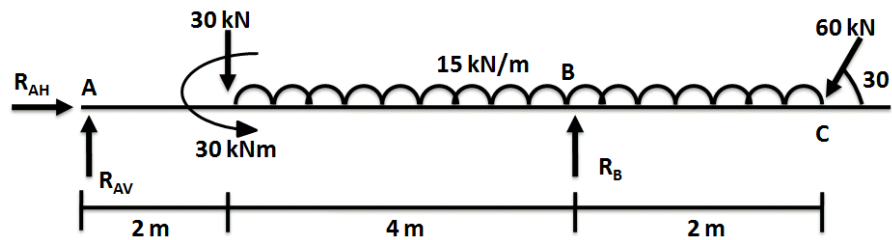
$$\mathbf{\theta = (70.81)^\circ}$$

Example- 2 Determine the reactions at support A and B for the beam loaded as shown in figure



Answer:

The F.B.D. of the beam is shown below



1)Applying $\sum M = 0$ $\downarrow +ve$ $\uparrow -ve$

Take the moment @ pt. A, we have,

$$+ (30 \times 2) - (30) - (R_B \times 6) + (15 \times 6 \times 5) + (60 \sin 30^\circ) = 0$$

$$R_{AV} - 30 - (15 \times 6) + R_B - (60 \sin 30^\circ) = 0$$

$$R_B = 120 \text{ kN}$$

2) $\sum F_y = 0$

$$\therefore R_{AV} = 30 \text{ kN}$$

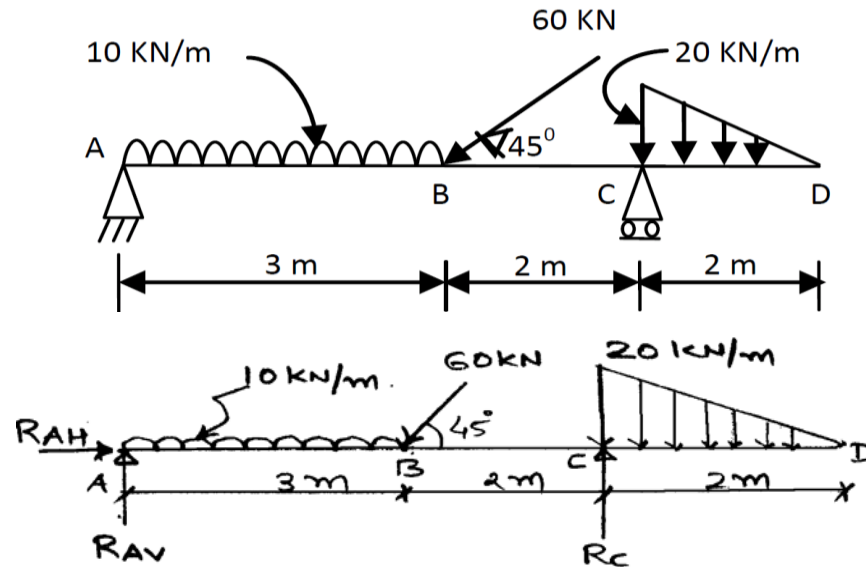
3) $\sum F_x = 0$

$$R_{AH} - 60 \cos 30^\circ = 0$$

$$\therefore R_{AH} = +51.96 \text{ kN}$$

$$\text{Now, } R_A = \sqrt{R_{AV}^2 + R_{AH}^2} = 60 \text{ kN}$$

Example: 3 Calculate reactions at support due to applied load on the beam as shown in Figure



Answer:

Showing the reactions at support.

1) Applying $\sum M = 0$

Take the moment @ pt. A, we have,

$$+ (10 \times 3 \times 1.5) + (60 \sin 45^\circ \times 3) - (R_C \times 5) + (1/2 \times 20 \times 2 \times 5.66) = 0$$

$$\therefore R_C = 57.096 \text{ KN } (\uparrow)$$

2) $\sum V = 0 \uparrow + Ve \quad \downarrow - Ve$

$$+ R_{AV} - (10 \times 3) - (60 \sin 45^\circ) + R_C - (1/2 \times 20 \times 2) = 0$$

Putting value of R_C , we have.

$$R_{AV} = 35.33 \text{ KN}$$

3) $\sum H = 0$

$$R_{AH} - 60 \cos 45^\circ = 0$$

$$R_{AH} = 42.43 \text{ KN}$$

$$\text{Now, } R_A = \sqrt{R_{AH}^2 + R_{AV}^2}$$

$$= \sqrt{(42.43)^2 + (35.33)^2}$$

$$= 55.21 \text{ KN } (\rightarrow)$$

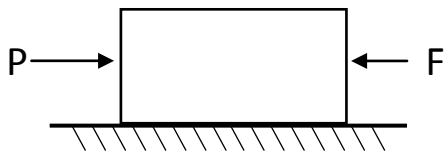
$$\tan \theta = \frac{R_{AV}}{R_{AH}} = \frac{35.33}{42.43}$$

$$\theta = (39.78)^\circ$$

UNIT II FRICTION

➤ Friction or Friction Force: -

When a body slide or tends to slide on a surface on which it is resting, a resisting force opposing the motion is produced at the contact surface. This resisting force is called friction or friction force.



P = External force

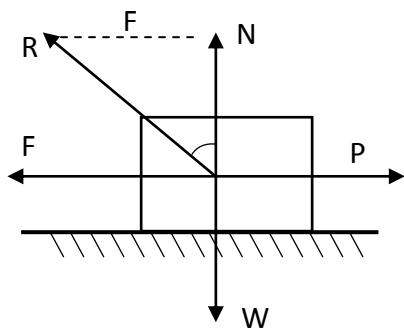
F = Friction force

Friction force (F) always act in the direction opposite to the movement of the body,

➤ Limiting Friction: -

When a body is at the verge of start of motion is called limiting friction or impending motion.

➤ Angle of Friction: -



- The angle between normal reaction (N) and resultant force(R) is called angle of friction.
- It is also called limiting angle of friction
- The value of ϕ is more for rough surface as compared to smooth surface.

W = weight of block,

F = Friction force

N = Normal reaction

R = Resultant force

P = external force

➤ Coefficient of Friction (μ): -

The ratio of limiting friction and Normal reaction is called coefficient of friction

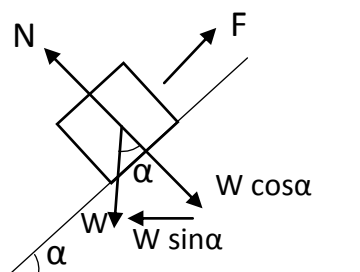
$$F \propto N$$

$$F = \mu N$$

$$\mu = \frac{F}{N}$$

➤ Angle of Repose: -

With increase in angle of the inclined surface, the maximum angle at which, body starts sliding down the plane is called angle of response.



- Consider a body, of weight W is resting on the plane inclined at angle (α) with horizontal.
- Weight has two components
 1. Parallel to the plane = $w \sin \alpha = F$
 2. Perpendicular to the plane = $w \cos \alpha = N$

$$\mu = \frac{F}{N} = \frac{w \sin \alpha}{w \cos \alpha} = \tan \alpha$$

1

As we know that $\mu = \tan \phi$
From equation 1 & 2

2

$$\alpha = \phi$$

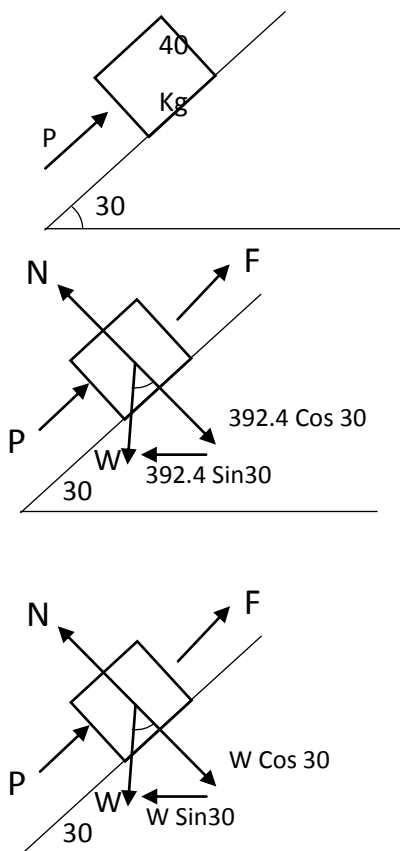
- Angle of friction = Angle of response = ϕ .

UNIT II FRICTION

➤ Law of static friction: -

1. The friction force always acts in a direction, opposite to that in which the body tends to move.
2. The magnitude of friction force is equal to the external force.
3. The ratio of limiting friction (F) & normal reaction (N) is constant.
4. The friction force does not depend upon the area of contact between the two surfaces.
5. The friction force depends upon the roughness of the surfaces.

Example -1: A 40 Kg mass is placed on the inclined plane making angle of 30° with horizontal, as shown in figure. A push “P” is applied parallel to the plane. If coefficient of static friction between the plane & the mass is 0.25. Find the maximum & minimum value of P between which the mass will be in the equilibrium.



1. Weight of block

$$W = mg = 40 \times 9.81 = 392.4 \text{ N}$$

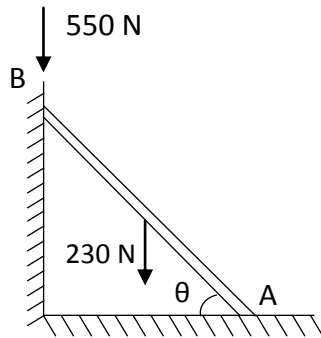
2. Minimum force (P) to maintain equilibrium.

- The force P is minimum, When the block is at point of sliding downwards.
- F will act upward along the plane
- Resolve forces parallel to plane
 $P + F = 392.4 \sin 30 = 196.2$
- Resolve forces perpendicular to plane
 $N = 392.4 \cos 30 = 339.83 \text{ N}$
 $F = \mu N = 84.96 \text{ N}$
 $F + P = 196.2$
 $P = 111.24 \text{ N} \dots \dots \dots \text{Minimum value of P}$

3. Maximum force to maintain equilibrium.

- The force P is maximum, when block is at the point of sliding upwards.
- F will be act downward along the plane.
- Resolve force perpendicular to plane.
 $N = 392.4 \cos 30 = 339.8 \text{ N}$
 $F = \mu N = 0.25 \times 339.8 = 84.96 \text{ N}$
- Resolve force parallel to plane.
 $P = F + 392.4 \sin 30 = 281.16 \text{ N} \dots \dots \text{Max of P}$

Example 2: A Uniform ladder AB weighting 230N & 4 m long is supported by vertical wall at top end B and by horizontal floor at bottom end A as shown in figure. A man weighting 550N stood at the top of the ladder. Determine minimum angle of ladder AB with floors for the stability of ladders. Take coefficient of friction between ladder and wall as $1/3$ & between ladder & Floor as $1/4$.



$$\mu_w = 1/3, \mu_f = 1/4.$$

- **Resolving force horizontally.**

$$R_w = F_f = \mu_f R_f = 1/4 R_f.$$

- **Resolving Forces Vertically.**

$$R_f + R_w = 550 + 230$$

$$R_f + \mu_w R_w = 780$$

$$R_f = 1/3 * 1/4 R_f = 780$$

$$1.083 R_f = 780$$

$$R_f = 720.22 \text{ N},$$

Now,

$$F_f = \mu_f R_f = 1/4 * 720.22 = 180.05 \text{ N}$$

$$R_w = 1/4 R_f = 1/4 * 720.22 = 180.05 \text{ N}$$

$$F_f = \mu_w R_w \quad F_f = \mu_w R_w = 1/3 * 180.05 = 60 \text{ N}$$

Taking moment @ A.

$$R_w * (4 \sin \theta) + F_w * (4 \cos \theta) = 550 * 4 \cos \theta + 230 * 2 \cos \theta$$

- **Dividing both side by $\cos \theta$.**

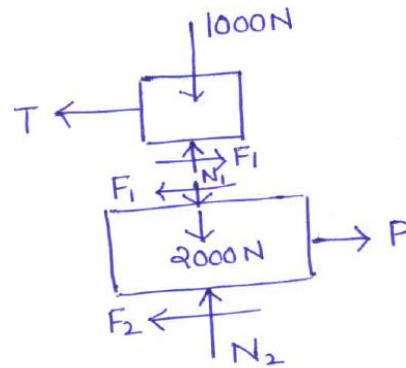
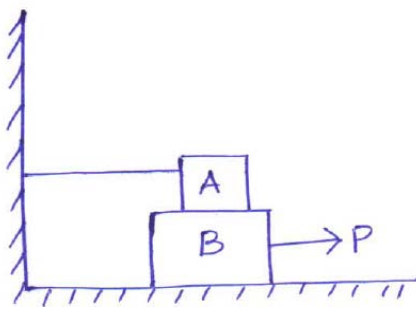
$$720.2 \tan \theta = 2420$$

$$\theta = 73.24^\circ.$$

Problem 1: Block A weighing 1000N rests over block B which weighs 2000N as shown in figure. Block A is tied to wall with a horizontal string. If the coefficient of friction between blocks A and B is 0.25 and between B and floor is $\frac{1}{3}$, what should be the value of P to move the block (B), if

- (a) P is horizontal.
- (b) P acts at 30° upwards to horizontal.

Solution: (a)



Considering block A,

$$\sum V = 0$$

$$N_1 = 1000N$$

Since F_1 is limiting friction,

$$\frac{F_1}{N_1} = \mu = 0.25$$

$$F_1 = 0.25N_1 = 0.25 \times 1000 = 250N$$

$$\sum H = 0$$

$$F_1 - T = 0$$

$$T = F_1 = 250N$$

Considering equilibrium of block B,

$$\sum V = 0$$

$$N_2 - 2000 - N_1 = 0$$

$$N_2 = 2000 + N_1 = 2000 + 1000 = 3000N$$

$$\frac{F_2}{N_2} = \mu = \frac{1}{3}$$

$$F_2 = 0.3N_2 = 0.3 \times 3000 = 900N$$

$$\sum H = 0$$

$$P = F_1 + F_2 = 250 + 1000 = 1250N$$

(b) When P is inclined:

$$\sum V = 0$$

$$N_2 - 2000 - N_1 + P \cdot \sin 30 = 0$$

$$\Rightarrow N_2 + 0.5P = 2000 + 1000$$

$$\Rightarrow N_2 = 3000 - 0.5P$$

From law of friction,

$$F_2 = \frac{1}{3} N_2 = \frac{1}{3} (3000 - 0.5P) = 1000 - \frac{0.5}{3} P$$

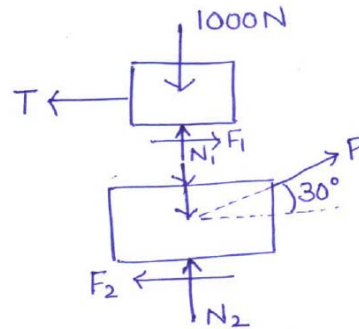
$$\sum H = 0$$

$$P \cos 30 = F_1 + F_2$$

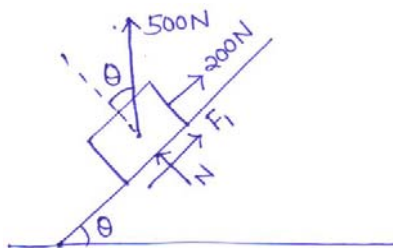
$$\Rightarrow P \cos 30 = 250 + \left(1000 - \frac{0.5}{3} P \right)$$

$$\Rightarrow P \left(\cos 30 + \frac{0.5}{3} \right) = 1250$$

$$\Rightarrow P = 1210.43N$$



Problem 2: A block weighing 500N just starts moving down a rough inclined plane when supported by a force of 200N acting parallel to the plane in upward direction. The same block is on the verge of moving up the plane when pulled by a force of 300N acting parallel to the plane. Find the inclination of the plane and coefficient of friction between the inclined plane and the block.



$$\sum V = 0$$

$$N = 500 \cdot \cos \theta$$

$$F_1 = \mu N = \mu \cdot 500 \cos \theta$$

$$\begin{aligned}\sum H &= 0 \\ 200 + F_1 &= 500 \cdot \sin \theta \\ \Rightarrow 200 + \mu \cdot 500 \cos \theta &= 500 \cdot \sin \theta\end{aligned}\tag{1}$$

$$\begin{aligned}\sum V &= 0 \\ N &= 500 \cdot \cos \theta \\ F_2 &= \mu N = \mu \cdot 500 \cdot \cos \theta\end{aligned}$$

$$\begin{aligned}\sum H &= 0 \\ 500 \sin \theta + F_2 &= 300 \\ \Rightarrow 500 \sin \theta + \mu \cdot 500 \cos \theta &= 300\end{aligned}\tag{2}$$

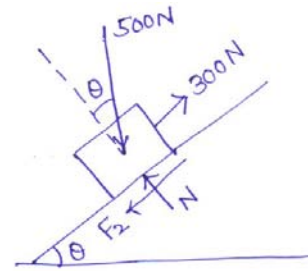
Adding Eqs. (1) and (2), we get

$$\begin{aligned}500 &= 1000 \cdot \sin \theta \\ \sin \theta &= 0.5 \\ \theta &= 30^\circ\end{aligned}$$

Substituting the value of θ in Eq. 2,

$$500 \sin 30 + \mu \cdot 500 \cos 30 = 300$$

$$\mu = \frac{50}{500 \cos 30} = 0.11547$$



ANALYSIS OF PLANE TRUSSES

Truss/ Frame: A pin jointed frame is a structure made of slender (cross-sectional dimensions quite small compared to length) members pin connected at ends and capable of taking load at joints.

Such frames are used as roof trusses to support sloping roofs and as bridge trusses to support deck.

Plane frame: A frame in which all members lie in a single plane is called plane frame. They are designed to resist the forces acting in the plane of frame. Roof trusses and bridge trusses are the example of plane frames.

Space frame: If all the members of frame do not lie in a single plane, they are called as space frame. Tripod, transmission towers are the examples of space frames.

Perfect frame: A pin jointed frame which has got just sufficient number of members to resist the loads without undergoing appreciable deformation in shape is called a perfect frame. Triangular frame is the simplest perfect frame and it has 03 joints and 03 members.

It may be observed that to increase one joint in a perfect frame, two more members are required. Hence, the following expression may be written as the relationship between number of joint j , and the number of members m in a perfect frame.

$$m = 2j - 3$$

- (a) When $LHS = RHS$, Perfect frame.
- (b) When $LHS < RHS$, Deficient frame.
- (c) When $LHS > RHS$, Redundant frame.

Assumptions

The following assumptions are made in the analysis of pin jointed trusses:

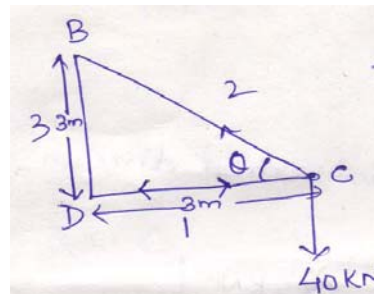
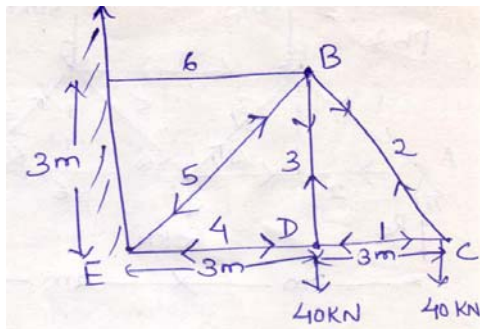
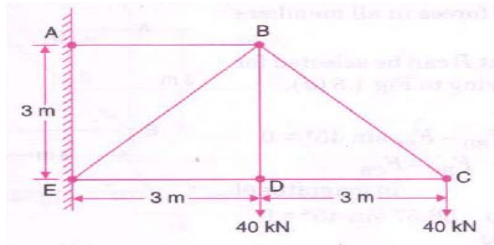
1. The ends of the members are pin jointed (hinged).
2. The loads act only at the joints.
3. Self weight of the members is negligible.

Methods of analysis

1. Method of joint
 2. Method of section
-

Problems on method of joints

Problem 1: Find the forces in all the members of the truss shown in figure.



$\theta =$

$$\Rightarrow \theta = 45^\circ$$

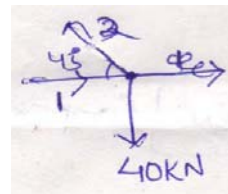
$$\tan_{\text{Joint C}}^{-1}$$

$$S_1 = S_2 \cos 45$$

$$\Rightarrow S_1 = 40 \text{ KN (Compression)}$$

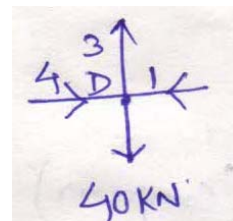
$$S_2 \sin 45 = 40$$

$$\Rightarrow S_2 = 56.56 \text{ KN (Tension)}$$

Joint D

$$S_3 = 40KN \text{ (Tension)}$$

$$S_1 = S_4 = 40KN \text{ (Compression)}$$

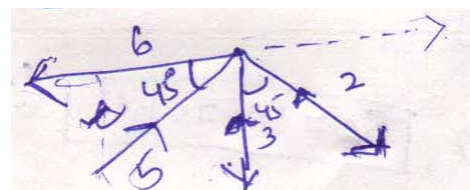


Joint B

Resolving vertically,

$$\sum V = 0$$

$$S_5 \sin 45 = S_3 + S_2 \sin 45$$



$$\Rightarrow S_5 = 113.137 \text{ KN (Compression)}$$

Resolving horizontally,

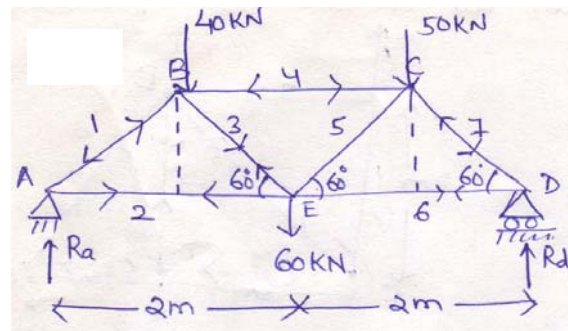
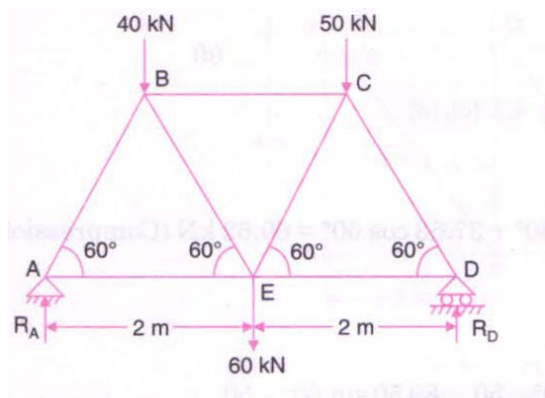
$$\sum H = 0$$

$$S_6 = S_5 \cos 45 + S_2 \cos 45$$

$$\Rightarrow S_6 = 113.137 \cos 45 + 56.56 \cos 45$$

$$\Rightarrow S_6 = 120 \text{ KN (Tension)}$$

Problem 2: Determine the forces in all the members of the truss shown in figure and indicate the magnitude and nature of the forces on the diagram of the truss. All inclined members are at 60° to horizontal and length of each member is 2m.



Taking moment at point A,

$$\sum M_A = 0$$

$$R_d \times 4 = 40 \times 1 + 60 \times 2 + 50 \times 3$$

$$\Rightarrow R_d = 77.5 \text{ KN}$$

Now resolving all the forces in vertical direction,

$$\sum V = 0$$

$$R_a + R_d = 40 + 60 + 50$$

$$\Rightarrow R_a = 72.5 \text{ KN}$$

Joint A

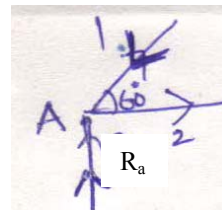
$$\sum V = 0$$

$$\Rightarrow R_a = S_1 \sin 60$$

$$\Rightarrow S_1 = 83.72 \text{ KN (Compression)}$$

$$\sum H = 0$$

$$\Rightarrow S_2 = S_1 \cos 60$$



$$\Rightarrow S_1 = 41.86 \text{KN (Tension)}$$

Joint D

$$\sum V = 0$$

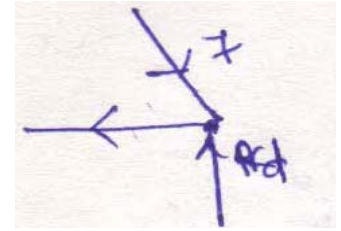
$$S_7 \sin 60 = 77.5$$

$$\Rightarrow S_7 = 89.5 \text{KN (Compression)}$$

$$\sum H = 0$$

$$S_6 = S_7 \cos 60$$

$$\Rightarrow S_6 = 44.75 \text{KN (Tension)}$$



Joint B

$$\sum V = 0$$

$$S_1 \sin 60 = S_3 \cos 60 + 40$$

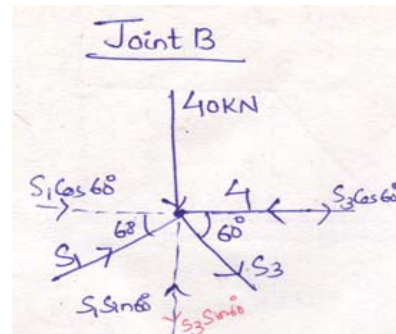
$$\Rightarrow S_3 = 37.532 \text{KN (Tension)}$$

$$\sum H = 0$$

$$S_4 = S_1 \cos 60 + S_3 \cos 60$$

$$\Rightarrow S_4 = 37.532 \cos 60 + 83.72 \cos 60$$

$$\Rightarrow S_4 = 60.626 \text{KN (Compression)}$$

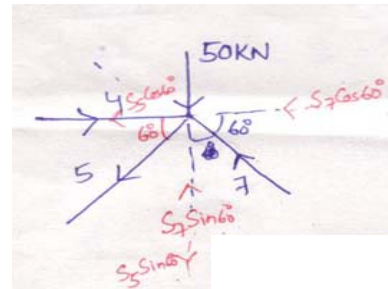


Joint C

$$\sum V = 0$$

$$S_5 \sin 60 + 50 = S_7 \sin 60$$

$$\Rightarrow S_5 = 31.76 \text{KN (Tension)}$$



Plane Truss (Method of Section)

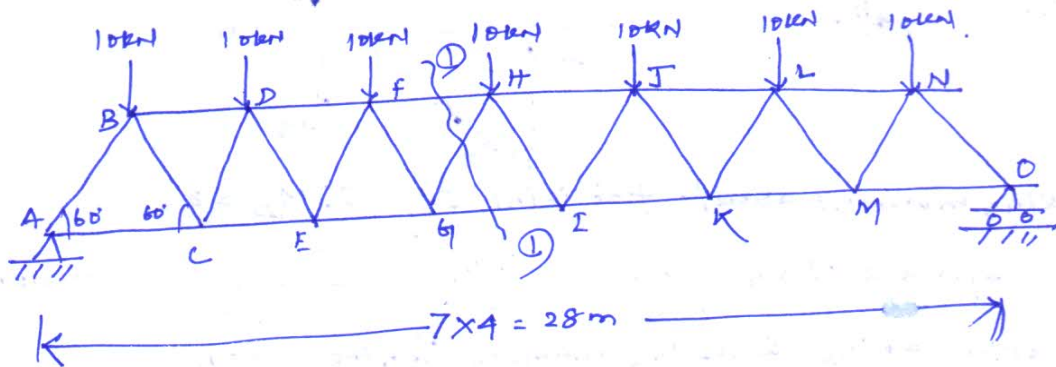
In case of analysing a plane truss, using method of section, after determining the support reactions a section line is drawn passing through not more than three members in which forces are unknown, such that the entire frame is cut into two separate parts.

~~Each~~ Each part should be in equilibrium under the action of loads, reactions and the forces in the members.

Method of section is preferred for the following cases:

- (i) analysis of large truss in which forces in only few members are required
- (ii) If method of joint fails to start or proceed with analysis for not getting a joint with only two unknown forces.

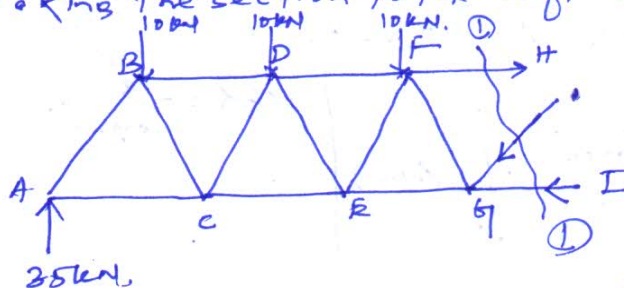
Example 1.



Determine the forces in the members FH, HG, and GI in the truss.
 Due to symmetry $R_A = R_O = \frac{1}{2} \times \text{total downward load}$

$$= \frac{1}{2} \times 70 = \boxed{35 \text{ kN}}$$

Taking the section to the left of the cut.



Taking moment about G

$$\sum M_G = 0$$

$$F_{FH} \times 4 \sin 60^\circ + 35 \times 12$$

$$= 10 \times 2 + 10 \times 6 + 10 \times 10$$

$$\Rightarrow F_{FH} = \frac{(20 + 60 + 100) - 420}{4 \sin 60^\circ}$$

$$= -69.28 \text{ kN}$$

Negative sign indicates that direction should have opposite i.e. it's compressive in nature.

Now resolving all the forces vertically $\Sigma Y = 0$

$$10 + 10 + 10 + F_{GH} \sin 60 = 35$$

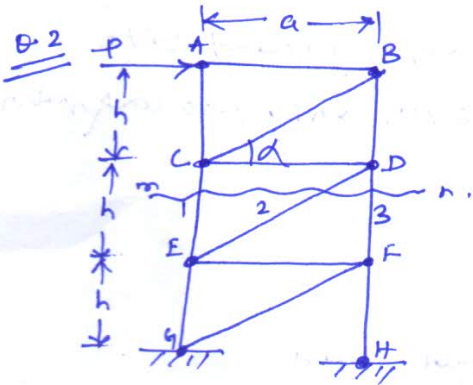
$$\Rightarrow F_{GH} = \frac{35 - 30}{\sin 60}$$

$$\Rightarrow \boxed{F_{GH} = 5.78 \text{ kN.}} \text{ (compressive)}$$

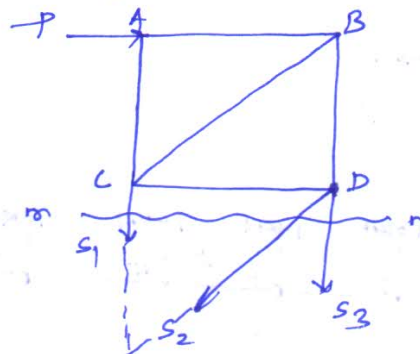
Resolving all the forces horizontally $\Sigma X = 0$.

$$F_{FH} + F_{GH} \cos 60 = F_{GI}$$

$$\Rightarrow F_{GI} = 69.28 + 5.78 \cos 60 = \boxed{72.17 \text{ kN.}} \text{ (tension)}$$



Using method of sections determine the axial forces in bars 1, 2 and 3.



Taking moment about joint D $\Sigma M_D = 0$.

$$S_1 \times a = P \times h \Rightarrow \boxed{S_1 = \frac{Ph}{a}} \text{ --- (1) (tension)}$$

Similarly taking E as the moment centre $\Sigma M_E = 0$

$$S_2 \times a + P \times 2h = 0$$

$$\Rightarrow \boxed{S_2 = -\frac{2Ph}{a}}$$

(-ve sign indicates direction of force will be opposite and it will be compressive in nature)

Resolving all the forces horizontally $\Sigma X = 0$.

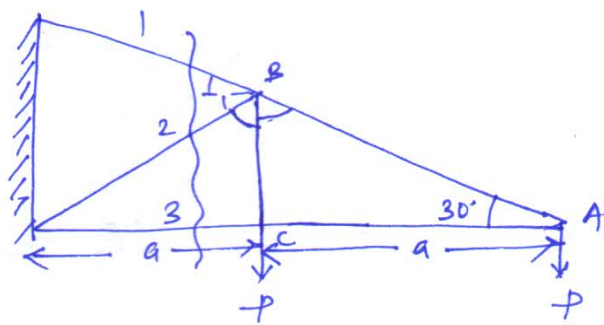
$$S_2 \cos \alpha = P$$

$$\Rightarrow S_2 = \frac{P}{\cos \alpha}$$

$$= \boxed{\frac{P \sqrt{a^2 + h^2}}{a}} \text{ (Ans)}$$

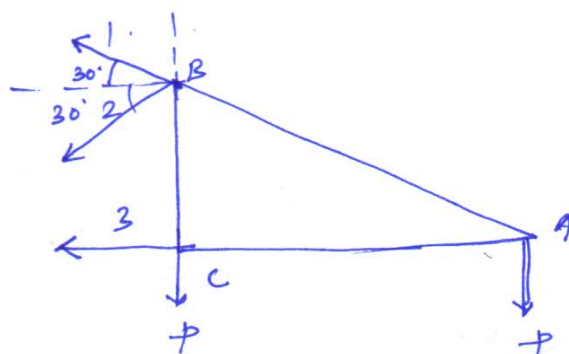
$$\cos \alpha = \frac{a}{\sqrt{a^2 + h^2}}$$

(2)



$$\frac{BC}{AC} = \tan 30^\circ$$

$$\Rightarrow BC = a \tan 30 = \boxed{0.578a}$$



$$\sum M_B = 0$$

$$S_3 \times 0.578a + P \times a = 0$$

$$\Rightarrow S_3 = \frac{-Pa}{0.578a} = -1.73P$$

(-ve sign indicates direction is opposite and it is compressive in nature)

Resolving vertically $\sum Y = 0$

$$S_1 \sin 30 = 2P + S_2 \sin 30$$

$$\Rightarrow S_1 = \frac{2P + S_2/2}{\sin 30} = (4P + S_2) \quad \text{--- (2)}$$

Now resolving horizontally $\sum X = 0$

$$S_1 \cos 30 + S_2 \cos 30 = 1.73P$$

$$\Rightarrow (4P + S_2) \times \frac{\sqrt{3}}{2} + S_2 \frac{\sqrt{3}}{2} = 1.73P$$

$$\Rightarrow 2\sqrt{3}P + \frac{\sqrt{3}}{2}S_2 + \frac{\sqrt{3}}{2}S_2 = 1.73P$$

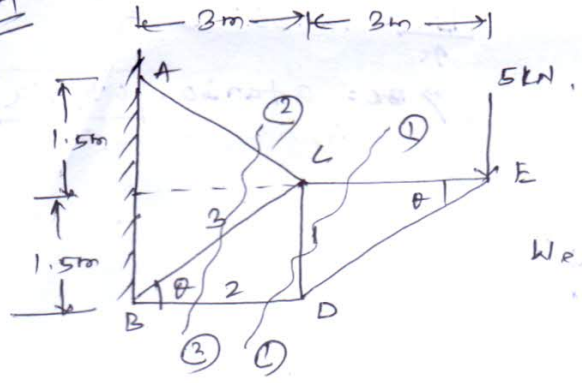
$$\Rightarrow \frac{\sqrt{3}}{2}S_2 = 1.73P - 2\sqrt{3}P$$

$$= -1.73P$$

$$\Rightarrow S_2 = \frac{-1.73P}{\sqrt{3}} = \boxed{-P} \quad (-ve \text{ sign indicates the direction is opposite and it is compressive})$$

$$\text{Now } S_1 = 4P - P = \boxed{3P} \quad (\text{tension})$$

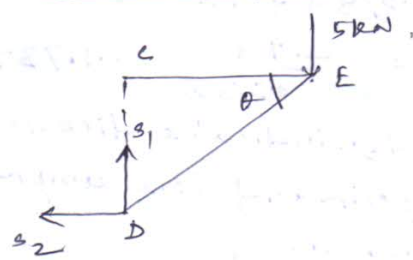
Q.1



Using method of sections,
find axial forces in each bar
1, 2 and 3 of the plane
truss.

We have $\tan \theta = \left(\frac{1.5}{3}\right) \Rightarrow \theta = 26.56^\circ$

considering section 1-1



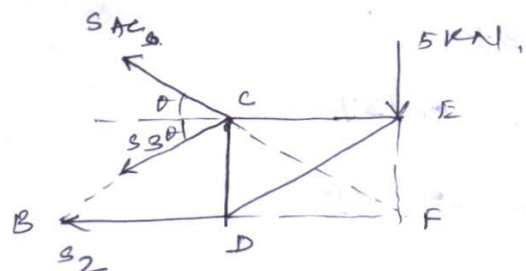
Resolving vertically, $\Sigma Y = 0$
 $S_1 = 5 \text{ kN}$ (tension)

Now taking moment about C
 $S_2 \times 1.5 + 5 \times 3 = 0$
 $\Rightarrow S_2 = -10 \text{ kN}$

-ve sign indicates direction should have been opposite

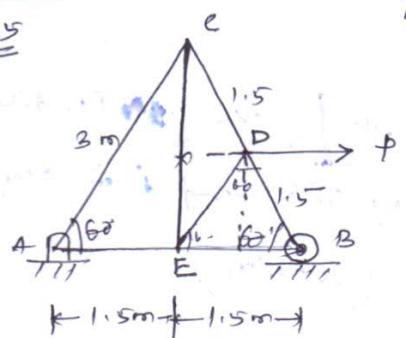
$S_2 = 10 \text{ kN}$ (compression)

considering section 2-2



Taking moment about F
 $\Sigma M_F = 0$
 $\Rightarrow S_3 = 0$

Q.2



Assignment

Using method of joint and
method of section find the axial
force in the bar X.

Method of Joint

considering the whole structure and
taking moment about A $\Sigma M_A = 0$.

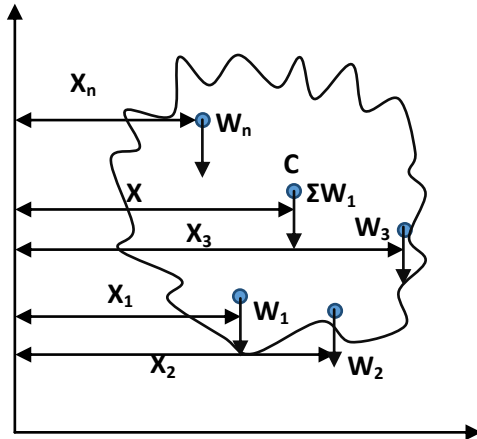
$R_B \times 3 = P \times 1.5 \sin 60$
 $\Rightarrow R_B = \frac{\sqrt{3}}{4} P$

CENTROID AND CENTER OF GRAVITY

UNIT III

Centre of Gravity

- It is defined as an imaginary point on which entire, length, area or volume of body is assumed to be concentrated.
- It is defined as a geometrical centre of object.



- The weight of various parts of body, which acts parallel to each other, can be replaced by an equivalent weight. This equivalent weight acts at a point, known as centre of gravity of the body
- The resultant of the force system will be algebraic sum of all parallel forces, therefore force

$$R = W_1 + W_2 + \dots + W_n$$
- It is represented as weight of entire body.

$$W = R = \sum_{i=1}^n w_i$$

- The location of resultant with reference to any axis (say y – y axis) can be determined by taking moment of all forces & by applying Varignon's theorem,
- Moment of resultant of force system about any axis = Moment of individual force about the same axis

$$R \cdot \bar{x} = W_1 x_1 + W_2 x_2 + \dots + W_n x_m$$

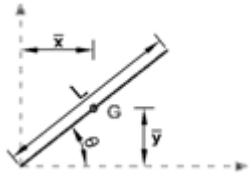
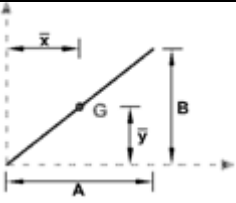
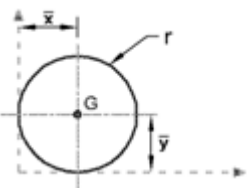
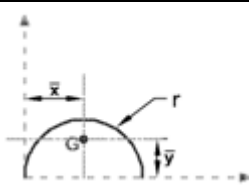
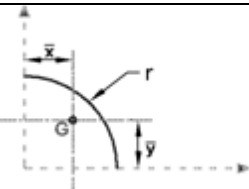
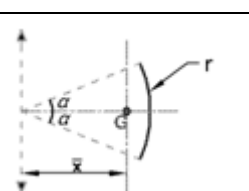
we can write,

$$\bar{x} = \frac{W_1 x_1 + W_2 x_2 + \dots + W_n x_m}{N} = \frac{\sum w_i x_i}{\sum w_i}$$

$$\bar{x} = \frac{\int x \, dw}{\int dw}$$

Similarly,

$$\bar{y} = \frac{\sum w_i y_i}{\sum w_i}$$

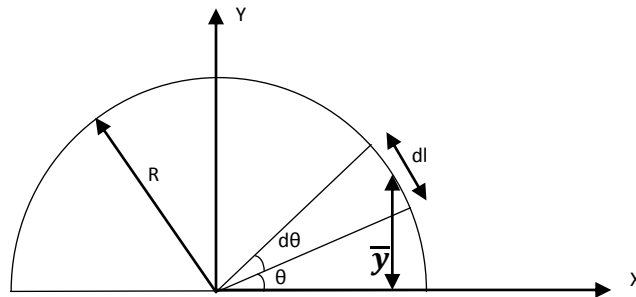
Line Element Centroid – Basic Shape				
Element name	Geometrical Shape	Length	$\bar{x}$	$\bar{y}$
Straight line		L	$\frac{L}{2} \cos \theta$	$\frac{L}{2} \sin \theta$
Straight line		$\sqrt{A^2 + B^2}$	$\frac{A}{2}$	$\frac{B}{2}$
Circular wire		$2\pi r$	r	r
Semi-circular		πr	r	$\frac{2r}{\pi}$
Quarter circular		$\frac{\pi r}{2}$	$\frac{2r}{\pi}$	$\frac{2r}{\pi}$
Circular arc		$2r\alpha$ (α in radian)	$\frac{r \sin \alpha}{\alpha}$	On Axis of Symmetry

Here,

$$\bar{x} = \frac{l_1 x_1 + l_2 x_2 + \dots + l_n x_n}{l_1 + l_2 + l_3 + \dots + l_n} = \frac{\sum l_i x_i}{\sum l}$$

$$\bar{y} = \frac{\sum l_i y_i}{\sum l}$$

Centroid of semi – circular arc



- A semi-circular arc be uniform thin wire or a thin rod, place it in such a way that y – axis is the axis of symmetry with this symmetry we have $\bar{x}=0$.

Here

$$\frac{y}{R} = \sin\theta$$

$$\therefore Y = \sin\theta R$$

$$\frac{dl}{R} = d\theta$$

$$dl = R \cdot d\theta$$

- Consider length of element is dl at an angle of θ as shown in fig.

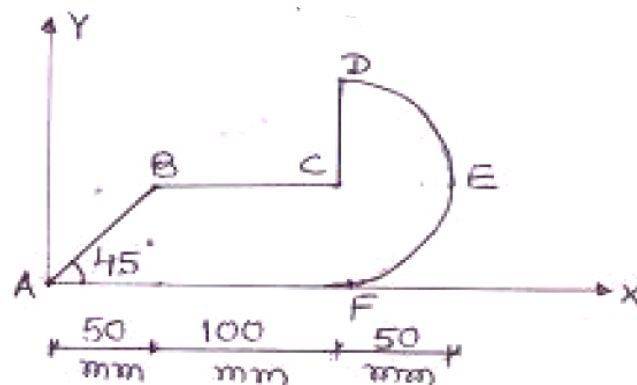
$$\bar{y} = \frac{\int y dl}{\int dl} = \frac{\int R \sin \theta R d\theta}{\int R d\theta}$$

$$= \frac{R \int \sin \theta d\theta}{\int d\theta}$$

$$= \frac{\int_0^\pi \sin \theta d\theta}{\int_0^\pi d\theta}$$

$$\bar{y} = \frac{2R}{\pi}$$

Example: 1. Determine the centroid of bar bent in to a shape as shown in figure.



Answer:

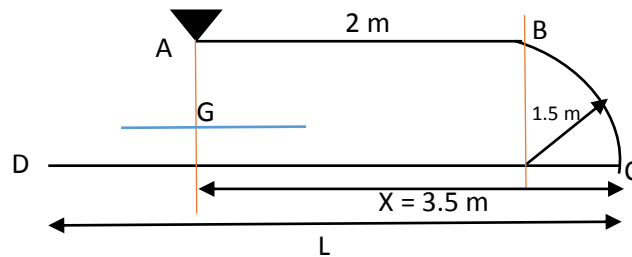
For finding out the centroid of given bar, let's divide the bar in to 4 – element as AB, BC, CD, DEF

Member	Length	x mm	Y mm	$lx(mm^2)$	$ly(mm^2)$
AB	$l_1 = \sqrt{50^2 + 50^2} = 70.71$	$x_1 = (50/2) = 25$	$y_1 = (50/2) = 25$	$l_1x_1 = 1767.75$	$l_1y_1 = 1767.75$
BC	$l_2 = 100$	$x_2 = (100/2) + 50 = 100$	$y_2 = 50$	$l_2x_2 = 10000$	$l_2y_2 = 5000$
CD	$l_3 = 50$	$x_3 = 50 + 100 = 150$	$y_3 = (50/2) + 50 = 75$	$l_3x_3 = 7500$	$l_3y_3 = 3750$
DEF	$l_4 = \pi r = 157.08$	$x_4 = 50 + 100 + (2r/\pi) = 181.83$	$y_4 = r = 50$	$l_4x_4 = 28561.85$	$l_4y_4 = 7853.95$

$$\bar{x} = \frac{l_1x_1 + l_2x_2 + \dots + l_nx_n}{l_1 + l_2 + l_3 + \dots + l_n} = \frac{47829.6}{377.79} = 126.60 \text{ mm}$$

$$\bar{y} = \frac{l_1y_1 + l_2y_2 + \dots + l_ny_n}{l_1 + l_2 + l_3 + \dots + l_n} = \frac{18371.7}{377.79} = 48.63 \text{ mm}$$

Example-2. Calculate length of part DE such that it remains horizontal when ABCDE is hanged through as shown in figure.



ANSWER :

- here, we want to determine length of $DC = l$ such that DC remains horizontal, for that centroidal axis passes through “A”.
- Reference axis is passing through c as shown in figure.

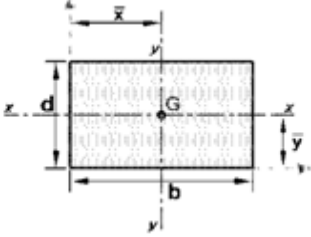
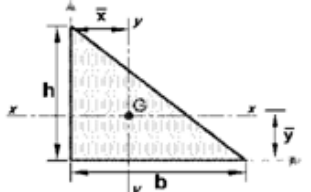
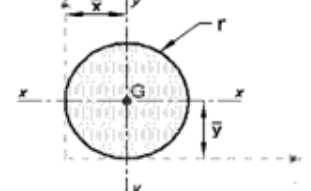
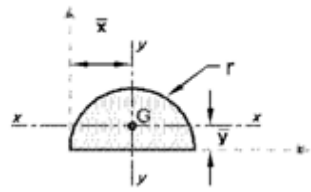
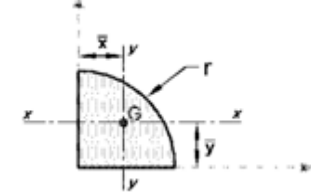
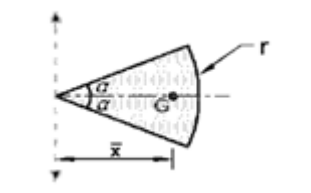
Part	Shape	Length	x mm	$lx(m^2)$
AB	Straight line	$l_1 = 2$	$x_1 = 1.5 - \frac{2}{2}$	$l_1 x_1 = 5$
BC	Semi-circular arc	$l_2 = \frac{2\pi r}{4}$	$x_2 = 1.5 - \frac{2r}{\pi}$	$l_2 x_2 = 1.284$
CD	Straight line	$l_3 = l$	$x_3 = \frac{l}{2}$	$l_3 x_3 = \frac{l^2}{2}$

$$\bar{x} = \frac{\sum l x}{\sum l} = \frac{0.5l^2 + 6.284}{4.356 + l} = 3.5$$

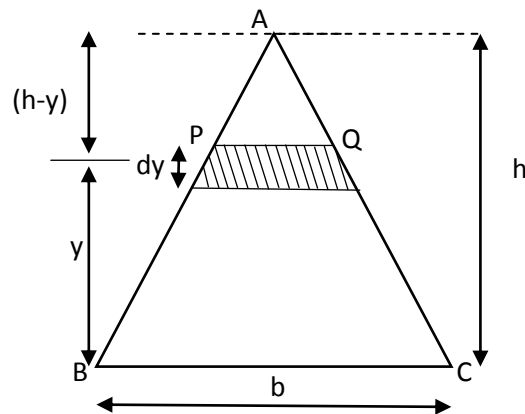
$$\therefore 15.246 + 3.5l = 0.5l^2 + 6.284$$

$$\therefore 0.5l^2 - 3.5l - 8.962 = 0$$

$$\therefore l = 8.993 \text{ m}$$

Area(Lamina) Element Centroid- Basic Shape				
Element name	Geometrical Shape	Area	$\bar{x}$	$\bar{y}$
Rectangle		bd	$\frac{b}{2}$	$\frac{d}{2}$
Triangle		$\frac{1}{2}bh$	$\frac{b}{3}$	$\frac{h}{3}$
Circle		πr^2	r	r
Semicircle		$\frac{\pi r^2}{2}$	r	$\frac{4r}{3\pi}$
Quarter circle		$\frac{\pi r^2}{4}$	$\frac{4r}{3\pi}$	$\frac{4r}{3\pi}$
Circular segment		αr^2 (α in radian)	$\frac{2 r \sin \alpha}{3 \alpha}$	On Axis of Symmetry

Centroid of a triangle area



- Place one side of the triangle on any axis, say $x - x$ axis as shown in fig.
- Consider a differential strip of width 'dy' at height y, by similar triangles $\triangle ABC$ & $\triangle CDB$

$$\frac{DE}{AB} = \frac{h-Y}{h}$$

$$\therefore DE = \left(1 - \frac{Y}{h}\right)b$$

$$= \left(b - \frac{Y}{h}b\right)$$

- Now, area of strip,

$$dA = \left(b - \frac{Y}{h}b\right) dy$$

- Now, we have

$$\bar{y} = \frac{\int y dA}{\int dA} = \frac{\int y dA}{A}$$

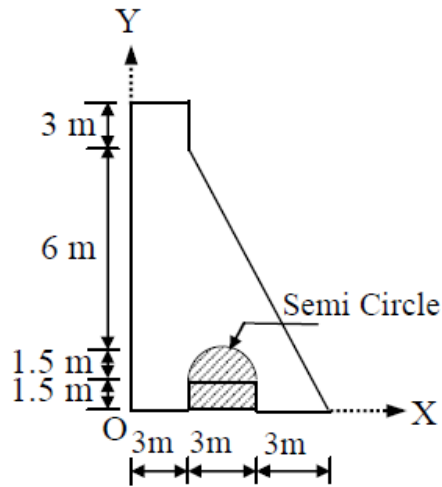
$$\therefore A\bar{y} = \int_0^h y dA$$

$$= \int_0^h y \left(b - \frac{b}{h} y\right) dy$$

$$\frac{1}{2} \times b \times h \times \bar{y} = \frac{bh^2}{2} - \frac{bh^2}{3}$$

$$\bar{y} = \frac{h}{3}$$

Example-3. Determine co-ordinates of centroid with respect to 'o' of the section as shown in figure.



Answer:

Let divide the given section in to 4 (four) pare

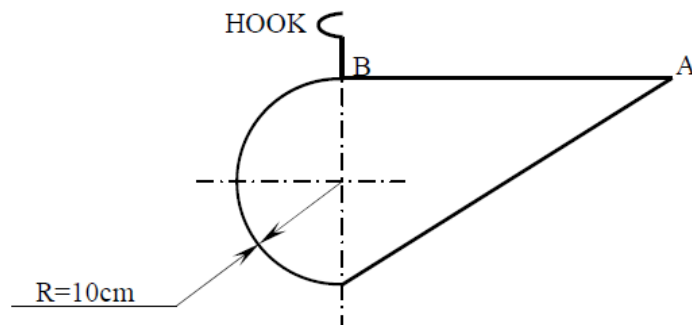
- (1) : Rectangular (3 X 12)
- (2) : Triangle (6 x 9)
- (3) : Rectangular (3 x 1.5)
- (4) : Semi – circular (r = 1.5m)

Sr. no	Shape	Area (m ²)	x (m)	Y(m)	Ax (m ³)	Ay (m ³)
1	Rectangle	$A_1 = 12 \times 3$ =36	$x_1 = \frac{3}{2}$ = 1.5	$y_1 = \frac{12}{2}$ = 6	$A_1 x_1$ = 54	$A_1 y_1 = 216$
2	Triangle	$A_1 = \frac{1}{2} \times 6 \times 9$ =27	$x_2 = 3 + \frac{6}{3}$ = 5	$y_2 = \frac{9}{3}$ = 3	$A_2 x_2$ = 135	$A_2 y_2 = 81$
3	Rectangle	$A_3 = -3 \times 1.5$ = -4.5	$x_3 = 3 + 1.5$ = 4.5	$y_3 = \frac{1.5}{2}$ = 0.75	$A_3 x_3$ = -20.25	$A_3 y_3$ = -3.375
4	Semi-circle	$A_4 = -\frac{\pi r^2}{2}$ = - 3.53	$x_4 = 3 + 1.5$ = 4.5	$y_4 = 1.5 + \frac{4r}{3\pi}$ = 2.134	$A_4 x_4$ = -15.885	$A_4 y_4$ = -7.53

$$\bar{x} = \frac{\sum Ax}{\sum A} = \frac{A_1 x_1 + A_2 x_2 + \dots + A_n x_n}{A_1 + A_2 + A_3 + \dots + A_n} = 2.78 \text{ mm}$$

$$\bar{Y} = \frac{\sum AY}{\sum A} = \frac{A_1 y_1 + A_2 y_2 + \dots + A_n y_n}{A_1 + A_2 + A_3 + \dots + A_n} = 5.20 \text{ mm}$$

Example 4 A lamina of uniform thickness is hung through a weight less hook at point B such that side AB remains horizontal as shown in fig. determine the length AB of the lamina.



Answer:

Let, length AB=L, for remains horizontal of given lamina moment of areas of lamina on either side of the hook must be equal.

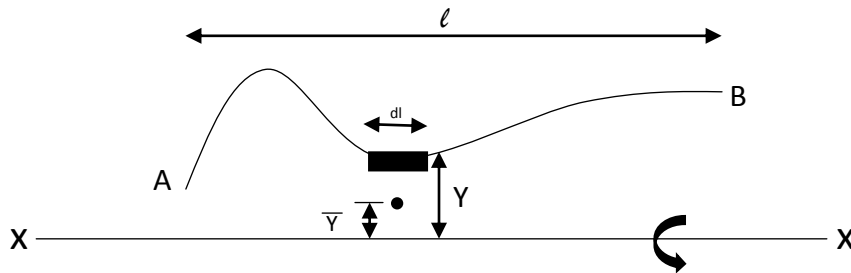
$$\therefore A_1 x_1 = A_2 x_2$$

$$\therefore \left(\frac{1}{2} \times L \times 20\right) \left(\frac{1}{3} \times L\right) = \left(\frac{10^2}{2} \times \pi\right) \left(\frac{4 \times (r=10)}{3\pi}\right)$$

$$\therefore \frac{20L^2}{6} = 157.08 \times 4.244$$

$$\therefore L = 14.14 \text{ cm}$$

Pappus Guldinus first theorem



- This theorem states that, “the area of surface of revolution is equal to the product of length of generating curves & the distance travelled by the centroid of the generating curve while the surface is being generated”.
- As shown in fig. consider small element having length dl & at ‘ y ’ distance from $x - x$ axis.
- Surface area dA by revolving this element $dA = 2\pi y \cdot dl$ (complete revolution)
- Now, total area,

$$\therefore A = \int dA = \int 2\pi y dl = 2\pi \int y dl$$

$$\therefore A = 2\pi \bar{y} l$$

- When the curve rotate by an angle ‘ θ ’

$$\therefore A = 2\pi \bar{y} l \frac{\theta}{2\pi} = \theta \bar{y} l$$

Pappus guldinus second theorem

- This the rem states that, “the volume of a body of revolution is equal to the product of the generating area & distance travelled by the centroid of revolving area while rotating around its axis of rotation.
- Consider area ‘ dA ’ as shown in fig. the volume generated by revolution will be

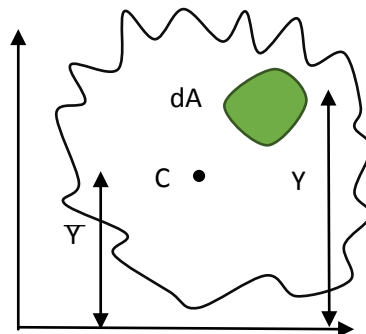
$$dv = Q \pi Y \cdot dA$$

- Now, the total volume generated by lamina,

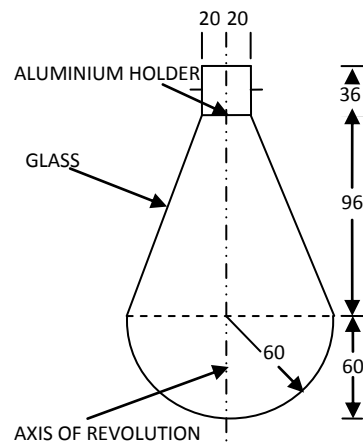
$$\begin{aligned} V &= \int dv = \int 2\pi y dA \\ &= 2\pi \bar{y} A \text{ (completed revolution) } \end{aligned}$$

- When the area revolves about ‘ θ ’ angle volume will be

$$V = 2\pi \bar{y} A \frac{\theta}{2\pi} = \theta \bar{y} A$$



Example-5. Find surface area of the glass to manufacture an electric bulb shown in fig using first theorem of Pappu's Guldinus.



Line	length	x mm	$lx(\text{mm}^2)$
AB	$L_1=20$	$x_1 = \frac{20}{2} = 10$	200
BC	$L_2=36$	$x_1 = 20$	720
CD	$L_3=\sqrt{40^2 + 96^2}$ $=104$	$x_3 = 20 + \frac{40}{2} = 40$	4160
DE	$L_4=\frac{\pi R}{2}$ $=94.25$	$x_4 = \frac{2r}{\pi} = 38.20$	36000

$$\bar{x} = \frac{\sum L x}{L} = 34.14\text{mm}$$

$$\begin{aligned}\text{Surface area} &= L \bar{x} = 254.25 \times 2\pi \times 34.14 \\ &= 54510.99\text{mm}^2\end{aligned}$$

MOMENT OF INERTIA

UNIT IV

Introduction

- The moment of force about any point is defined as product of force and perpendicular distance between direction of force and point under consideration. It is also called as first moment of force.
- In fact, moment does not necessary involve force term, a moment of any other physical term can also be determined simply by multiplying magnitude of physical quantity and perpendicular distance. Moment of areas about reference axis has been taken to determine the location of centroid. Mathematically it was defined as,

Moment = area x perpendicular distance.

$$M = (A \times y)$$

- If the moment of moment is taken about same reference axis, it is known as moment of inertia in terms of area, which is defined as,

Moment of inertia = moment x perpendicular distance.

$$I_A = (M \times y) = A \cdot y \times y = A y^2$$

- Where I_A is area moment of inertia, A is area and 'y' is the distance between centroid of area and reference axis. On similar notes, moment of inertia is also determined in terms of mass, which is defined as,

$$I_m = mr^2$$

- Where 'm' is mass of body, 'r' is distance between center of mass of body and reference axis and I_m is mass of moment of inertia about reference axis. It must be noted here that for same area or mass moment of inertia will be change with change in location of reference axis.

➤ **Theorem of parallel Axis: -**

- It states, “If the moment of inertia of a plane area about an axis through its center of gravity is denoted by I_G , then moment of inertia of the area about any other axis AB parallel to the first and at a distance ‘h’ from the center of gravity is given by,

$$I_{AB} = I_G + ah^2$$

- Where I_{AB} = moment of inertia of the area about AB axis

I_G = Moment of inertia of the area about centroid

a = Area of section

h = Distance between center of gravity (centroid) of the section and axis AB.

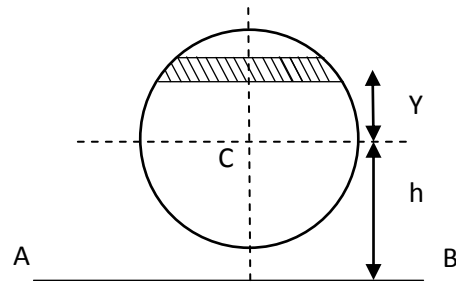
Proof: -

- Consider a strip of a circle, whose moment of inertia is required to be found out a line ‘AB’ as shown in figure.

Let d_a = Area of the strip.

y = Distance of the strip from the C.G. of the section

h = Distance between center of gravity of the section and the ‘AB’ axis.



- We know that moment of inertia of the whole section about an axis passing through the center of gravity of the section.

$$= d_a y^2$$

- And M.I of the whole section about an axis passing through centroid.

$$I_G = \sum d_a y^2$$

- Moment of inertia of the section about the AB axis

$$\begin{aligned} I_{AB} &= \sum d_a (h+y)^2 \\ &= \sum d_a (h^2 + 2hy + y^2) \\ &= ah^2 + I_G \end{aligned}$$

- It may be noted that $\sum d_a h^2 = ah$ and $\sum y^2 d_a = I_G$ and $\sum d_a y$ is the algebraic sum of moments of all the areas, about an axis through center of gravity of the section and is equal $a\bar{y}$, where $\bar{y}$ is the distance between the section and the axis passing through the center of gravity which obviously is zero.

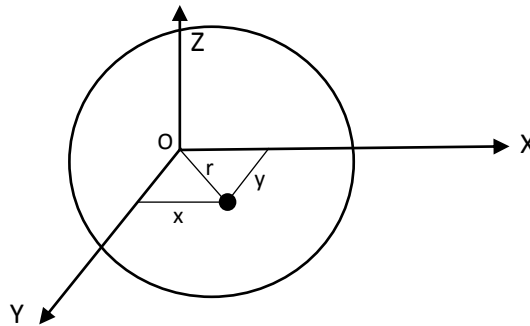
➤ **Theorem of Perpendicular Axis: -**

- It states, If I_{XX} and I_{YY} be the moment of inertia of a plane section about two perpendicular axis meeting at 'o' the moment of inertia I_{ZZ} about the axis Z-Z, perpendicular to the plane and passing through the intersection of X-X and Y-Y is given by,

$$I_{ZZ} = I_{XX} + I_{YY}$$

Proof: -

- consider a small lamina (P) of area ' d_a ' having co-ordinates as ox and oy two mutually perpendicular axes on a plane section as shown in figure.
- Now, consider a plane OZ perpendicular ox and oy. Let (r) be the distance of the lamina (p) from z-z axis such that $op = r$.



- From the geometry of the figure, we find that,
$$r^2 = x^2 + y^2$$
- We know that the moment of inertia of the lamina 'p' about x-x axis,

$$I_{XX} = d_a \cdot y^2$$

$$\text{Similarly, } I_{YY} = d_a x^2$$

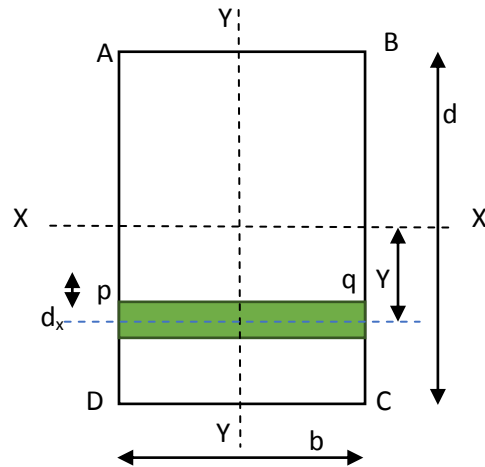
$$\text{and } I_{ZZ} = d_a r^2$$

$$= d_a (x^2 + y^2)$$

$$= d_a x^2 + d_a y^2$$

$$I_{ZZ} = I_{XX} + I_{YY}$$

➤ **Moment of Inertia of a Rectangular Section: -**



- Consider a rectangular section ABCD as shown in fig. whose moment of inertia is required to be found out.
- Let, b = width of the section
 d = Depth of the section
- Now, consider a strip PQ of thickness d_y parallel to x-x axis and at a distance y -from it as shown in fig.

$$\text{Area of strip} = b \cdot d_y$$

- We know that moment of inertia of the strip about x-x axis,

$$= \text{Area} \times y^2$$

$$= (b \cdot d_y) y^2$$

- Now, moment of inertia of the whole section may be found out by integrating the about equation for the whole length of the lamina i.e. from $-d/2$ to $+d/2$

$$I_{XX} = \int_{-d/2}^{+d/2} b \cdot y^2 d y$$

$$I_{XX} = b \int_{-d/2}^{+d/2} y^2 d y$$

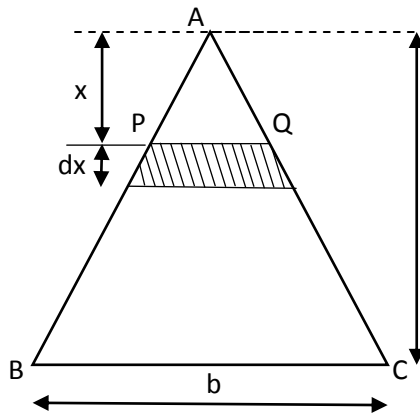
$$= \left[\frac{y^3}{3} \right]_{-d/2}^{+d/2}$$

$$= \frac{bd^3}{12}$$

$$\text{Similarly, } I_{YY} = \frac{db^3}{12}$$

If it is square section,

$$I_{xx} = I_{yy} = \frac{b^4}{12} = \frac{d^4}{12}$$



Let, b = Base of the triangular section.

h = height of the triangular section.

Now, consider a small strip PQ of thickness 'dx' at a distance from the vertex A as shown in figure, we find that the two triangle APQ and ABC are similar.

$$\frac{PQ}{BC} = \frac{x}{h} \quad \text{or} \quad PQ = \frac{BC \cdot x}{h} = \frac{b \cdot x}{h}$$

We know that area of the strip PQ = $\frac{b \cdot x}{h} dx$

$$\begin{aligned} \text{And moment of inertia of the strip about the base BC} \\ &= \text{Area} \times (\text{Distance})^2 \\ &= \frac{b \cdot x}{h} dx (h-x)^2 \end{aligned}$$

- Now, moment of inertia of the whole triangular section may be found out by integrating the above equation for the above equation for the whole height of the triangle i.e. from 0 to h .

$$\begin{aligned} I_{BC} &= \int_0^h \frac{b \cdot x}{h} (h-x)^2 dx \\ &= \frac{b}{h} \int_0^h (h^2 + x^2 + 2hx) x dx \\ &= \frac{b}{h} \left[\frac{x^2 y^2}{2} + \frac{x^4}{4} + \frac{2hx^3}{3} \right]_0^h \\ I_{BC} &= \frac{bh^3}{12} \end{aligned}$$

- We know that the distance between center of gravity of the triangular section and Base BC,

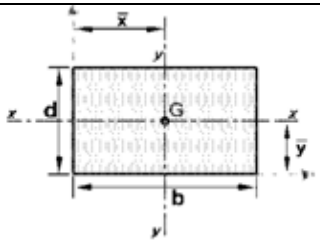
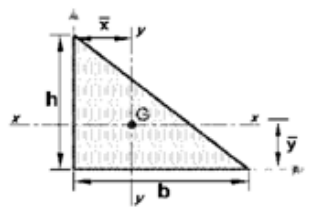
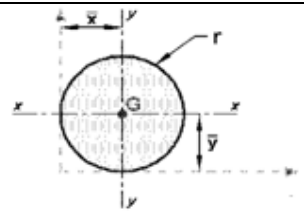
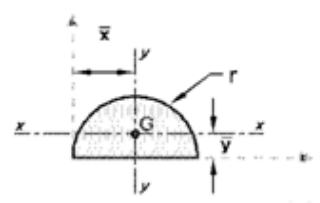
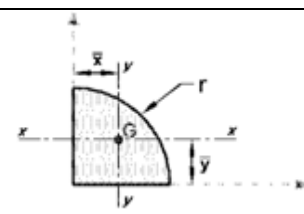
$$d = \frac{h}{3}$$

- so, Moment of the inertia of the triangular section about an axis through its center through its center of gravity parallel to x-x axis,

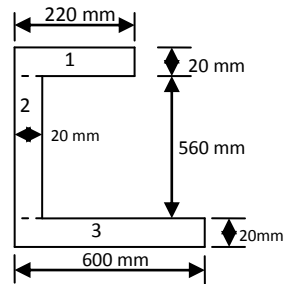
$$\begin{aligned} I_G &= I_{BC} - ad^2 \\ &= \frac{bh^3}{12} - \left(\frac{bh}{3} \right) \left(\frac{h}{3} \right)^2 \\ I_G &= \frac{bh^3}{36} \end{aligned}$$

Note: - The moment of inertia of section about an axis through its vertex and parallel to the base.

$$\begin{aligned} I_{top} &= I_G + ad^2 \\ &= \frac{bh^3}{36} + \left(\frac{bh}{3} \right) \left(\frac{2h}{3} \right)^2 \\ &= \frac{9bh^3}{36} \\ &= \frac{bh^3}{4} \end{aligned}$$

Area (Lamina) Element – Moment of Inertia (Basic Shape)				
Element name	Geometrical Shape	Area	I_{xx}	I_{yy}
Rectangle		bd	$\frac{bd^3}{12}$	$\frac{db^3}{12}$
Triangle		$\frac{1}{2}bh$	$\frac{bh^3}{36}$	$\frac{hb^3}{36}$
Circle		πr^2	$\frac{\pi d^4}{64}$	$\frac{\pi d^4}{64}$
Semicircle		$\frac{\pi r^2}{2}$	$0.11 r^4$	$\frac{\pi d^4}{128}$
Quarter circle		$\frac{\pi r^2}{4}$	$0.055 r^4$	$0.055 r^4$
d= diameter				

Example – 1: Find out moment of inertia at horizontal and vertical centroid axes, top and bottom edge of the given lamina.



Answer: -

1) centroid of given lamina

Let's divide the given lamina in to three Rectangle

- (1) Top rectangle 200 x 20 mm²
- (2) Middle rectangle 20 x 600 mm²
- (3) Bottom rectangle 580 x 20 mm²

Sr no	Shape	Area (mm ²)	X (mm)	Y (mm)	AX (mm ²)	AY (mm ²)
1	1	$A_1 = 200 \times 20 = 4000$	$X_1 = 20 + \frac{200}{2} = 120$	$Y_1 = 20 + 560 + \frac{20}{2} = 590$	$A_1 X_1 = 480,000$	$A_1 Y_1 = 2,36,0000$
2	2	$A_2 = 600 \times 20 = 12000$	$X_2 = \frac{20}{2} = 10$	$Y_2 = \frac{600}{2} = 300$	$A_2 X_2 = 1,20,000$	$A_2 Y_2 = 3,60,0000$
3	3	$A_3 = 580 \times 20 = 11600$	$X_3 = \frac{580}{2} + 20 = 310$	$Y_3 = \frac{20}{2} = 10$	$A_3 X_3 = 35,96,000$	$A_3 Y_3 = 116000$
		$\Sigma A = 27600$			$\Sigma AX = 4196000$	$\Sigma AY = 6076000$

$$\bar{Y} = \frac{\Sigma AY}{\Sigma A} = \frac{6076000}{27600} = 220.15 \text{ mm}$$

$$\bar{X} = \frac{\Sigma AX}{\Sigma A} = \frac{4196000}{27600} = 152.03 \text{ mm}$$

(2) Moment of inertia about centroid horizontal axis: -

Sr No	Area (mm ²)	h (mm)	Ah ² (mm ⁴)	I _G (mm ⁴)	I _{XX} = I _G + Ah ²
1	$A_1 = 4000$	$h_1 = y_t - \frac{d_1}{2} = 369.85$	$A_1 h_1^2 = 5.4716 \times 10^8$	$I_{G1} = b_1 h_1^3 / 12 = 1.33334 \times 10^5$	$I_1 = 5.4729 \times 10^8$
2	$A_2 = 12000$	$h_2 = y_t - \frac{d_2}{2} = 79.85$	$A_2 h_2^2 = 7.6512 \times 10^7$	$I_{G2} = b_2 h_2^3 / 12 = 3.6 \times 10^8$	$I_2 = 4.3651 \times 10^8$
3	$A_3 = 11600$	$h_3 = y_b - \frac{d_3}{2} = 210.15$	$A_3 h_3^2 = 5.1229 \times 10^8$	$I_{G3} = b_3 h_3^3 / 12 = 3.8667 \times 10^5$	$I_3 = 5.1268 \times 10^8$

Now, Moment of inertia at centroid horizontal axis

$$I_{XX} = I_1 + I_2 + I_3$$

$$= 1.4965 \times 10^9 \text{ mm}^4$$

(3) Moment of inertia about centroid vertical axis: -

Shape No	Area (mm ²)	h (mm)	Ah ² (mm ⁴)	I _G (mm ⁴)	I _{yy} = I _G + Ah ²
1	A ₁ = 4000	h ₁ = X ₁ - X ₁ = 32.03	A ₁ h ₁ ² = 4.1036 x 10 ⁶	I _{G1} = d ₁ b ₁ ³ /12 = 1.33334 x 10 ⁷	I ₁ = 1.7437 x 10 ⁷
2	A ₂ = 12000	h ₁ = X ₁ - X ₂ = 142.03	A ₂ h ₂ ² = 2.4207 x 10 ⁸	I _{G2} = d ₂ b ₂ ³ /12 = 4 x 10 ⁵	I ₂ = 2.4247 x 10 ⁸
3	A ₃ = 11600	h ₁ = X ₃ - X ₁ = 310	A ₃ h ₃ ² = 1.1148 x 10 ⁹	I _{G3} = d ₃ b ₃ ³ /12 = 3.2519 x 10 ⁸	I ₃ = 1.4399 x 10 ⁹

Now, Moment of inertia at centroidal axis

$$I_{yy} = I_1 + I_2 + I_3 \\ = 1.6998 \times 10^9 \text{ mm}^4$$

(4) Moment of inertia about top edge of horizontal axis: -

Shape no	Area (mm ²)	h (mm)	Ah ² (mm ⁴)	I _G (mm ⁴)	I _{tt} = I _G + Ah ²
1	A ₁ = 4000	h ₁ = $\frac{d_1}{2}$ = 10	A ₁ h ₁ ² = 4 x 10 ⁵	I _{G1} = b ₁ d ₁ ³ /12 = 1.33334 x 10 ⁵	I ₁ = 5.3334 x 10 ⁵
2	A ₂ = 12000	h ₂ = $\frac{d_2}{2}$ = 300	A ₂ h ₂ ² = 1.08 x 10 ⁹	I _{G2} = b ₂ d ₂ ³ /12 = 3.6 x 10 ⁹	I ₂ = 1.44 x 10 ⁹
3	A ₃ = 11600	h ₃ = $\frac{d_3}{2}$ = 590	A ₃ h ₃ ² = 4.038 x 10 ⁹	I _{G3} = b ₃ d ₃ ³ /12 = 3.8667 x 10 ⁵	I ₃ = 4.0384 x 10 ⁹

Now, Moment of inertia at top edge of horizontal axis

$$I_{tt} = I_1 + I_2 + I_3 \\ = 5.4789 \times 10^9 \text{ mm}^4$$

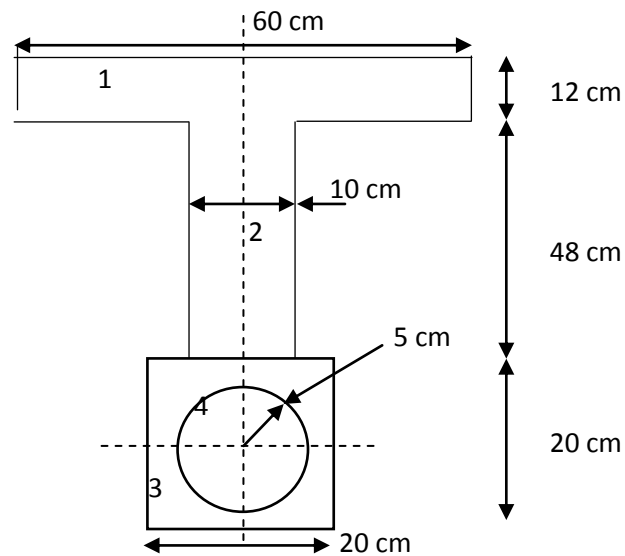
(5) Moment of inertia about bottom edge of horizontal axis: -

Shape no	Area (mm ²)	h (mm)	Ah ² (mm ⁴)	I _G (mm ⁴)	I _{bb} = I _G + Ah ²
1	A ₁ = 4000	h ₁ = d ₂ - $\frac{d_1}{2}$ = 590	A ₁ h ₁ ² = 1.3924 x 10 ⁹	I _{G1} = b ₁ d ₁ ³ /12 = 1.33334 x 10 ⁵	I ₁ = 1.3925 x 10 ⁹
2	A ₂ = 12000	h ₂ = $\frac{d_2}{2}$ = 300	A ₂ h ₂ ² = 1.08 x 10 ⁹	I _{G2} = b ₂ d ₂ ³ /12 = 3.6 x 10 ⁵	I ₂ = 1.44 x 10 ⁹
3	A ₃ = 11600	h ₃ = $\frac{d_3}{2}$ = 10	A ₃ h ₃ ² = 1.16 x 10 ⁶	I _{G3} = b ₃ d ₃ ³ /12 = 3.8667 x 10 ⁵	I ₃ = 1.5467 x 10 ⁶

Now, Moment of inertia at bottom edge of horizontal axis

$$I_{tt} = I_1 + I_2 + I_3 \\ = 2.834 \times 10^9 \text{ mm}^4$$

Example-2: Determine moment of inertia of a section shown in figure about horizontal centroid axis.



Answer: -

(1) Centroid of given lamina

Let's divide the given lamina in to four part

- (i) Top rectangular 60 x 12 cm²
- (ii) Middle rectangular 10 x 48 cm²
- (iii) Bottom square 20 x 20 cm²
- (iv) Deduct circle of radius 5 cm from bottom square

SR NO.	Shape	Area (cm ²)	Y (cm)	AY (cm ³)
1	1	$A_1 = 60 \times 12 = 720$	$Y_1 = 20 + 48 + \frac{12}{2} = 74$	$A_1 Y_1 = 34560$
2	2	$A_2 = 10 \times 48 = 480$	$Y_2 = 20 + \frac{48}{2} = 300$	$A_2 Y_2 = 21120$
3	3	$A_3 = 20 \times 20 = 400$	$Y_3 = \frac{20}{2} = 10$	$A_3 Y_3 = 4000$
4	4	$A_4 = -\pi r^2 = -78.54$	$Y_4 = \frac{20}{2} = 10$	$A_4 Y_4 = -785.4$
		$\Sigma A = 1521.46$		$\Sigma AY = 58894.6$

$$\bar{Y} = \frac{\Sigma AY}{\Sigma A} = \frac{58894.6}{1521.46} = 38.70 \text{ cm}$$

(2) Moment of inertia about centroid horizontal axis: -

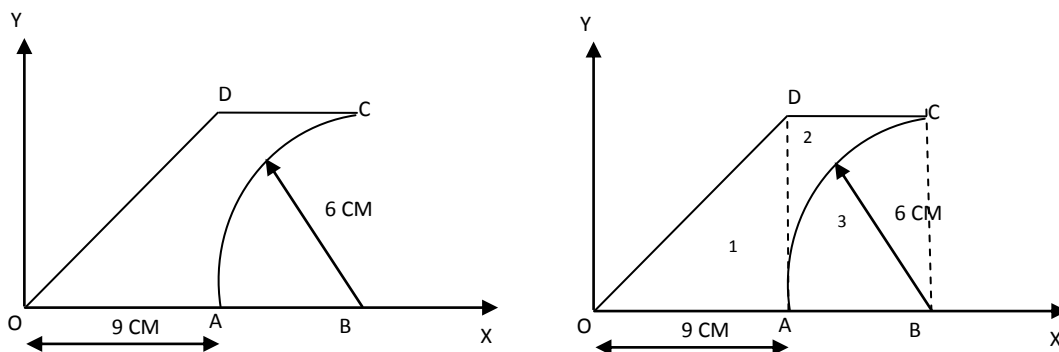
Shape no	Area (cm ²)	h (cm)	Ah ² (cm ⁴)	I _G (cm ⁴)	I _{XX} = I _G + Ah ²
1	A ₁ = 720	$h_1 = y_t - \frac{d_1}{2} = 35.3$	$A_1 h_1^2 = 897.1 \times 10^3$	$I_{G1} = b_1 h_1^3 / 12 = 8640$	$I_1 = 905824.8$
2	A ₂ = 480	$h_2 = y_t - \frac{d_2}{2} = 17.3$	$A_2 h_2^2 = 143.65 \times 10^3$	$I_{G2} = b_2 h_2^3 / 12 = 92160$	$I_2 = 235819.2$
3	A ₃ = 400	$h_3 = y_b - \frac{d_3}{2} = 28.7$	$A_3 h_3^2 = 329.4 \times 10^3$	$I_{G3} = b_3 h_3^3 / 12 = 13333.34$	$I_3 = 342809.34$
4	A ₄ = 78.54	H ₄ = 28.7	$A_4 h_4^2 = -64.6 \times 10^3$	$I_{G3} = \pi d^4 / 64 = -490.8$	$I_3 = -65183.48$

Now, Moment of inertia at centroid horizontal axis

$$I_{XX} = I_1 + I_2 + I_3$$

$$= 1.419 \times 10^6 \text{ cm}^4$$

Example-3: - Find the moment of inertia about Y-axis and X-axis for the area shown in fig.



(1) Moment of inertia about x- axis (o-x line)

Sr No	Area (cm ²)	h (cm)	Ah ² (cm ⁴)	I _G (cm ⁴)	I _{OX} = I _G + Ah ²
1	$A_1 = \frac{1}{2}bh = 4000$	$h_1 = \frac{h}{3} = 2$	$A_1 h_1^2 = 108$	$I_{G1} = bh^3 / 36 = 54$	$I_1 = 162$
2	$A_2 = d \times d = 12000$	$h_2 = \frac{d}{2} = 3$	$A_2 h_2^2 = 324$	$I_{G2} = d^4 / 12 = 108$	$I_2 = 432$
3	$A_3 = \frac{\pi}{4}r^2 = 11600$	$h_3 = \frac{4r}{3\pi} = 2.55$	$A_3 h_3^2 = 183.35$	$I_{G3} = 0.055r^4 = 71.28$	$I_3 = 254.62$

Now, Moment of inertia at centroid horizontal axis

$$I_{XX} = I_1 + I_2 + I_3$$

$$= 339.37 \text{ cm}^4$$

(2) Moment of inertia about y- axis (OY - line)

Shape no	Area (cm ²)	h (cm)	Ah ² (cm ⁴)	I _G (cm ⁴)	I _{OY} = I _G + Ah ²
1	A ₁ = 27	h ₁ = 6	$A_1 h_1^2 = 972$	$I_{G1} = b^3 h / 36 = 121.5$	$I_1 = 1093.5$
2	A ₂ = 12	h ₂ = 12	$A_2 h_2^2 = 5184$	$I_{G2} = d^4 / 12 = 108$	$I_2 = 5292$
3	A ₃ = 12.45	h ₃ = 12.45	$A_3 h_3^2 = 4381.9$	$I_{G3} = 0.055r^4 = 71.28$	$I_3 = 4456.35$

Now, Moment of inertia at centroid horizontal axis

$$I_{XX} = I_1 + I_2 - I_3$$

$$= 1929.15 \text{ cm}^4$$

UNIT V

KINEMATICS AND KINETICS

CONCEPT OF MOTION

A body is said to be in motion if it changes its position with respect to its surroundings. The nature of path of displacement of various particles of a body determines the type of motion. The motion may be of the following types :

1. Rectilinear translation
2. Curvilinear translation
3. Rotary or circular motion.

Rectilinear translation is also known as *straight line motion*. Here particles of a body move in straight parallel paths. *Rectilinear means forming straight lines and translation means behaviour*. Rectilinear translation will mean behaviour by which straight lines are formed. Thus, when a body moves such that its particles form parallel straight paths the body is said to have rectilinear translation.

In a *curvilinear translation the particles of a body move along circular arcs or curved paths*.

Rotary or circular motion is a special case of curvilinear motion where particles of a body move along *concentric circles* and the *displacement is measured in terms of angle in radians or revolutions*.

DEFINITIONS

1. Displacement. If a particle has rectilinear motion with respect to some point which is assumed to be fixed, its displacement is its total change of position during any interval of time. The point of reference usually assumed is one which is at rest with respect to the surfaces of the earth.

The unit of displacement is same as that of distance or length. In M.K.S. or S.I. system it is *one metre*.

2. Rest and motion. A body is said to be at *rest* at an instant (means a small interval of time) if its position with respect to the surrounding objects remains unchanged during that instant.

A body is said to be in *motion* at an instant if it changes its position with respect to its surrounding objects during that instant.

Actually, nothing is absolutely at rest or absolutely in motion : *all rest or all motion is relative only*.

3. Speed. The speed of body is defined as *its rate of change of its position with respect to its surroundings irrespective of direction*. It is a *scalar quantity*. It is measured by distance covered per unit time.

Mathematically, speed

$$= \frac{\text{Distance covered}}{\text{Time taken}} = \frac{S}{t}$$

Its units are m/sec or km/hour.

4. Velocity. The velocity of a body is *its rate of change of its position with respect to its surroundings in a particular direction*. It is a *vector quantity*. It is measured by the distance covered in a particular direction per unit time.

i.e.,
$$\text{Velocity} = \frac{\text{Distance covered (in a particular direction)}}{\text{Time taken}}$$

$$v = \frac{S}{t}$$

Its units are same as that of speed i.e., m/sec or km/hour.

5. Uniform velocity. If a body travels equal distances in equal intervals of time in the same direction it is said to be moving with a uniform or constant velocity. If a car moves 50 metres with a constant velocity in 5 seconds, its velocity will be equal to,

$$\frac{50}{5} = 10 \text{ m/s.}$$

6. Variable velocity. If a body travels unequal distances in equal intervals of time, in the same direction, then it is said to be moving with a variable velocity or if it changes either its speed or its direction or both shall again be said to be moving with a variable velocity.

7. Average velocity. The average or mean velocity of a body is the velocity with which the distance travelled by the body in the same interval of time, is the same as that with the variable velocity.

If u = initial velocity of the body
 v = final velocity of the body
 t = time taken
 S = distance covered by the body

Then average velocity $= \frac{u+v}{2}$

and
$$S = \left(\frac{u+v}{2} \right) \times t$$

8. Acceleration. The rate of change of velocity of a body is called its acceleration. When the velocity is increasing the acceleration is reckoned as *positive*, when decreasing as *negative*. It is represented by a or f .

If u = initial velocity of a body in m/sec
 v = final velocity of the body in m/sec
 t = time interval in seconds, during which the change has occurred,

Then acceleration,
$$a = \frac{v-u}{t} \frac{\text{m/sec}}{\text{sec}}$$

or
$$a = \frac{v-u}{t} \text{ m/sec}^2$$

From above, it is obvious that if *velocity of the body remains constant, its acceleration will be zero*.

9. Uniform acceleration. If the velocity of a body changes by equal amounts in equal intervals of time, the body is said to move with uniform acceleration.

10. Variable acceleration. If the velocity of a body changes by unequal amount in equal intervals of time, the body is said to move with variable acceleration.

DISPLACEMENT-TIME GRAPHS

Refer to Fig. (a). The graph is parallel to the time-axis indicating that the *displacement is not changing with time*. The *slope of the graph is zero*. The body has no velocity and is at rest.

Refer to Fig. (b). The displacement increases linearly with time. The displacement increases by equal amounts in equal intervals of time. *The slope of the graph is constant*. In other words, the body is moving with a *uniform velocity*.

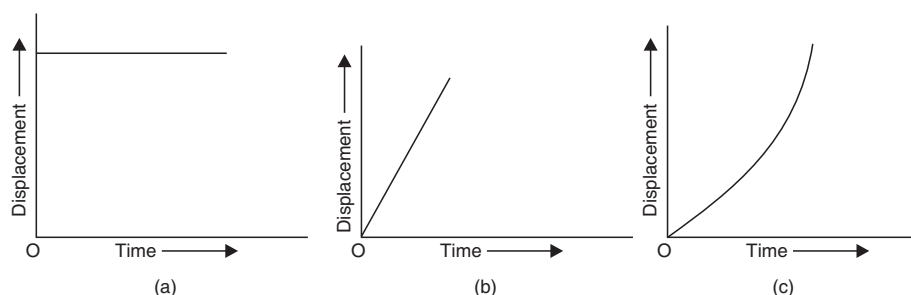


Fig. Displacement-time graphs

Refer to Fig. (c). The displacement time graph is a *curve*. This means that the displacement is not changing by equal amounts in equal intervals of time. The slope of the graph is different at different times. In other words, the velocity of the body is changing with time. The motion of the body is accelerated.

7.4. VELOCITY-TIME GRAPHS

Refer to Fig. (a). The velocity of the body increases linearly with time. The slope of the graph is constant, *i.e.*, velocity changes by equal amounts in equal intervals of time. In other words, the *acceleration of the body is constant*. Also, at time $t = 0$, the velocity is finite. Thus, the body, *moving with a finite initial velocity, is having a constant acceleration*.

Refer to Fig. (b). The body has a finite initial velocity. As the time passes, the velocity decreases linearly with time until its final velocity becomes zero, *i.e.* it comes to rest. Thus, the body has a *constant deceleration* (or retardation) since the *slope of the graph is negative*.

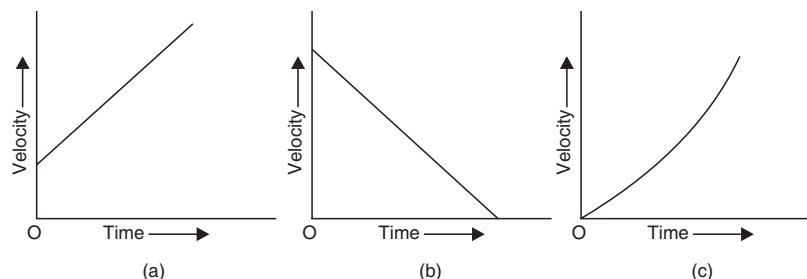


Fig. Velocity-time graphs

Refer to Fig. (c). The velocity-time graph is a *curve*. The slope is therefore, different at different times. In other words, the *velocity is not changing at a constant rate*. The body does not have a uniform acceleration since the acceleration is changing with time.

EQUATIONS OF MOTION UNDER UNIFORM ACCELERATION

First Equation of Motion. *Relation between u , v , a and t .*

Let us assume that a body starts with an initial velocity u and acceleration a . After time t , it attains a velocity v . Therefore, the change in velocity in t seconds = $v - u$. Hence, the change in velocity in one second = $\frac{v - u}{t}$. By definition, this is equal to the acceleration a .

$$\text{Thus,} \quad a = \frac{v - u}{t}$$

$$\text{or} \quad at = v - u$$

$$\text{or} \quad v = u + at$$

Second Equation of Motion. *Relation between S , u , a and t .*

Let a body moving with an initial uniform velocity u is accelerated with a uniform acceleration a for time t . After time t its final velocity is v . The distance S which the body travels in time t is determined as follows :

Now, since the acceleration is uniform, *i.e.*, the velocity changes by an equal amount in equal intervals of time, it is obvious that the average velocity is just the average of initial and final velocities.

$$\text{Average velocity} = \left(\frac{u + v}{2} \right)$$

$$\therefore \text{Distance travelled} = \text{average velocity} \times \text{time}$$

$$S = \left(\frac{u + v}{2} \right) \times t$$

$$\text{or} \quad S = \left(\frac{u + u + at}{2} \right) \times t \quad (\because v = u + at)$$

$$= \left(u + \frac{at}{2} \right) \times t$$

$$\text{or} \quad S = ut + \frac{1}{2} at^2$$

Third Equation of Motion. *Relation u , v , a and S . We know, that*

$$S = \text{average velocity} \times \text{time}$$

$$= \left(\frac{u + v}{2} \right) \times t$$

$$= \left(\frac{u + v}{2} \right) \times \left(\frac{v - u}{a} \right) \quad \left(\because t = \frac{v - u}{a} \right)$$

$$= \frac{v^2 - u^2}{2a}$$

$$\therefore v^2 - u^2 = 2aS$$

DISTANCE COVERED IN n th SECOND BY A BODY MOVING WITH UNIFORM ACCELERATION

Let u = initial velocity of the body

a = acceleration

S_{nth} = distance covered in n th second

then
$$S_{nth} = \left(\begin{array}{c} \text{distance covered} \\ \text{in } n \text{ second, } s_n \end{array} \right) - \left(\begin{array}{c} \text{distance covered in } (n-1) \\ \text{second, } s_{n-1} \end{array} \right)$$

Using the relation,

$$S_n = un + \frac{1}{2} an^2 \quad (\because t = n)$$

and

$$\begin{aligned} S_{n-1} &= u(n-1) + \frac{1}{2} a (n-1)^2 \\ &= u(n-1) + \frac{1}{2} a (n^2 - 2n + 1) \end{aligned}$$

$\therefore$

$$\begin{aligned} S_{nth} &= S_n - S_{n-1} \\ &= \left(un + \frac{1}{2} an^2 \right) - \left[u(n-1) + \frac{1}{2} a (n^2 - 2n + 1) \right] \\ &= un + \frac{1}{2} an^2 - un + u - \frac{1}{2} an^2 + an - a/2 \\ &= u + an - a/2 \end{aligned}$$

$\therefore$

$$S_{nth} = u + a/2(2n - 1)$$

1. A car accelerates from a velocity of 36 km/hour to a velocity of 108 km/hour in a distance of 240 m. Calculate the average acceleration and time required.

Sol. Initial velocity,

$$\begin{aligned} u &= 36 \text{ km/hour} \\ &= \frac{36 \times 1000}{60 \times 60} = 10 \text{ m/sec} \end{aligned}$$

Final velocity,

$$\begin{aligned} v &= 108 \text{ km/hour} \\ &= \frac{108 \times 1000}{60 \times 60} = 30 \text{ m/sec} \end{aligned}$$

Distance,

$$S = 240 \text{ m.}$$

Average acceleration, $a = ?$

Using the relation,

$$\begin{aligned} v^2 - u^2 &= 2aS \\ (30)^2 - (10)^2 &= 2 \times a \times 240 \\ 900 - 100 &= 480 a \end{aligned}$$

or

$$a = \frac{800}{480} = 1.67 \text{ m/sec}^2. \text{ (Ans.)}$$

or

Time required,

$$t = ?$$

$$v = u + at$$

$$30 = 10 + 1.67 \times t$$

$\therefore$

$$t = \frac{(30 - 10)}{1.67} = 11.97 \text{ sec. (Ans.)}$$

2. A body has an initial velocity of 16 m/sec and an acceleration of 6 m/sec². Determine its speed after it has moved 120 metres distance. Also calculate the distance the body moves during 10th second.

Sol. Initial velocity, $u = 16$ m/sec
 Acceleration, $a = 6$ m/sec²
 Distance, $S = 120$ metres
Speed, $v = ?$

Using the relation,

$$\begin{aligned} v^2 - u^2 &= 2aS \\ v^2 - (16)^2 &= 2 \times 6 \times 120 \\ v^2 &= (16)^2 + 2 \times 6 \times 120 \\ &= 256 + 1440 = 1696 \\ v &= 41.18 \text{ m/sec. (Ans.)} \end{aligned}$$

or

Distance travelled in 10th sec ; $S_{10\text{th}} = ?$

Using the relation,

$$\begin{aligned} S_{n\text{th}} &= u + \frac{a}{2} (2n - 1) \\ S_{10\text{th}} &= 16 + \frac{6}{2} (2 \times 10 - 1) = 16 + 3 (20 - 1) \\ &= 73 \text{ m. (Ans.)} \end{aligned}$$

3. On turning a corner, a motorist rushing at 15 m/sec, finds a child on the road 40 m ahead. He instantly stops the engine and applies brakes, so as to stop the car within 5 m of the child, calculate : (i) retardation, and (ii) time required to stop the car.

Sol. Initial velocity, $u = 15$ m/sec
 Final velocity, $v = 0$
 Distance, $S = 40 - 5 = 35$ m.
(i) Retardation, $a = ?$

Using the relation,

$$\begin{aligned} v^2 - u^2 &= 2aS \\ 0^2 - 15^2 &= 2 \times a \times 35 \end{aligned}$$

$\therefore a = -3.21 \text{ m/sec}^2. \text{ (Ans.)}$

[– ve sign indicates that the acceleration is negative, i.e., retardation]

(ii) Time required to stop the car, $t = ?$

Using the relation,

$$\begin{aligned} v &= u + at \\ 0 &= 15 - 3.21 \times t \end{aligned} \quad (\because a = -3.21 \text{ m/sec}^2)$$

$\therefore t = \frac{15}{3.21} = 4.67 \text{ s. (Ans.)}$

4. A burglar's car had a start with an acceleration 2 m/sec². A police vigilant party came after 5 seconds and continued to chase the burglar's car with a uniform velocity of 20 m/sec. Find the time taken, in which the police will overtake the car.

Sol. Let the police party overtake the burglar's car in t seconds, after the instant of reaching the spot.

Distance travelled by the burglar's car in t seconds, S_1 :

Initial velocity, $u = 0$

Acceleration, $a = 2 \text{ m/sec}^2$

Time, $t = (5 + t) \text{ sec.}$

Using the relation,

$$S = ut + \frac{1}{2} at^2$$

$$\begin{aligned} S_1 &= 0 + \frac{1}{2} \times 2 \times (5 + t)^2 \\ &= (5 + t)^2 \end{aligned} \quad \dots(i)$$

Distance travelled by the police party, S_2 :

Uniform velocity, $v = 20 \text{ m/sec.}$

Let $t = \text{time taken to overtake the burglar's car}$

$\therefore$ Distance travelled by the party,

$$S_2 = v \times t = 20t \quad \dots(ii)$$

For the police party to overtake the burglar's car, the two distances S_1 and S_2 should be equal.

i.e.,

$$\begin{aligned} S_1 &= S_2 \\ (5 + t)^2 &= 20t \\ 25 + t^2 + 10t &= 20t \\ t^2 - 10t + 25 &= 0 \end{aligned}$$

$$\therefore t = \frac{+10 \pm \sqrt{100 - 100}}{2}$$

or

$$t = 5 \text{ sec. (Ans.)}$$

5. A car starts from rest and accelerates uniformly to a speed of 80 km/hour over a distance of 500 metres. Calculate the acceleration and time taken.

If a further acceleration raises the speed to 96 km/hour in 10 seconds, find the acceleration and further distance moved.

The brakes are now applied and the car comes to rest under uniform retardation in 5 seconds. Find the distance travelled during braking.

Sol. Considering the **first period of motion** :

Initial velocity, $u = 0$

Velocity attained, $v = \frac{80 \times 1000}{60 \times 60} = 22.22 \text{ m/sec.}$

Distance covered, $S = 500 \text{ m}$

If a is the acceleration and t is the time taken,

Using the relation :

$$\begin{aligned} v^2 - u^2 &= 2aS \\ (22.22)^2 - 0^2 &= 2 \times a \times 500 \end{aligned}$$

$$\therefore a = \frac{(22.22)^2}{2 \times 500} = 0.494 \text{ m/sec}^2. \text{ (Ans.)}$$

Also,

$$v = u + at$$

$$22.22 = 0 + 0.494 \times t$$

$$\therefore t = \frac{22.22}{0.494} = 45 \text{ sec. (Ans.)}$$

Now considering the **second period of motion**,
Using the relation,

$$v = u + at$$

where

$$v = 96 \text{ km/hour} = \frac{96 \times 1000}{60 \times 60} = 26.66 \text{ m/sec}$$

$$u = 80 \text{ km/hour} = 22.22 \text{ m/sec}$$

$$t = 10 \text{ sec}$$

$$\therefore 26.66 = 22.22 + a \times 10$$

$$\therefore a = \frac{26.66 - 22.22}{10} = 0.444 \text{ m/sec}^2. \text{ (Ans.)}$$

To calculate distance covered, using the relation

$$S = ut + \frac{1}{2} at^2$$

$$= 22.22 \times 10 + \frac{1}{2} \times 0.444 \times 10^2$$

$$= 222.2 + 22.2 = 244.4$$

$$\therefore S = 244.4 \text{ m. (Ans.)}$$

During the period when brakes are applied :

Initial velocity, $u = 96 \text{ km/hour} = 26.66 \text{ m/sec}$

Final velocity, $v = 0$

Time taken, $t = 5 \text{ sec.}$

Using the relation,

$$v = u + at$$

$$0 = 26.66 + a \times 5$$

$$\therefore a = \frac{-26.66}{5} = -5.33 \text{ m/sec}^2.$$

(-ve sign indicates that acceleration is negative *i.e.*, retardation)

Now using the relation,

$$v^2 - u^2 = 2aS$$

$$0^2 - (26.66)^2 = 2 \times -5.33 \times S$$

$$\therefore S = \frac{26.66^2}{2 \times 5.33} = 66.67 \text{ m.}$$

$$\therefore \text{Distance travelled during braking} = 66.67 \text{ m. (Ans.)}$$

6. Two trains A and B moving in opposite directions pass one another. Their lengths are 100 m and 75 m respectively. At the instant when they begin to pass, A is moving at 8.5 m/sec with a constant acceleration of 0.1 m/sec² and B has a uniform speed of 6.5 m/sec. Find the time the trains take to pass.

Sol. Length of train A = 100 m

Length of train B = 75 m

∴ Total distance to be covered

$$= 100 + 75 = 175 \text{ m}$$

Imposing on the two trains A and B, a velocity equal and opposite to that of B.

Velocity of train A = (8.5 + 6.5) = 15.0 m/sec

and velocity of train B = 6.5 – 6.5 = 0.

Hence the train A has to cover the distance of 175 m with an acceleration of 0.1 m/sec² and an initial velocity of 15.0 m/sec.

Using the relation,

$$S = ut + \frac{1}{2} at^2$$

$$175 = 15t + \frac{1}{2} \times 0.1 \times t^2$$

$$3500 = 300t + t^2$$

or $t^2 + 300t - 3500 = 0$

$$t = \frac{-300 \pm \sqrt{90000 + 14000}}{2} = \frac{-300 \pm 322.49}{2}$$

$$= 11.24 \text{ sec.}$$

Hence the trains take 11.24 seconds to pass one another. (Ans.)

7. The distance between two stations is 2.6 km. A locomotive starting from one station, gives the train an acceleration (reaching a speed of 40 km/h in 0.5 minutes) until the speed reaches 48 km/hour. This speed is maintained until brakes are applied and train is brought to rest at the second station under a negative acceleration of 0.9 m/sec². Find the time taken to perform this journey.

Sol. Considering the motion of the locomotive starting from the first station.

Initial velocity $u = 0$

Final velocity $v = 40 \text{ km/hour}$

$$= \frac{40 \times 1000}{60 \times 60} = 11.11 \text{ m/sec.}$$

Time taken, $t = 0.5 \text{ min or } 30 \text{ sec.}$

Let 'a' be the resulting acceleration.

Using the relation,

$$v = u + at$$

$$11.11 = 0 + 30a$$

∴ $a = \frac{11.11}{30} = 0.37 \text{ m/sec}^2.$

Let $t_1 = \text{time taken to attain the speed of } 48 \text{ km/hour}$

$$\left(\frac{48 \times 1000}{60 \times 60} = 13.33 \text{ m/sec.} \right)$$

Again, using the relation,

$$v = u + at$$

$$13.33 = 0 + 0.37t_1$$

$$\therefore t_1 = \frac{13.33}{0.37} = 36 \text{ sec.} \quad \dots(i)$$

and the distance covered in this interval is given by the relation,

$$S_1 = ut_1 + \frac{1}{2}at_1^2$$

$$= 0 + \frac{1}{2} \times 0.37 \times 36^2 = 240 \text{ m.}$$

Now, considering the motion of the *retarding period* before the locomotive comes to rest at the second station (i.e., portion *BC* in Fig. 7.3).

Now,

$$u = 13.33 \text{ m/sec}$$

$$v = 0$$

$$a = -0.9 \text{ m/sec}^2$$

Let

$$t = t_3 \text{ be the time taken}$$

Using the relation,

$$v = u + at$$

$$0 = 13.33 - 0.9t_3$$

$$\therefore t_3 = \frac{13.33}{0.9} = 14.81 \text{ sec} \quad \dots(ii)$$

and distance covered,

$$S_3 = \text{average velocity} \times \text{time}$$

$$= \left(\frac{13.33 + 0}{2} \right) \times 14.81 = 98.7 \text{ m}$$

$\therefore$ Distance covered with constant velocity of 13.33 m/sec,

$$S_2 = \text{total distance between two stations} - (S_1 + S_3)$$

$$= (2.6 \times 1000) - (240 + 98.7) = 2261.3 \text{ m.}$$

$\therefore$ Time taken to cover this distance,

$$t_2 = \frac{2261.3}{13.33} = 169.6 \text{ sec} \quad \dots(iii)$$

Adding (i), (ii) and (iii)

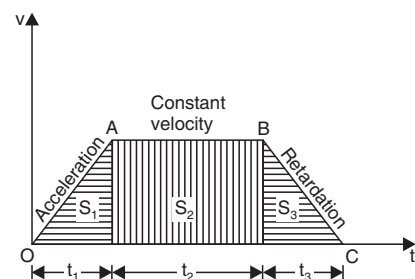
Total time taken,

$$T = t_1 + t_2 + t_3$$

$$= 36 + 169.6 + 14.81$$

$$= 220.41 \text{ sec. (Ans.)}$$

8. Two trains A and B leave the same station on parallel lines. A starts with a uniform acceleration of 0.15 m/sec^2 and attains a speed of 24 km/hour when the steam is required to keep speed constant. B leaves 40 seconds after with uniform acceleration of 0.30 m/sec^2 to attain a maximum speed of 48 km/hour . When will B overtake A ?



Sol. Motion of train A :

Uniform acceleration, $a_1 = 0.15 \text{ m/sec}^2$

Initial velocity, $u_1 = 0$

Final velocity, $v_1 = 24 \text{ km/hour}$

$$= \frac{24 \times 1000}{60 \times 60} = \frac{20}{3} \text{ m/sec.}$$

Let t_1 be the time taken to attain this velocity (in seconds).

Using the relation,

$$v = u + at$$

$$\frac{20}{3} = 0 + 0.15t_1$$

$$\therefore t_1 = \frac{20}{3 \times 0.15} = 44.4 \text{ sec.}$$

Also, distance travelled during this interval,

$$\begin{aligned} S_1 &= ut_1 + \frac{1}{2}at_1^2 \\ &= 0 + \frac{1}{2} \times 0.15 \times 44.4^2 \\ &= 148 \text{ m.} \end{aligned}$$

Motion of train B :

Initial velocity, $u_2 = 0$

Acceleration, $a_2 = 0.3 \text{ m/sec}^2$

Final velocity, $v_2 = 48 \text{ km/hr}$

$$= \frac{48 \times 1000}{60 \times 60} = \frac{40}{3} \text{ m/sec.}$$

Let t_2 be the time taken to travel this distance, say S_2 .

Using the relation,

$$v = u + at$$

$$\frac{40}{3} = 0 + 0.3t_2$$

$$\therefore t_2 = \frac{40}{3 \times 0.3} = 44.4 \text{ sec}$$

and

$$\begin{aligned} S_2 &= u_2t_2 + \frac{1}{2}a_2t_2^2 \\ &= 0 + \frac{1}{2} \times 0.3 \times (44.4)^2 \\ &= 296 \text{ m.} \end{aligned}$$

Let the train B overtake the train A when they have covered a distance S from the start. And let the train B take t seconds to cover the distance.

Thus, time taken by the train $A = (t + 40) \text{ sec.}$

Total distance moved by train A,

$$S = 148 + \text{distance covered with constant speed}$$

$$\begin{aligned} S &= 148 + [(t + 40) - t_1] \frac{20}{3} \\ &= 148 + [t + 40 - 44.4] \times \frac{20}{3} \\ &= 148 + (t - 4.4) \times \frac{20}{3} \end{aligned} \quad \dots(i)$$

$[(t + 40) - t_1]$ is the time during which train A moves with constant speed]

Similarly, total distance travelled by the train B,

$$\begin{aligned} S &= 296 + \text{distance covered with constant speed} \\ &= 296 + (t - 44.4) \times \frac{40}{3} \end{aligned} \quad \dots(ii)$$

Equating (i) and (ii),

$$\begin{aligned} 148 + (t - 4.4) \frac{20}{3} &= 296 + (t - 44.4) \times \frac{40}{3} \\ 148 + \frac{20}{3} t - \frac{88}{3} &= 296 + \frac{40}{3} t - \frac{1776}{3} \\ \left(\frac{40}{3} - \frac{20}{3} \right) t &= 148 - 296 + \frac{1776}{3} - \frac{88}{3} \end{aligned}$$

or

$$t = 62.26 \text{ sec.}$$

Hence, the train B overtakes the train A after 62.26 sec. of its start. (Ans.)

9. Two stations A and B are 10 km apart in a straight track, and a train starts from A and comes to rest at B. For three quarters of the distance, the train is uniformly accelerated and for the remainder uniformly retarded. If it takes 15 minutes over the whole journey, find its acceleration, its retardation and the maximum speed it attains.

Sol. Refer to Fig. 7.4.

Distance between A and B,

$$S = 10 \text{ km} = 10,000 \text{ m}$$

Considering the motion in the first part :

Let

$$u_1 = \text{initial velocity} = 0$$

$$a_1 = \text{acceleration}$$

$$t_1 = \text{time taken}$$

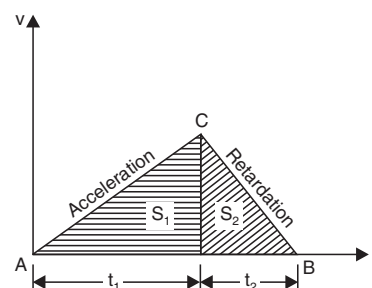
$$S_1 = \text{distance travelled.}$$

Using the relation,

$$S = ut + \frac{1}{2} at^2$$

$$S_1 = 0 + \frac{1}{2} a_1 t_1^2 = \frac{1}{2} a_1 t_1^2 \quad \dots(i)$$

$$7500 = \frac{1}{2} a_1 t_1^2 \quad \dots(ii)$$



$$[\because S_1 = 3/4 \times 10,000 = 7500 \text{ m}]$$

Also, for the second retarding part

$$\begin{aligned} u_2 &= \text{initial velocity} \\ &= \text{final velocity at the end of first interval} \\ &= 0 + a_1 t_1 = a_1 t_1 \end{aligned}$$

Hence $v_2 = \text{final velocity at the end of second part}$

$$\begin{aligned} &= u_2 - a_2 t_2 \\ &= a_1 t_1 - a_2 t_2 \\ &= 0, \text{ because the train comes to rest} \end{aligned}$$

$\therefore a_1 t_1 = a_2 t_2$

or $\frac{a_1}{a_2} = \frac{t_2}{t_1} \quad \dots(iii)$

Also, $S_2 = \text{distance travelled in the second part}$

$$\begin{aligned} &= \text{average velocity} \times \text{time} \\ &= \left(\frac{a_1 t_1 + 0}{2} \right) \times t_2 \\ &= \frac{a_1 t_1}{2} \cdot t_2 \quad \dots(iv) \end{aligned}$$

Adding (i) and (iv),

$$\begin{aligned} S_1 + S_2 &= \frac{a_1 t_1^2}{2} + \frac{a_1 t_1}{2} \cdot t_2 \\ &= \frac{a_1 t_1}{2} (t_1 + t_2) \end{aligned}$$

or $S_1 + S_2 = \frac{a_1 t_1}{2} \times 900 \quad (\because t_1 + t_2 = 15 \text{ min.} = 900 \text{ sec})$

$$10,000 = \frac{a_1 t_1}{2} \times 900 \quad (\because S_1 + S_2 = 10 \text{ km} = 10,000 \text{ m})$$

or $a_1 t_1 = \frac{20,000}{900} = \frac{200}{9}$

But $a_1 t_1 = \text{maximum velocity}$

Hence **max. velocity** $= \frac{200}{9} = 22.22 \text{ m/sec (Ans.)}$

Also, from eqn. (ii)

$$7500 = \frac{1}{2} \times 22.22 \times t_1$$

or $t_1 = \frac{7500}{11.11} = 675 \text{ sec}$

$\therefore t_2 = 900 - 675 = 225 \text{ sec}$

Now from eqn. (iii),

$$\frac{a_1}{a_2} = \frac{t_2}{t_1} = \frac{225}{675} = \frac{1}{3}$$

$\therefore 3a_1 = a_2$

Also, $v_{\max} = 22.22 = a_1 t_1$

$\therefore a_1 = \frac{22.22}{675} = 0.0329 \text{ m/sec}^2. \text{ (Ans.)}$

and $a_2 = 3a_1$
 $= 3 \times 0.0329$
 $= 0.0987 \text{ m/sec}^2. \text{ (Ans.)}$

MOTION UNDER GRAVITY

It has been seen that bodies falling to earth (through distances which are small as compared to the radius of the earth) and entirely unrestricted, increase in their velocity by about 9.81 m/sec for every second during their fall. This acceleration is called the acceleration due to gravity and is conventionally denoted by 'g'. Though the value of this acceleration varies a little at different parts of the earth's surface but the generally adopted value is 9.81 m/sec².

For downward motion

$$\begin{array}{l} a = +g \\ v = u + gt \\ h = ut + \frac{1}{2}gt^2 \\ \downarrow \\ v^2 - u^2 = 2gh \end{array}$$

For upward motion

$$\begin{array}{l} a = -g \\ v = u - gt \\ h = ut - \frac{1}{2}gt^2 \\ \uparrow \\ v^2 - u^2 = -2gh \end{array}$$

SOME HINTS ON THE USE OF EQUATIONS OF MOTION

- (i) If a body starts from rest, its initial velocity, $u = 0$
- (ii) If a body comes to rest ; its final velocity, $v = 0$
- (iii) When a body is thrown upwards with a velocity u , time taken to reach the maximum height $= \frac{u}{g}$ and velocity on reaching the maximum height is zero (i.e., $v = 0$) . This value of t is obtained by equating $v = u - gt$ equal to zero.

- (iv) Greatest height attained by a body projected upwards with a velocity $u = \frac{u^2}{2g}$, which is obtained by substituting $v = 0$ in the equation $v^2 - u^2 = -2gh$.

- (v) Total time taken to reach the ground $= \frac{2u}{g}$, the velocity on reaching the ground being $\sqrt{2gh}$.

$$(\because v^2 - u^2 = 2gh \text{ or } v^2 - 0^2 = 2gh \text{ or } v = \sqrt{2gh})$$

- (vi) The velocity with which a body reaches the ground is same with which it is thrown upwards.

10. A stone is dropped from the top of tower 100 m high. Another stone is projected upward at the same time from the foot of the tower, and meets the first stone at a height of 40 m. Find the velocity, with which the second stone is projected upwards.

Sol. Motion of the first particle :

Height of tower $= 100 \text{ m}$
 Initial velocity, $u = 0$
 Height, $h = 100 - 40 = 60 \text{ m}.$

Let t be the time (in seconds) when the two particles meet after the first stone is dropped from the top of the tower.

Refer to Fig. 7.5.

Using the relation,

$$h = ut + \frac{1}{2}gt^2$$

$$60 = 0 + \frac{1}{2} \times 9.81 t^2$$

$$\therefore t = \sqrt{\frac{120}{9.81}} = 3.5 \text{ sec.}$$

Motion of the second particle :

Height, $h = 40 \text{ m}$

Time, $t = 3.5 \text{ sec.}$

Let u be the initial velocity with which the second particle has been projected upwards.

Using the relation,

$$h = ut - \frac{1}{2}gt^2 \quad (\because \text{Particle is projected upwards})$$

$$40 = u \times 3.5 - \frac{1}{2} \times 9.81 \times 3.5^2$$

$$3.5u = 40 + \frac{1}{2} \times 9.81 \times 3.5^2$$

$$u = 28.6 \text{ m/sec. (Ans.)}$$

11. A body projected vertically upwards attains a maximum height of 450 m. Calculate the velocity of projection and compute the time of flight in air. At what altitude will this body meet a second body projected 5 seconds later with a speed of 140 m/sec ?

Sol. Maximum height attained by the body

$$= 450 \text{ m}$$

Let

u = initial velocity of the body

v = final velocity of the body = 0

Using the relation,

$$v^2 - u^2 = -2gh \quad (\because \text{body is thrown upwards})$$

$$0^2 - u^2 = -2 \times 9.81 \times 450$$

$$u = 94 \text{ m/sec. (Ans.)}$$

Let ' t ' be the time taken by the body in reaching the highest point from the point of projection.

Then, using the relation,

$$v = u - gt$$

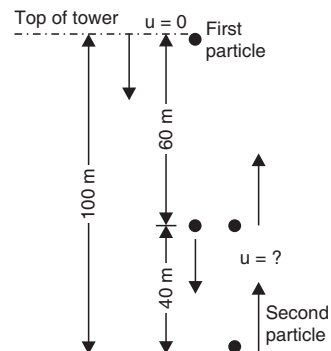
$$0 = 94 - 9.81t$$

$$\therefore t = \frac{94}{9.81} = 9.6 \text{ sec.}$$

$\therefore$ Total time of flight in air

$$= 2 \times 9.6 = 19.2 \text{ sec. (Ans.)}$$

($\because$ The body will take the same time in returning also)



Let the second body meet the first body at a height 'h' from the ground. Let 't' be the time taken by the first body.

Then, time taken by the second body
 $= (t - 4)$ sec.

Considering the motion of first body

$$\begin{aligned} h &= ut - \frac{1}{2} gt^2 \\ &= 94t - \frac{1}{2} \times 9.81t^2 \end{aligned} \quad \dots(i)$$

Considering the motion of the second body

$$h = 140(t - 5) - \frac{1}{2} \times 9.81(t - 5)^2 \quad \dots(ii)$$

Equating (i) and (ii), we get

$$\begin{aligned} 94t - \frac{1}{2} \times 9.81t^2 &= 140(t - 5) - \frac{1}{2} \times 9.81(t - 5)^2 \\ 188t - 9.81t^2 &= 280(t - 5) - 9.81(t - 5)^2 \\ 188t - 9.81t^2 &= 280t - 1400 - 9.81(t - 5)^2 \\ 188t - 9.81t^2 &= 280t - 1400 - 9.81t^2 + 98.1t - 245.25 \end{aligned}$$

From which $t = 8.65$ sec.

Putting this in eqn. (i), we get

$$\begin{aligned} h &= 94 \times 8.65 - \frac{1}{2} \times 9.81 \times 8.65^2 \\ &= 813.3 - 367 = 446.3 \text{ m.} \end{aligned}$$

Hence, the second body will meet the first one at a height of 446.3 m from the ground. (Ans.)

12. Two stones are thrown vertically upwards one from the ground with a velocity of 30 m/sec and another from a point 40 metres above with a velocity of 10 m/sec. When and where will they meet?

Sol. Refer to Fig.

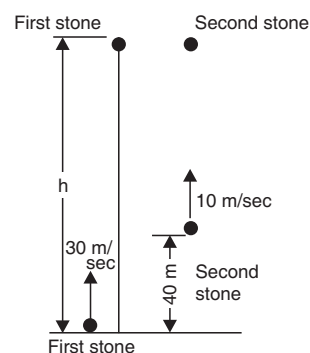
Let the two stones meet after 't' seconds from their start at a height of 5 metres from the ground.

Motion of first stone :

u = initial velocity = 30 m/sec
 h = vertical distance travelled
 t = time taken

Using the relation,

$$\begin{aligned} h &= ut - \frac{1}{2} gt^2 \\ (\because \text{stone is thrown upwards}) \\ h &= 30t - \frac{1}{2} \times 9.81t^2 \end{aligned} \quad \dots(i)$$



Motion of second stone :

Vertical distance travelled

$$h' = h - 40$$

$$u = 10 \text{ m/sec.}$$

Again using the relation,

$$h = ut + \frac{1}{2}gt^2$$

$$(h - 40) = 10t - \frac{1}{2} \times 9.8t^2 \quad \dots(ii)$$

Subtracting (ii) from (i),

$$40 = 20t$$

$$t = 2 \text{ sec. (Ans.)}$$

Substituting this value in eqn. (i), we get

$$h = 30 \times 2 - \frac{1}{2} \times 9.81 \times 2^2 = 40.38 \text{ m. (Ans.)}$$

Hence, the two stones meet after 2 seconds at 40.38 m from the ground.

13. A stone is thrown from the ground vertically upwards, with a velocity of 40 m/sec. After 3 seconds another stone is thrown in the same direction and from the same place. If both of the stones strike the ground at the same time, compute the velocity with which the second stone was thrown.

Sol. Motion of first stone :

$$u = \text{velocity of projection} = 40 \text{ m/sec}$$

$$v = \text{velocity at the maximum height} = 0$$

$$t = \text{time taken to reach the maximum height} = ?$$

Using the relation,

$$v = u - gt \quad (\because \text{stone is moving upward})$$

$$0 = 40 - 9.81t$$

or

$$t = \frac{40}{9.81} = 4 \text{ sec.}$$

Therefore, total time taken by the first stone to return to the earth = 4 + 4 = 8 sec (because the time taken to reach the maximum height is same as that to come down to earth).

Therefore, the time taken by the second stone to return to the earth = 8 - 3 = 5 sec.

or time taken to reach the maximum height = 5/2 = 2.5 sec.

Motion of second stone :

$$u = \text{velocity of projection} = ?$$

$$v = \text{final velocity at max. height} = 0$$

$$t = \text{time taken to reach the max. height}$$

Using the relation,

$$v = u - gt$$

$$0 = u - 9.81 \times 2.5$$

 $\therefore$

$$u = 9.81 \times 2.5 = 24.5 \text{ m/sec.}$$

Hence, the velocity of projection of second stone
= 24.5 m/sec. (Ans.)

14. A body, falling freely under the action of gravity passes two points 15 metres apart vertically in 0.3 seconds. From what height, above the higher point, did it start to fall.

Sol. Refer to Fig. 7.7.

Let the body start from O and pass two points A and B , 15 metres apart in 0.3 second after traversing the distance OA .

Let $OA = h$

Considering the motion from O to A ,

Initial velocity, $u = 0$

Using the relation,

$$h = ut + \frac{1}{2}gt^2 \quad (\because \text{the body is falling downward})$$

$$h = 0 + \frac{1}{2}gt^2 \quad \dots(i)$$

Considering the motion from O to B .

Initial velocity, $u = 0$

Time taken, $t = (t + 0.3)$ sec.

$$\text{Again, using the relation, } h + 15 = 0 + \frac{1}{2}g(t + 0.3)^2 \quad \dots(ii)$$

Subtracting, (i) from (ii),

$$15 = \frac{1}{2}g(t + 0.3)^2 - \frac{1}{2}gt^2$$

$$30 = g(t^2 + 0.6t + 0.09) - gt^2$$

$$30 = gt^2 + 0.6gt + 0.09g - gt^2$$

$$\therefore 0.6gt = 30 - 0.09g$$

$$t = \frac{30}{0.6g} - \frac{0.09g}{0.6g} = 5.1 - 0.15 = 4.95 \text{ sec.} \quad \dots(iii)$$

Substituting the value of t in eqn. (i), we get

$$h = \frac{1}{2} \times 9.81 \times (4.95)^2 = 120.2 \text{ m. (Ans.)}$$

15. A stone dropped into a well is heard to strike the water after 4 seconds. Find the depth of the well, if the velocity of sound is 350 m/sec.

Sol. Initial velocity of stone, $u = 0$

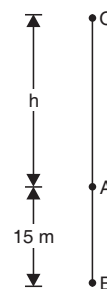
Let t = time taken by stone to reach the bottom of the well,

and h = depth of the well

Using the relation,

$$h = ut + \frac{1}{2}gt^2$$

$$h = 0 + \frac{1}{2} \times 9.8t^2 = 4.9t^2 \quad \dots(i)$$



Also, the time taken by the sound to reach the top

$$\begin{aligned}
 &= \frac{\text{Depth of the well}}{\text{Velocity of sound}} \\
 &= \frac{h}{350} = \frac{4.9t^2}{350} \quad \dots(ii)
 \end{aligned}$$

Total time taken = time taken by the stone to reach the bottom of the well
+ time taken by sound to reach the ground
= 4 seconds (given)

$$\therefore t + \frac{4.9t^2}{350} = 4$$

or $4.9t^2 + 350t - 1400 = 0$

or
$$t = \frac{-350 \pm \sqrt{(350)^2 + 4 \times 4.9 \times 1400}}{2 \times 4.9}$$

$$= \frac{-350 + 387.2}{9.8} = 3.8 \text{ sec}$$

$$\therefore t = 3.8 \text{ sec.}$$

Substituting the value in eqn. (i), we get

$$h = 4.9 \times (3.8)^2 = 70.8 \text{ m}$$

Hence, the depth of well = 70.8 m. (Ans.)

VARIABLE ACCELERATION

16. The equation of motion of a particle is $S = -6 - 5t^2 + t^3$

where S is in metres and t in seconds.

Calculate : (i) The displacement and the acceleration when the velocity is zero.

(ii) The displacement and the velocity when the acceleration is zero.

Sol. The equation of motion is

$$S = -6 - 5t^2 + t^3 \quad \dots(\text{given}) \quad \dots(i)$$

Differentiating both sides,

$$\frac{ds}{dt} \quad \text{or} \quad v = -10t + 3t^2$$

$$\therefore v = -10t + 3t^2 \quad \dots(ii)$$

Again, differentiating both sides,

$$\frac{dv}{dt} \quad \text{or} \quad a = -10 + 6t$$

$$\therefore a = -10 + 6t \quad \dots(iii)$$

Now, (i) **When the velocity is zero,**

$$v = -10t + 3t^2 = 0$$

$$\therefore t(3t - 10) = 0$$

$$t = \frac{10}{3} = 3.33 \text{ sec.} \quad (\text{ignoring } t = 0 \text{ which means start})$$

Substituting this value in eqns. (i) and (iii),

$$\begin{aligned} S &= \text{displacement} \\ &= -6 - 5 \times 3.33^2 + 3.33^3 \\ &= -6 - 55.44 + 36.92 \\ &= -24.52 \text{ m. (Ans.)} \end{aligned}$$

The negative sign indicates that distance is travelled in the other direction.

Also,

$$\begin{aligned} a &= \text{acceleration} \\ &= -10 + 6 \times \frac{10}{3} = 10 \text{ m/sec}^2. \text{ (Ans.)} \end{aligned}$$

(ii) When the acceleration is zero

$$a = -10 + 6t = 0$$

$\therefore$

$$6t = 10$$

or

$$t = \frac{10}{6} = \frac{5}{3} = 1.67 \text{ sec.}$$

Substituting this value in eqns. (i) and (ii), we get

$$\begin{aligned} S &= \text{displacement} \\ &= -6 - 5t^2 + t^3 = -6 - 5 \times (1.67)^2 + (1.67)^3 \\ &= -6 - 13.94 + 4.66 = -15.28 \text{ m. (Ans.)} \end{aligned}$$

The -ve sign again means that the distance is travelled in the other direction.

Also,

$$\begin{aligned} v &= -10t + 3t^2 \\ &= -10 \times 1.67 + 3 \times (1.67)^2 = -16.7 + 8.36 \\ &= -8.34 \text{ m/sec. (Ans.)} \end{aligned}$$

17. If a body be moving in a straight line and its distance S in metres from a given point in the line after t seconds is given by the equation

$$S = 20t + 3t^2 - 2t^3.$$

Calculate : (a) The velocity and acceleration at the start.

(b) The time when the particle reaches its maximum velocity.

(c) The maximum velocity of the body.

Sol. The equation of motion is

$$S = 20t + 3t^2 - 2t^3 \quad \dots(i)$$

Differentiating both sides

$$\frac{dS}{dt} = v = 20 + 6t - 6t^2 \quad \dots(ii)$$

Again, differentiating

$$\frac{d^2S}{dt^2} = \frac{dv}{dt} = a = 6 - 12t \quad \dots(iii)$$

(a) At start, $t = 0$

Hence from eqns. (ii) and (iii),

$$v = 20 + 0 - 0 = 20 \text{ m/sec. (Ans.)}$$

$$a = 6 - 12 \times 0 = 6 \text{ m/sec. (Ans.)}$$

(b) When the particle reaches its maximum velocity

$$a = 0$$

i.e.,

$$6 - 12t = 0$$

$$\therefore t = 0.5 \text{ sec. (Ans.)}$$

(b) The maximum velocity of the body

When

$$t = 0.5 \text{ sec.}$$

$$\begin{aligned} v_{\max} &= 20 + 6t - t^2 \\ &= 20 + 6 \times 0.5 - 6 \times 0.5^2 \\ &= 20 + 3 - 1.5 \\ &= 21.5 \text{ m/sec. (Ans.)} \end{aligned}$$

SELECTED QUESTIONS EXAMINATION PAPERS

18. Two trains A and B leave the same station on parallel lines. A starts with uniform acceleration of 0.15 m/s^2 and attains a speed of 24 km/hour when the steam is reduced to keep the speed constant. B leaves 40 seconds after with a uniform acceleration of 0.30 m/s^2 to attain a maximum speed of 48 km/hour . When will B overtake A ?

Sol. Motion of train A:

Uniform acceleration, $a_1 = 0.15 \text{ m/s}^2$

Initial velocity, $u_1 = 0$

Final velocity, $v_1 = 24 \text{ km/h}$

$$= \frac{24 \times 1000}{60 \times 60} = \frac{20}{3} \text{ m/sec}$$

Let t_1 be the time taken to attain this velocity (in seconds)

Using the relation:

$$v = u + at$$

$$\frac{20}{3} = 0 + 0.15 \times t_1$$

$$\therefore t_1 = \frac{20}{3 \times 0.15} = 44.4 \text{ sec}$$

Also, distance travelled during this interval,

$$\begin{aligned} s_1 &= u_1 t_1 + \frac{1}{2} a_1 t_1^2 \\ &= 0 + \frac{1}{2} \times 0.15 \times 44.4^2 = 148 \text{ m} \end{aligned}$$

Motion of train B:

Initial velocity, $u_2 = 0$

Acceleration, $a_2 = 0.3 \text{ m/sec}^2$

Final velocity, $v_2 = 48 \text{ km/h}$

$$= \frac{48 \times 1000}{60 \times 60} = \frac{40}{3} \text{ m/sec}$$

Let t_2 be taken to travel this distance, say s_2

Using the relation:

$$v = u + at$$

$$\frac{40}{3} = 0 + 0.3 \times t_2$$

$$\therefore t_2 = \frac{40}{3 \times 0.3} = 44.4 \text{ s}$$

and

$$\begin{aligned} s_2 &= u_2 t_2 + \frac{1}{2} a_2 t_2^2 \\ &= 0 + \frac{1}{2} \times 0.3 \times (44.4)^2 = 296 \text{ m} \end{aligned}$$

Let the train B overtake the train A when they have covered a distance s from the start. And let the train B take t seconds to cover the distance.

Thus, time taken by the train $A = (t + 40)$ sec.

Total distance moved by train A .

$$\begin{aligned} s &= 148 + \text{distance covered with constant speed} \\ &= 148 + [(t + 40) - t_1] \times 20/3 \\ &= 148 + [t + 40 - 44.4] \times 20/3 \\ &= 148 + (t - 4.4) \times 20/3 \end{aligned} \quad \dots(i)$$

$[(t + 40) - t_2]$ is the time during which train A moves with constant speed].

Similarly, total distance travelled by the train B ,

$$\begin{aligned} s &= 296 + \text{distance covered with constant speed} \\ &= 296 + (t - 44.4) \times 40/3 \end{aligned} \quad \dots(ii)$$

Equating (i) and (ii)

$$148 + (t - 4.4) \times 20/3 = 296 + (t - 44.4) \times 40/3$$

$$148 + \frac{20}{3}t - \frac{88}{3} = 296 + \frac{40}{3}t - \frac{1776}{3}$$

$$\left(\frac{40}{3} - \frac{20}{3}\right)t = 148 - 296 + \frac{1776}{3} - \frac{88}{3}$$

$$t = 62.26 \text{ s}$$

Hence, train B , overtakes train A after 62.26 s of its start. **(Ans.)**

19. A cage descends a mine shaft with an acceleration of 1 m/s^2 . After the cage has travelled 30 m, stone is dropped from the top of the shaft. Determine: (i) the time taken by the stone to hit the cage, and (ii) distance travelled by the cage before impact.

Sol. Acceleration of cage,

$$a = 1 \text{ m/s}^2$$

Distance travelled by the shaft before dropping of the stone = 30 m

(i) Time taken by the stone to hit the cage = ?

Considering motion of the stone.

Initial velocity, $u = 0$

Let t = time taken by the stone to hit the cage, and

h_1 = vertical distance travelled by the stone before the impact.

Using the relation,

$$h = ut + \frac{1}{2}gt^2$$

$$h_1 = 0 + \frac{1}{2} \times 9.8 t^2 = 4.9 t^2 \quad \dots(i)$$

Now let us consider motion of the cage for 30 m

Initial velocity, $u = 0$

Acceleration, $a = 1.0 \text{ m/s}^2$.

Let $t' =$ time taken by the shaft to travel 30 m

Using the relation,

$$s = ut + \frac{1}{2} at^2$$

$$30 = 0 + \frac{1}{2} \times 1 \times (t')^2$$

$$t' = 7.75 \text{ s.}$$

It means that cage has travelled for 7.75 s before the stone was dropped. Therefore total time taken by the cage before impact = $(7.75 + t)$.

Again using the relation:

$$s = ut + \frac{1}{2} at^2$$

$$s_1 = 0 + \frac{1}{2} \times 1 \times (7.75 + t)^2 \quad \dots(ii)$$

In order that stone may hit the cage the two distances must be equal *i.e.*, equating (i) and (ii).

$$4.9 t^2 = \frac{1}{2} \times (7.75 + t)^2$$

$$4.9 = 0.5 (60 + t^2 + 15.5 t)$$

$$9.8 = t^2 + 15.5 t + 60$$

or
or

$$t^2 + 15.5 t - 50.2 = 0$$

$$t = \frac{-15.5 \pm \sqrt{(15.5)^2 + 4 \times 50.2}}{2} = \frac{-15.5 \pm \sqrt{441.05}}{2}$$

$$= \frac{-15.5 \pm 21.0}{2} = 2.75 \text{ s} \quad (\text{neglecting -ve sign})$$

$$\therefore \quad t = 2.75 \text{ s. (Ans.)}$$

(ii) Distance travelled by the cage before impact = ?

Let $s_2 =$ distance travelled by the cage before impact.

We know total time taken by the cage before impact.

$$= 7.75 + 2.75 = 10.5 \text{ s.}$$

Now using the relation,

$$s_2 = ut + \frac{1}{2} at^2$$

$$= 0 + \frac{1}{2} \times 1 \times (10.5)^2 = 55.12 \text{ m}$$

Hence distance travelled by the cage before impact = **55.12 m. (Ans.)**

8.9. D' ALEMBERT'S PRINCIPLE

D' Alembert, a French mathematician, was the first to point out that on the lines of *equation of static equilibrium*, *equation of dynamic equilibrium* can also be established by introducing *inertia force* in the direction opposite the acceleration in addition to the real forces on the plane.

Static equilibrium equations are :

$$\Sigma H \text{ (or } P_x) = 0, \Sigma V \text{ (or } \Sigma P_y) = 0, \Sigma M = 0$$

Similarly when different external forces act on a system in motion, the algebraic sum of all the forces (including the *inertia force*) is zero. This is explained as under :

We know that, $P = ma$ (Newton's second law of motion)

or $P - ma = 0$ or $P + (-ma) = 0$

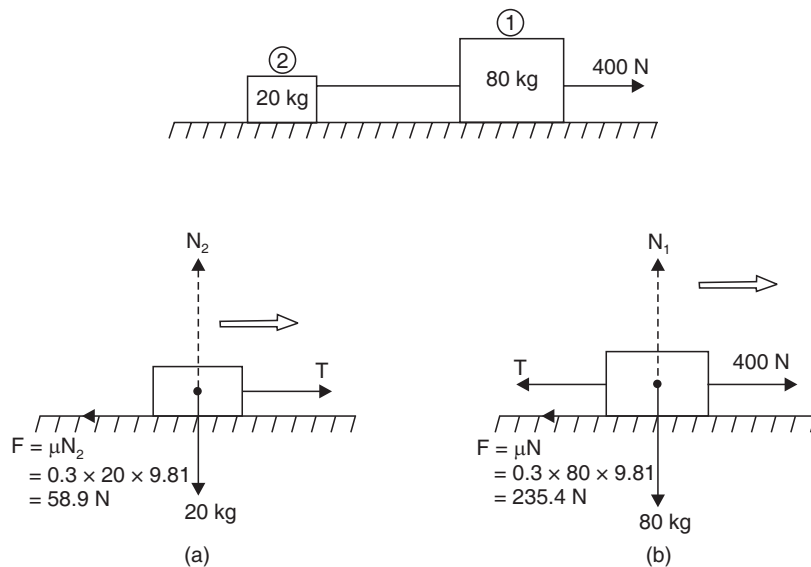
The expression in the block $(-ma)$ is the *inertia force* and negative sign signifies that it acts in a direction opposite to that of acceleration/retardation a .

It is also known as the “*principle of kinostatics*”.

Example 8.15. Two bodies of masses 80 kg and 20 kg are connected by a thread and move along a rough horizontal surface under the action of a force 400 N applied to the first body of mass 80 kg as shown in Fig. 8.6. The co-efficient of friction between the sliding surfaces of the bodies and the plane is 0.3.

Determine the acceleration of the two bodies and the tension in the thread, using D' Alembert's principle.

Sol. Refer to Figs. 8.5 and 8.6



Acceleration of the bodies, a :

As per D' Alembert's principle for dynamic equilibrium condition the algebraic sum of all the active forces acting on a system should be zero.

The various forces acting on the bodies are :

- (i) Force applied = 400 N
- (ii) Inertia force = $(80 + 20) a$
- (iii) Frictional force = $0.3 \times 80 \times 9.81 + 0.3 \times 20 \times 9.81$
 $= 235.4 + 58.9 = 294.3 \text{ N}$

$$\therefore 400 - (80 + 20) a = 294.3 = 0$$

or
$$a = \frac{400 - 294.3}{(80 + 20)} = 1.057 \text{ m/s}^2. \text{ (Ans.)}$$

Tension in the thread between the two masses, T :

Considering free body diagrams of the masses 80 kg and 20 kg separately as shown in Fig. (a) and (b).

Applying D' Alembert's principle for Fig. 8.6 (a), we get

$$400 - T - 80 \times 1.057 - 0.3 \times 80 \times 9.81 = 0$$

$$\therefore \quad \quad \quad \mathbf{T = 80 \text{ N. (Ans.)}$$

Now, applying D' Alembert's principle for Fig. 8.6 (b), we get

$$T - 0.3 \times 20 \times 9.81 - 20 \times 1.057 = 0$$

$$\therefore \quad \quad \quad \mathbf{T = 80 \text{ N. (Ans.)}$$

It may be noted that the same answer is obtained by considering the two masses separately.

MOTION OF A LIFT

Consider a lift (elevator or cage etc.) carrying some mass and moving with a uniform acceleration.

Let

m = mass carried by the lift in kg,

$W (= m.g)$ = weight carried by the lift in newtons,

a = uniform acceleration of the lift, and

T = tension in the cable supporting the lift.

There could be the following *two* cases :

- (i) When the lift is moving *upwards*, and
- (ii) When the lift is moving *downwards*.

1. Lift moving upwards :

Refer to Fig. 8.7.

The net upward force, which is responsible for the motion of the lift

$$= T - W = T - m.g \quad \dots(i)$$

Also, this force = mass $\times$ acceleration

$$= m.a \quad \dots(ii)$$

Equating (i) and (ii), we get

$$T - m.g = m.a$$

$$\therefore \quad T = m.a + m.g = m(a + g) \quad \dots(8.4)$$

2. Lift moving downwards :

Refer to Fig. 8.8.

Net downward force responsible for the motion of the lift

$$= W - T = m.g - T \quad \dots(i)$$

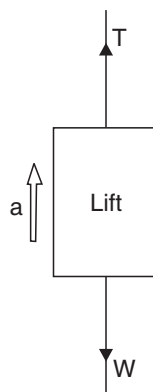


Fig. 8.7. Lift moving upwards.

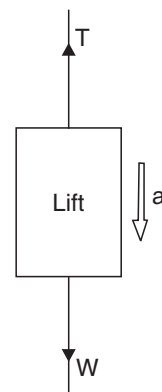


Fig. 8.8. Lift moving downwards.

$$\begin{aligned}\text{Also, this force} &= \text{mass} \times \text{acceleration} \\ &= m.a\end{aligned}\quad \dots(ii)$$

Equating (i) and (ii), we get

$$m.g - T = m.a$$

$$\therefore T = m.g - m.a = m(g - a)$$

16. An elevator cage of mass 900 kg when empty is lifted or lowered vertically by means of a wire rope. A man of mass 72.5 kg is standing in it. Find :

- (a) The tension in the rope,
- (b) The reaction of the cage on the man, and
- (c) The force exerted by the man on the cage, for the following two conditions :
 - (i) when the cage is moving up with an acceleration of 3 m/s^2 and
 - (ii) when the cage is moving down with a uniform velocity of 3 m/s .

Sol. Mass of the cage, $M = 900 \text{ kg}$

Mass of the man, $m = 72.5 \text{ kg}$.

(i) **Upward acceleration, $a = 3 \text{ m/s}^2$**

(a) Let T be the tension in the rope in newtons

The various forces acting on the cage are :

1. Tension, T of the rope acting vertically upwards.
2. Total mass $= M + m$, of the cage and the man acting vertically downwards.

As the cage moves upwards, $T > (M + m)g$

$$\therefore \text{Net accelerating force} = T - (M + m)g = (M + m)a$$

$$\therefore T - (M + m)g = (M + m)a \quad \dots(i)$$

Substituting the given values, we get

$$T - (900 + 72.5)9.81 = (900 + 72.5) \times 3$$

$$\therefore T = 12458 \text{ N. (Ans.)}$$

(b) Let ' R ' be the reaction of the cage on the man in newtons.

Considering the various forces, the equation of motion is

$$R - mg = m.a \quad \dots(ii)$$

or

$$\begin{aligned}R &= mg + ma = m(g + a) \\ &= 72.5(9.81 + 3) = 928.7 \text{ N. (Ans.)}\end{aligned}$$

(c) The force exerted by the man on the cage must be equal to the force exerted by the cage on the man (Newton's third law of motion).

$$\therefore \text{Force exerted by the man on the cage} = 928.7 \text{ N. (Ans.)}$$

(ii) **When the cage moves with a uniform velocity 3 m/s :**

When the cage moves with a uniform velocity, acceleration is equal to zero.

(a) Tension in the rope, T :

Putting $a = 0$ in eqn. (i), we get

$$T - (M + m)g = (M + m) \times 0 = 0$$

$$\begin{aligned}\therefore T &= (M + m)g \\ &= (900 + 72.5) \times 9.81 = 9540 \text{ N. (Ans.)}\end{aligned}$$

(b) Also from equation (ii)

When $a = 0$,

$$\begin{aligned} R &= mg + m \times 0 = mg \\ &= 72.5 \times 9.81 = \mathbf{711.2 \text{ N. (Ans.)}} \end{aligned}$$

(c) Force exerted by the man on the cage

$$\begin{aligned} &= \text{force exerted by the cage on the man} \\ &= \mathbf{711.2 \text{ N. (Ans.)}} \end{aligned}$$

17. An elevator of mass 500 kg is ascending with an acceleration of 3 m/s². During this ascent its operator whose mass is 70 kg is standing on the scales placed on the floor. What is the scale reading? What will be total tension in the cables of the elevator during his motion?

Sol. Mass of the elevator, $M = 500 \text{ kg}$

Acceleration, $a = 3 \text{ m/s}^2$

Mass of the operator, $m = 70 \text{ kg}$

Pressure (R) exerted by the man, when the lift moves upward with an acceleration of 3 m/s²,

$$\begin{aligned} R &= mg + ma = m(g + a) \\ &= 70(9.81 + 3) = \mathbf{896.7 \text{ N. (Ans.)}} \end{aligned}$$

Now, tension in the cable of elevator

$$\begin{aligned} T &= M(g + a) + m(g + a) \\ &= (M + m)(g + a) \\ &= (500 + 70)(9.81 + 3) = \mathbf{7301.7 \text{ N. (Ans.)}} \end{aligned}$$

MOTION OF TWO BODIES CONNECTED BY A STRING PASSING OVER A SMOOTH PULLEY

Fig. 8.9 shows two bodies of weights W_1 and W_2 respectively hanging vertically from a weightless and inextensible string, passing over a smooth pulley. Let T be the common tension in the string. If the pulley were not smooth, the tension would have been different in the two sides of the string.

Let W_1 be greater than W_2 and a be the acceleration of the bodies and their motion as shown.

Consider the motion of body 1:

Forces acting on it are : W_1 (downwards) and T (upwards).

$$\therefore \text{Resulting force} = W_1 - T \text{ (downwards)} \quad \dots(i)$$

Since this weight is moving downward, therefore, force acting on this weight

$$= \frac{W_1}{g} \cdot a \quad \dots(ii)$$

Equating (i) and (ii)

$$W_1 - T = \frac{W_1}{g} a \quad \dots(1)$$

Now consider the motion of body 2:

Forces acting on it are : T (upwards) W_2 (downwards)

$$\therefore \text{Resultant force} = T - W_2 \quad \dots(iii)$$

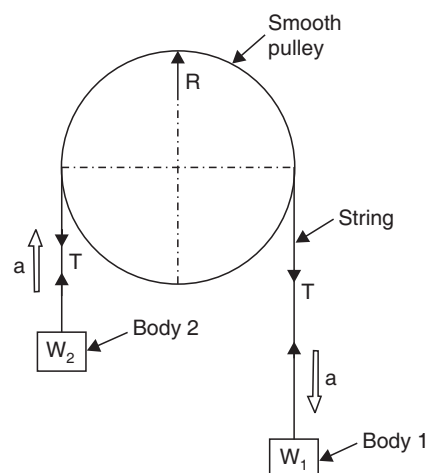


Fig. 8.9

Since the body is moving upwards therefore force acting on the body

$$= \frac{W_2}{g} \cdot a \quad \dots(iv)$$

Equating (iii) and (iv)

$$T - W_2 = \frac{W_2}{g} \cdot a \quad \dots(2)$$

Now adding eqns. (1) and (2), we get

$$W_1 - W_2 = \left(\frac{W_1 + W_2}{g} \right) a$$

from which,
$$a = \left(\frac{W_1 + W_2}{W_1 + W_2} \right) \cdot g$$

From equation (2),

$$T - W_2 = \frac{W_2}{g} a$$

$$T = W_2 + \frac{W_2}{g} a = W_2 \left(1 + \frac{a}{g} \right)$$

Substituting the value of 'a' from equation (8.6), we get

$$T = W_2 \left[1 + \left(\frac{W_1 - W_2}{W_1 + W_2} \right) \cdot \frac{g}{g} \right]$$

from which,
$$T = \frac{2 W_1 W_2}{W_1 + W_2}$$

Reaction of the pulley,

$$R = T + T = 2T$$

$$= \frac{4W_1 W_2}{W_1 + W_2}$$

Example 8.18. Two bodies weighing 45 N and 60 N are hung to the ends of a rope, passing over a frictionless pulley. With what acceleration the heavier weight comes down ? What is the tension in the string ?

Sol. Weight of heavier body, $W_1 = 60$ N

Weight of lighter body, $W_2 = 45$ N

Acceleration of the system, $a = ?$

Using the relation,

$$a = \frac{g(W_1 - W_2)}{(W_1 + W_2)} = \frac{9.81(60 - 45)}{(60 + 45)} = 1.4 \text{ m/s}^2. \text{ (Ans.)}$$

Tension in the string, $T = ?$

Using the relation,

$$T = \frac{2 W_1 W_2}{W_1 + W_2} = \frac{2 \times 60 \times 45}{(60 + 45)} = 51.42 \text{ N. (Ans.)}$$

Example 8.19. A system of frictionless pulleys carries two weights hung by inextensible cords as shown in Fig. . Find :

- The acceleration of the weights and tension in the cords.
- The velocity and displacement of weight '1' after 5 seconds from start if the system is released from rest.

Sol. Weight, $W_1 = 80 \text{ N}$
Weight, $W_2 = 50 \text{ N}$

Let $T =$ tension (constant throughout the cord, because pulleys are frictionless, and cord is continuous).

When weight W_1 travels unit distance then weight W_2 travels half the distance. Acceleration is proportional to the distance.

$\therefore$ If $a =$ acceleration of weight W_1
then, $a/2 =$ acceleration of weight W_2 .

It is clear from the figure that weight W_1 moves downward and weight W_2 moves upward.

(i) **Acceleration of weights, $T = ?$**

Consider the motion of weight W_1 :

$$W_1 - T = \frac{W_1}{g} a$$

$$80 - T = \frac{80}{g} \times a \quad \dots(i)$$

Consider the motion of weight W_2 :

$$2T - W_2 = \frac{W_2}{g}$$

$$2T - 50 = \frac{50}{g} \times \frac{a}{2} \quad \dots(ii)$$

Multiplying eqn. (i) by 2 and adding eqns. (i) and (ii), we get

$$110 = \frac{185}{g} a$$

$$\therefore a = \frac{110 \times 9.81}{185} = 5.8 \text{ m/s}^2$$

Hence **acceleration of $W_1 = 5.8 \text{ m/s}^2$. (Ans.)**

and **acceleration of $W_2 = 5.8/2 = 2.9 \text{ m/s}^2$. (Ans.)**

Substituting the value of ' a ' in eqn. (i), we get

$$80 - T = \frac{80}{9.81} \times 5.8$$

$$\therefore T = 32.7 \text{ N. (Ans.)}$$

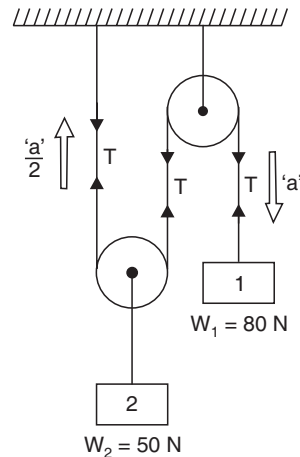
(ii) **Velocity and displacement of weight W_1 after 5 sec. = ?**

$$u = 0, a = 5.8 \text{ m/s}^2, t = 5 \text{ s}$$

$$\therefore v = u + at = 0 + 5.8 \times 5 = 29 \text{ m/s. (Ans.)}$$

and

$$s = ut + \frac{1}{2} at^2 = 0 + \frac{1}{2} \times 5.8 \times 5^2 = 72.5 \text{ m. (Ans.)}$$



MOTION OF TWO BODIES CONNECTED AT THE EDGE OF A HORIZONTAL SURFACE

Fig. 8.11 shows two bodies of weights W_1 and W_2 respectively connected by a light inextensible string. Let the body 1 hang free and body 2 be placed on a rough horizontal surface. Let the body 1 move downwards and the body 2 move along the surface of the plane. We know that the velocity and acceleration of the body will be the same as that of the body 2, therefore tension will be same throughout the string. Let μ be the co-efficient of friction between body 2 and the horizontal surface.

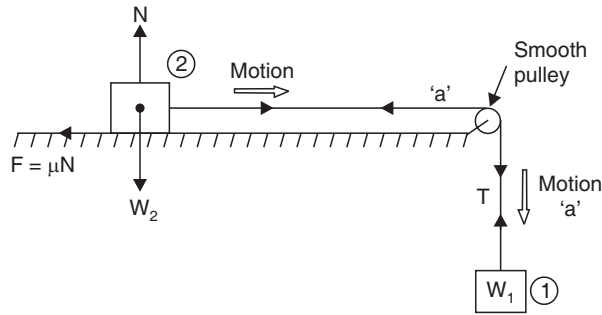


Fig. 8.11

Normal reaction at the surface, $N = W_2$

and force of friction, $F = \mu N = \mu W_2$

Let a = acceleration of the system

T = tension in the string.

Consider the motion of body 1 :

Forces acting on it are : W_1 (downwards) and T (upwards)

Resultant force $= W_1 - T$... (i)

Since the body is moving downwards, therefore force acting on this body

$$= \frac{W_1}{g} \cdot a \quad \dots (ii)$$

$$\text{Equating (i) and (ii), } W_1 - T = \frac{W_1}{g} a \quad \dots (1)$$

Now consider the motion of body 2 :

Forces acting on it are : T (towards right), Force of friction F (towards left).

$\therefore$ Resultant force $= T - F = T - \mu W_2$... (iii)

Since, the body is moving horizontally with acceleration, therefore force acting on this body

$$= \frac{W_2}{g} \cdot a \quad \dots (iv)$$

Equating (iii) and (iv), we get

$$T - \mu W_2 = \frac{W_2}{g} a \quad \dots (2)$$

Adding equations (1) and (2), we get

$$W_1 - \mu W_2 = \frac{W_1}{g} a + \frac{W_2}{g} a$$

or

$$W_1 - \mu W_2 = \frac{a}{g} (W_1 + W_2)$$

or

$$a = \left(\frac{W_1 - \mu W_2}{W_1 + W_2} \right) g$$

Substituting this value of 'a' in equation (1), we get

$$W_1 - T = \frac{W_1}{g} \left(\frac{W_1 - \mu W_2}{W_1 + W_2} \right) g$$

$$T = W_1 - W_1 \left(\frac{W_1 - \mu W_2}{W_1 + W_2} \right)$$

$$T = W_1 \left[1 - \frac{W_1 - \mu W_2}{W_1 + W_2} \right]$$

$$= W_1 \left[\frac{W_1 + W_2 - W_1 + \mu W_2}{W_1 + W_2} \right]$$

i.e.,

$$T = \frac{W_1 W_2 (1 + \mu)}{W_1 + W_2}$$

For *smooth horizontal surface* ; putting $\mu = 0$ in equations (8.9) and (8.10), we get

$$a = \frac{W_1 \cdot g}{W_1 + W_2}$$

and

$$T = \frac{W_1 W_2}{W_1 + W_2}$$

20. Find the acceleration of a solid body A of weight 8 N, when it is being pulled by another body of weight 6 N along a smooth horizontal plane as shown in Fig. 8.12.

Sol. Refer to Fig.

Weight of body B, $W_1 = 6 \text{ N}$

Weight of body A, $W_2 = 8 \text{ N}$

Acceleration of body, $a = ?$

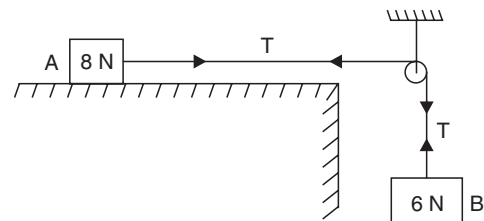
Tension in the string, $T = ?$

Equation of motion for body B

$$6 - T = \frac{6}{g} \cdot a \quad \dots(i)$$

Equation of motion for body A

$$T = \frac{8}{g} \cdot a \quad \dots(ii)$$



235 Adding (i) and (ii), we get

$$6 = \frac{14}{g} \cdot a$$

$$\therefore a = \frac{6 \times 9.81}{14} = 4.2 \text{ m/s}^2. \text{ (Ans.)}$$

Substituting this value of a in (i), we get

$$6 - T = \frac{6}{9.81} \times 4.2$$

$$\therefore T = 3.43 \text{ N. (Ans.)}$$

21. Two blocks shown in Fig. have weights $A = 8 \text{ N}$ and $B = 10 \text{ N}$ and co-efficient of friction between the block A and horizontal plane, $\mu = 0.2$.

If the system is released, from rest and the block A falls through a vertical distance of 1.5 m , what is the velocity acquired by it? Neglect the friction in the pulley and extension of the string.

Sol. Refer to Fig. 8.13.

Considering vertical string portion:

$$8 - T = \frac{8}{g} \cdot a \quad \dots(i)$$

Considering horizontal string portion :

$$T - F = \frac{10}{g} \cdot a$$

$$\text{or} \quad T - \mu N_B = \frac{10}{g} \cdot a$$

$$\text{or} \quad T - 0.2 \times 10 = \frac{10}{g} a$$

$$\text{or} \quad T - 2 = \frac{10}{g} a$$

Adding (i) and (ii)

$$6 = \frac{18a}{g}$$

$$\therefore a = \frac{6 \times 9.81}{18} = 3.27 \text{ m/s}^2$$

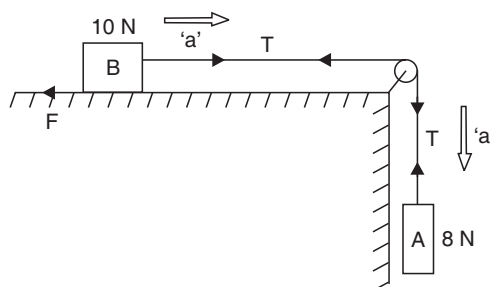
Now using the relation :

$$v^2 - u^2 = 2as \quad \text{or} \quad v^2 - u^2 = 2 \times 3.27 \times 1.5$$

$$\therefore v = 3.13 \text{ m/s}$$

Hence the velocity acquired by weight A = **3.13 m/s. (Ans.)**

22. A body '1' of weight 20 N is held on a rough horizontal table. An elastic string connected to the body '1' passes over a smooth pulley at the end of the table and then under a second smooth pulley carrying a body '2' of weight 10 N as shown in Fig. 8.14. The other end of the string is fixed to a point above the second pulley. When the 20 N body is released, it moves with an acceleration of $g/5$. Determine the value of co-efficient of friction between the block and the table.



$$(\because N_B = W_B = 10 \text{ newtons})$$

...(ii)

Sol. Weight of body '1', $W_1 = 20 \text{ N}$

Weight of body '2', $W_2 = 10 \text{ N}$

Acceleration of body '1' $a = g/5$

Let T = tension in string in newtons, and
 μ = co-efficient of friction between
 block and the table.

Considering the motion of body '1' :

$$T - \mu W_1 = \frac{W_1}{g} a$$

$$\text{or} \quad T - \mu \times 20 = \frac{20}{g} \times \frac{g}{5} = 4 \quad \dots(i)$$

Considering the motion of body '2' :

A little consideration will show that the acceleration of the body '2' will be half of that of the body '1' i.e., $g/10$.

$$\text{Now,} \quad W_2 - 2T = \frac{W_2}{g} \times \frac{a}{2}$$

$$\text{or} \quad 10 - 2T = \frac{10}{g} \times \frac{g}{10} = 1 \quad \dots(ii)$$

Now multiplying eqn. (i) by 2 and adding eqns. (i) and (ii), we get

$$10 - 40\mu = 9$$

$$\therefore \quad 40\mu = 1 \text{ or } \mu = \mathbf{0.025. (Ans.)}$$

Example 8.23. A string passing across a smooth table at right angle to two opposite edges has two masses M_1 and M_2 ($M_1 > M_2$) attached to its ends hanging vertically as shown in Fig. 8.15. If a mass M be attached to the portion of the string which is on the table, find the acceleration of the system when left to itself.

Sol. Refer to Fig. 8.15.

Let T_1 and T_2 be the tensions in the two portions of the strings.

Acceleration of the system, $a = ?$

We know that

$$W_1 = M_1 g, \quad W_2 = M_2 g$$

$\therefore$ Equations of motion are :

$$M_1 g - T_1 = M_1 a \quad \dots(i)$$

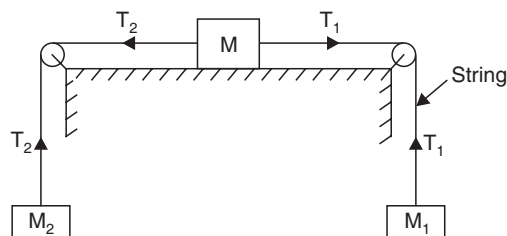
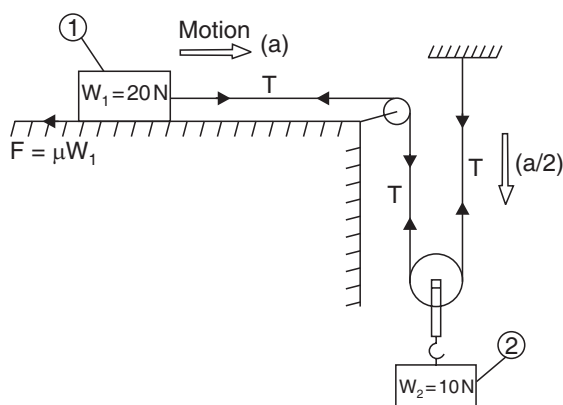
$$T_1 - T_2 = M \cdot a \quad \dots(ii)$$

$$T_2 - M_2 g = M_2 \cdot a \quad \dots(iii)$$

Adding (i), (ii) and (iii), we get

$$M_1 g - M_2 g = a (M_1 + M + M_2)$$

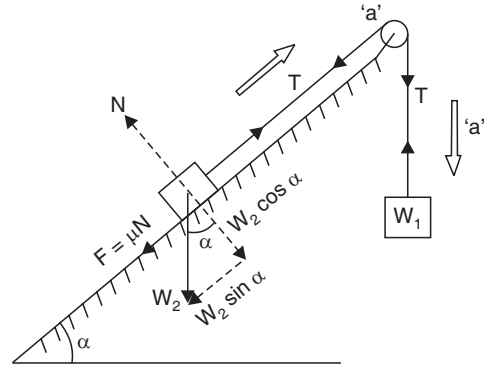
$$a = \left[\frac{M_1 - M_2}{M_1 + M + M_2} \right] \times g. \quad (\text{Ans.})$$



MOTION OF TWO BODIES CONNECTED BY A STRING ONE END OF WHICH IS HANGING FREE AND THE OTHER LYING ON A ROUGH INCLINED PLANE

Fig. 8.16 shows two bodies of weight W_1 and W_2 respectively connected by a light inextensible string. Let the body 1 of weight W_1 hang free and body 2 of weight W_2 be placed on an inclined rough surface. The velocity and acceleration of the body 1 will be the same as that of body 2. Since the string is inextensible, therefore, tension will be same throughout.

Let a = acceleration of the system
 α = inclination of the plane
 μ = co-efficient of friction between body and the inclined surface
 T = tension in the string.



Consider the motion of body 1 :

Forces acting on it are : W_1 (downwards), T (upwards)

Resultant force = $W_1 - T$

...(i)

Since the body is moving downwards, therefore force acting on the body

$$= \frac{W_1}{g} \cdot a \quad \text{...(ii)}$$

Equating (i) and (ii)

$$W_1 - T = \frac{W_1}{g} \cdot a \quad \text{...(1)}$$

Now consider the motion of body 2 :

Normal reaction at the surface,

$$N = W_2 \cos \alpha$$

$\therefore$ Force of friction, $F = \mu N = \mu W_2 \cos \alpha$

The forces acting on the body 2 as shown are :

T (upwards), $W \sin \alpha$ (downwards)

and

$F = \mu W_2 \cos \alpha$ (downwards)

$\therefore$ Resultant force = $T - W_2 \sin \alpha - \mu W_2 \cos \alpha$... (iii)

Since, this body is moving along the inclined surface with acceleration therefore force acting on this body

$$= \frac{W_2}{g} a \quad \text{...(iv)}$$

Equating (iii) and (iv), we get

$$T - W_2 \sin \alpha - \mu W_2 \cos \alpha = \frac{W_2}{g} a \quad \text{...(2)}$$

Adding equations (1) and (2), we get

$$W_1 - W_2 \sin \alpha - \mu W_2 \cos \alpha = \frac{a}{g} (W_1 + W_2)$$

$$\therefore a = \frac{g(W_1 - W_2 \sin \alpha - \mu W_2 \cos \alpha)}{W_1 + W_2}$$

Substituting this value of 'a' in equation (1), we get

$$\begin{aligned} W_1 - T &= \frac{W_1}{g} a \\ T &= W_1 - \frac{W_1}{g} a = W_1 \left(1 - \frac{a}{g} \right) \\ &= W_1 \left[1 - \frac{W_1 - W_2 \sin \alpha - \mu W_2 \cos \alpha}{W_1 + W_2} \right] \\ &= W_1 \left[\frac{W_1 + W_2 - W_1 + W_2 \sin \alpha + \mu W_2 \cos \alpha}{W_1 + W_2} \right] \\ &= W_1 W_2 \left[\frac{1 + \sin \alpha + \mu \cos \alpha}{W_1 + W_2} \right] \\ \text{i.e., } T &= \frac{W_1 W_2 (1 + \sin \alpha + \mu \cos \alpha)}{W_1 + W_2} \end{aligned}$$

For smooth inclined surface ; putting $\mu = 0$ in equations (8.13) and (8.14).

$$a = \frac{g(W_1 - W_2 \sin \alpha)}{W_1 + W_2}$$

and

$$T = \frac{W_1 W_2 (1 + \sin \alpha)}{W_1 + W_2}$$

Example 8.24. A body weighing 8 N rests on a rough plane inclined at 15° to the horizontal. It is pulled up the plane, from rest, by means of a light flexible rope running parallel to the plane. The portion of the rope, beyond the pulley hangs vertically down and carries a weight of 60 N at the end. If the co-efficient of friction for the plane and the body is 0.22, find:

- The tension in the rope,
- The acceleration in m/s^2 , with which the body moves up the plane, and
- The distance in metres moved by the body in 2 seconds, starting from rest.

Sol. Refer to Fig.

Let T newton be the tension in the string and $a \text{ m/s}^2$ the acceleration of the system.

Considering motion of 60 N weight

(W_1) :

$$60 - T = \frac{60}{g} \cdot a \quad \dots(i)$$

Considering motion of 8 N weight

(W_2) :

$$T - W_2 \sin \alpha - F = \frac{W_2}{g} \cdot a$$

$$T - 8 \sin \alpha - \mu N = \frac{8}{g} \cdot a$$

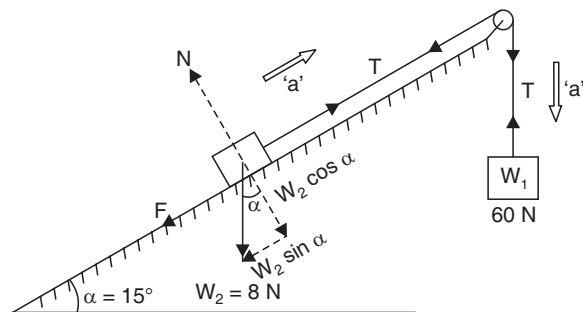


Fig. 8.17

$$T - 8 \sin \alpha - 0.22 \times 8 \cos \alpha = \frac{8}{g} \cdot a \quad (\because N = W_2 \cos \alpha = 8 \cos \alpha) \quad \dots(ii)$$

Adding (i) and (ii)

$$60 - 8 \sin \alpha - 0.22 \times 8 \cos \alpha = \frac{68}{g} \cdot a$$

$$60 - 8 \sin 15^\circ - 1.76 \cos 15^\circ = \frac{68}{9.81} \times a$$

$$60 - 2.07 - 1.7 = \frac{68}{9.81} \times a$$

$$\therefore \quad a = 8.11 \text{ m/s}^2. \text{ (Ans.)}$$

Substituting this value of 'a' in equation (i), we get

$$T = 60 - \frac{60}{9.81} \times 8.11 = 10.39 \text{ N. (Ans.)}$$

Distance moved in 5 seconds, $s = ?$

Initial velocity, $u = 0$

Time, $t = 2 \text{ s.}$

Using the relation : $s = ut + \frac{1}{2} at^2$

$$\therefore \quad s = 0 + \frac{1}{2} \times 8.11 \times 2^2 = 16.22 \text{ m. (Ans.)}$$

Example 8.25. Determine the resulting motion of the body '1' assuming the pulleys to be smooth and weightless as shown in Fig. . If the system starts from rest, determine the velocity of the body '1' after 5 seconds.

Sol. Weight of body '1', $W_1 = 20 \text{ N}$

Weight of body '2', $W_2 = 30 \text{ N}$

Let $T =$ tension in the string, and

$a =$ acceleration of the body '1'.

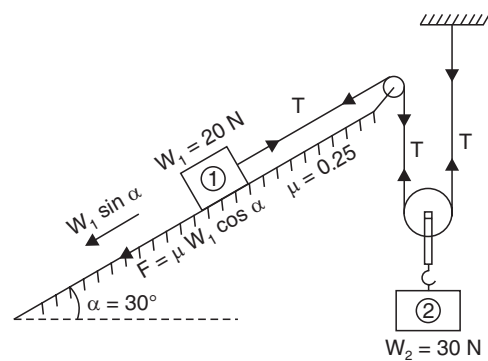
Considering the motion of body '1' :

$$T - W_1 \sin \alpha - \mu W_1 \cos \alpha = \frac{W_1}{g} a$$

$$\text{or} \quad T - 20 \sin 30^\circ - 0.25 \times 20 \cos 30^\circ = \frac{20}{g} \times a$$

$$\text{or} \quad T - 10 - 4.33 = \frac{20}{g} a$$

$$\text{or} \quad T - 14.33 = \frac{20}{g} a \quad \dots(i)$$



Considering the motion of body '2' :

A little consideration will show that the acceleration of body '2' will be half the acceleration of body '1' (i.e., $a/2$).

$$\therefore 30 - 2T = \frac{30}{g} \times \frac{a}{2} = \frac{15}{g} a \quad \dots(ii)$$

Multiplying eqn. (i) by 2 and adding eqns. (i) and (ii), we get

$$1.34 = \frac{55}{g} a$$

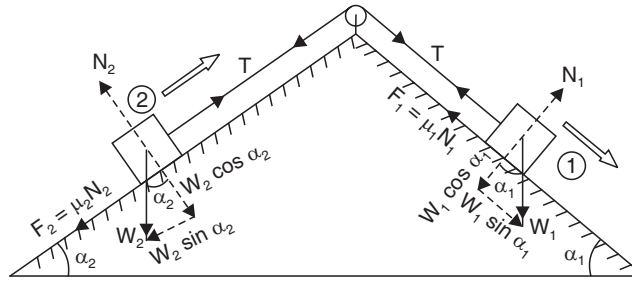
$$\therefore a = \frac{1.34 \times g}{55} = \frac{1.34 \times 9.81}{55} = 0.239 \text{ m/s}^2$$

$\therefore$ Velocity of body '1' after 5 sec., if the system starts from rest,

$$v = u + at = 0 + 0.239 \times 5 = \mathbf{1.195 \text{ m/s. (Ans.)}}$$

8.14. MOTION OF TWO BODIES CONNECTED OVER ROUGH INCLINED PLANES

Fig. shows two bodies of weight W_1 and W_2 respectively resting on the two inclined planes with inclinations α_1 and α_2 respectively.



Let a = acceleration of the system

μ_1 = co-efficient of friction between body 1 and the inclined plane 1 and

μ_2 = co-efficient of friction between body 2 and the inclined plane 2.

Consider the motion of body 1 :

Normal reaction at the surface,

$$N_1 = W_1 \cos \alpha_1$$

$$\therefore \text{ Force of friction, } F_1 = \mu_1 N_1 = \mu_1 W_1 \cos \alpha_1$$

The forces acting on body 1 are :

T (upwards), force of friction F_1 (upwards) and $W_1 \sin \alpha_1$ (downwards) as shown in Fig. 8.19.

$$\therefore \text{ Resultant force} = W_1 \sin \alpha_1 - T - \mu_1 W_1 \cos \alpha_1 \quad \dots(i)$$

Since this body is moving downwards, the force acting on this body

$$= \frac{W_1}{g} \cdot a \quad \dots(ii)$$

Equating (i) and (ii)

$$W_1 \sin \alpha_1 - T - \mu_1 W_1 \cos \alpha_1 = \frac{W_1}{g} \cdot a \quad \dots(1)$$

Now consider motion of body 2 :

Normal reaction at the surface,

$$N_2 = W_2 \cos \alpha_2$$

$$\therefore \text{ Force of friction, } F_2 = \mu_2 N_2 = \mu_2 W_2 \cos \alpha_2$$

The forces acting on body 2 are :

T (upwards), force of friction of F_2 (downwards) and $W_2 \sin \alpha_2$ (downwards) as shown in

Fig.

$$\text{Resultant force} = T - W_2 \sin \alpha_2 - \mu_2 W_2 \cos \alpha_2 \quad \dots(iii)$$

Since the body is moving upwards, the force acting on the body

$$= \frac{W_2}{g} a \quad \dots(iv)$$

Equating (iii) and (iv)

$$T - W_2 \sin \alpha_2 - \mu_2 W_2 \cos \alpha_2 = \frac{W_2}{g} a \quad \dots(2)$$

Adding eqns. (1) and (2), we get

$$W_1 \sin \alpha_1 - W_2 \sin \alpha_2 - \mu_1 W_1 \cos \alpha_1 - \mu_2 W_2 \cos \alpha_2 = \frac{a}{g} (W_1 + W_2)$$

$$\therefore a = \frac{g (W_1 \sin \alpha_1 - W_2 \sin \alpha_2 - \mu_1 W_1 \cos \alpha_1 - \mu_2 W_2 \cos \alpha_2)}{W_1 + W_2} \quad \dots(8.17)$$

Substituting this value of 'a' in equation (1), we get

$$\begin{aligned} W_1 \sin \alpha_1 - T - \mu_1 W_1 \cos \alpha_1 \\ = \frac{W_1 \times g}{g} \times \frac{(W_1 \sin \alpha_1 - W_2 \sin \alpha_2 - \mu_1 W_1 \cos \alpha_1 - \mu_2 W_2 \cos \alpha_2)}{W_1 + W_2} \end{aligned}$$

$$\begin{aligned} \therefore T &= (W_1 \sin \alpha_1 - \mu_1 W_1 \cos \alpha_1) \\ &\quad - \frac{W_1 (W_1 \sin \alpha_1 - W_2 \sin \alpha_2 - \mu_1 W_1 \cos \alpha_1 - \mu_2 W_2 \cos \alpha_2)}{W_1 + W_2} \end{aligned}$$

or

$$\begin{aligned} T &= \frac{1}{(W_1 + W_2)} [(W_1 + W_2) (W_1 \sin \alpha_1 - \mu_1 W_1 \cos \alpha_1) - W_1 (W_1 \sin \alpha_1 \\ &\quad - W_2 \sin \alpha_2 - \mu_1 W_1 \cos \alpha_1 - \mu_2 W_2 \cos \alpha_2)] \\ &= \frac{1}{(W_1 + W_2)} \times [W_1^2 \sin \alpha_1 - \mu_1 W_1^2 \cos \alpha_1 + W_1 W_2 \sin \alpha_1 \\ &\quad - \mu_1 W_1 W_2 \cos \alpha_1 - W_1^2 \sin \alpha_1 + W_1 W_2 \sin \alpha_2 \\ &\quad + \mu_1 W_1^2 \cos \alpha_1 + \mu_2 W_1 W_2 \cos \alpha_2] \\ &= \frac{1}{W_1 + W_2} (W_1 W_2 \sin \alpha_1 + W_1 W_2 \sin \alpha_2 - \mu_1 W_1 W_2 \cos \alpha_1 + \mu_2 W_1 W_2 \cos \alpha_2) \end{aligned}$$

$$= \left[\frac{W_1 W_2 (\sin \alpha_1 + \sin \alpha_2) - W_1 W_2 (\mu_1 \cos \alpha_1 - \mu_2 \cos \alpha_2)}{W_1 + W_2} \right]$$

$$= \frac{1}{W_1 + W_2} [W_1 W_2 (\sin \alpha_1 + \sin \alpha_2) - W_1 W_2 (\mu_1 \cos \alpha_1 - \mu_2 \cos \alpha_2)]$$

i.e.,
$$T = \frac{W_1 W_2}{W_1 + W_2} (\sin \alpha_1 + \sin \alpha_2 - \mu_1 \cos \alpha_1 + \mu_2 \cos \alpha_2) \quad \dots(8.18)$$

For smooth inclined plane : putting $\mu_1 = 0$ and $\mu_2 = 0$ in equations (8.17) and (8.18), we get

$$a = \frac{g (W_1 \sin \alpha_1 - W_2 \sin \alpha_2)}{W_1 + W_2} \quad \dots(8.19)$$

and
$$T = \frac{W_1 W_2}{W_1 + W_2} (\sin \alpha_1 + \sin \alpha_2) \quad \dots(8.20)$$

26. Blocks A and B weighing 10 N and 4 N respectively are connected by a weightless rope passing over a frictionless pulley and are placed on smooth inclined planes making 60° and 45° with the horizontal as shown in Fig. . Determine :

- (i) The tension in the string and
- (ii) Velocity of the system 3 seconds after starting from rest.

Sol. Refer to Fig.

Let 'T' be the tension in the rope and 'a' the acceleration of the system.

(i) Tension, T = ?

For block A :

Resolving forces parallel to the plane :

$$10 \sin 60^\circ - T = \frac{10}{g} \cdot a \quad \dots(i)$$

For block B :

Resolving forces parallel to the plane,

$$T - 4 \sin 45^\circ = \frac{4}{g} \cdot a \quad \dots(ii)$$

Adding (i) and (ii), we get

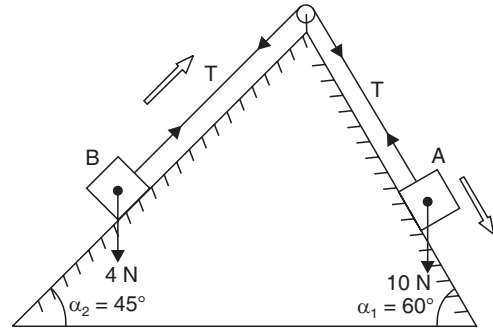
$$10 \sin 60^\circ - 4 \sin 45^\circ = \frac{14}{g} \cdot a$$

$$8.66 - 2.83 = \frac{14}{9.81} \times a$$

$$a = 4.08 \text{ m/s}^2$$

Substituting this value of equations 'a' in (i), we get

$$10 \sin 60^\circ - T = \frac{10}{9.81} \times 4.08$$



$$\begin{aligned}
 \therefore T &= 10 \sin 60^\circ - \frac{10}{9.81} \times 4.08 \\
 &= 8.66 - 4.16 = \mathbf{4.5 \text{ N. (Ans.)}}
 \end{aligned}$$

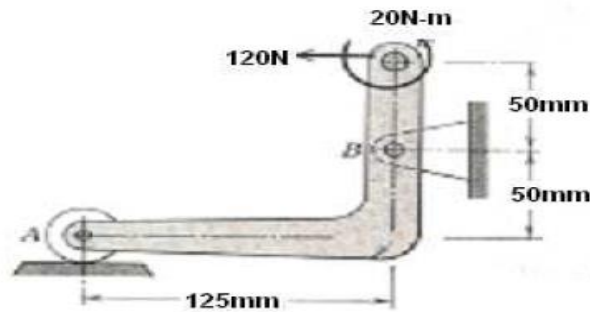
(ii) Velocity after 3 seconds, $v = ?$

Using the relation :

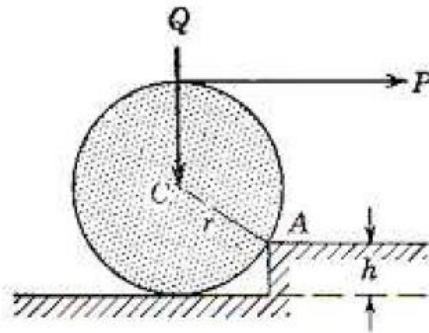
$$\begin{aligned}
 v &= u + at \\
 &= 0 + 4.08 \times 3 & (\because u = 0) \\
 &= \mathbf{12.24 \text{ m/s. (Ans.)}}
 \end{aligned}$$

UNIT I

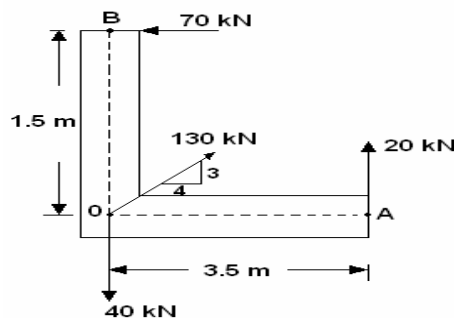
1. Calculate the magnitude of the force supported by the pin at B for the bell crank loaded and supported as shown in Figure



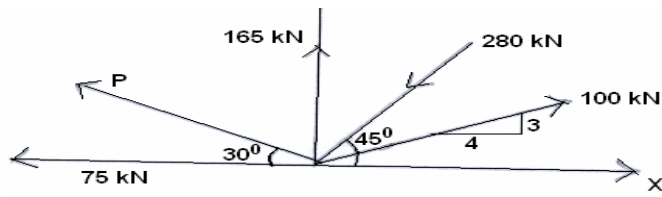
2. A roller of radius $r = 0.3$ m and weight $Q = 2000$ N is to be pulled over a curb of height $h = 0.15$ m. by a horizontal force P applied to the end of a string wound around the circumference of the roller. Find the magnitude of P required to start the roller over the curb. [3 Marks]
{As shown in the Figure }



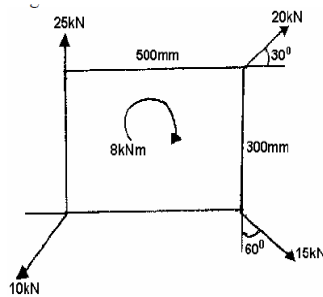
3. State and Prove Lami's Theorem
4. Distinguish between co-planar and non-co planar forces. Classify the various types of forces.
5. Forces are applied to an angle bracket as shown in figure 2. Determine the magnitude and direction of the resultant



6. State and prove Varignon's Theorem
7. State and prove parallelogram law of forces.
8. Calculate the magnitude of "P" and the resultant of the force system shown in figure. The algebraic sum of horizontal components of all these forces is -325 kN.[4]



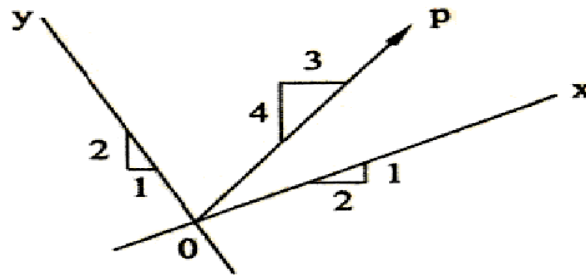
9. Determine the magnitude, direction and position of the resultant of the system of forces as shown in figure.



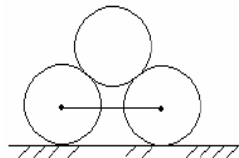
OR

10. What do you mean by coplanar concurrent force system? Explain with suitable example. [2]

11. If the X component is as shown in figure of P is 893 N, determine P and its Y component. [3]



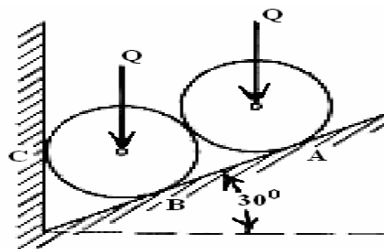
12. Two smooth cylinders of 3 m diameter and 100 N weight are separated by a chord of 4 m long. They support another smooth cylinder of diameter 3 m and 200 N weight as shown in figure. Find the tension in



the chord.

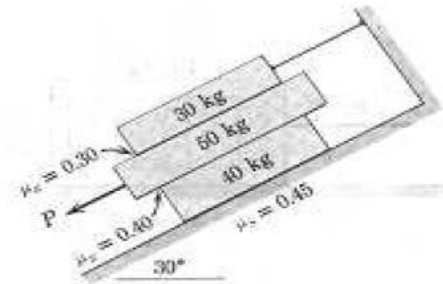
13.a) Define free body diagram, Transmissibility of a force and resultant of a force.

b) Two identical rollers, each of weight 100 N, are supported by an inclined plane and a vertical wall as shown in figure. Assuming smooth surfaces, find the reactions induced at the points of support A, B and C

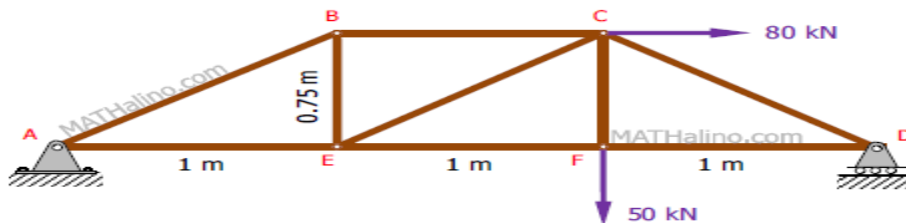


UNIT II

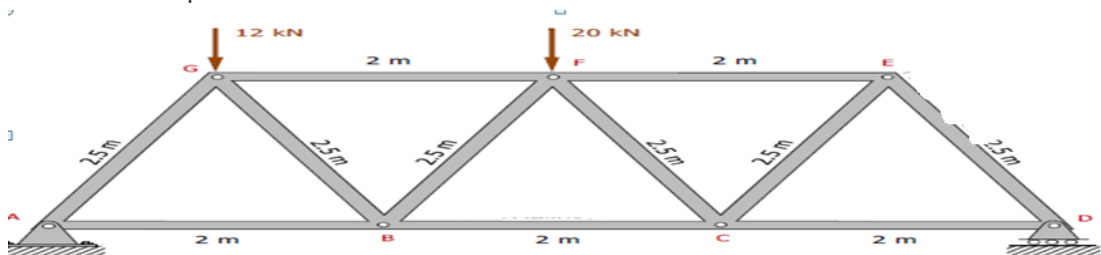
1. A block weighing 50 N is resting on a horizontal plane. A horizontal force of 10 N is applied to start the sliding of the block. Find
 - i. coefficient of friction
 - ii. angle of friction
 - iii. resultant force.
2. The three flat blocks are positioned on the 30° incline as shown in Figure, and a force P parallel to the incline is applied to the middle block. The upper block is prevented from moving by a wire which attaches it to the fixed support. The coefficient of static friction for each of the three pairs of mating surfaces is shown. Determine the maximum value which P may have before any slipping takes place



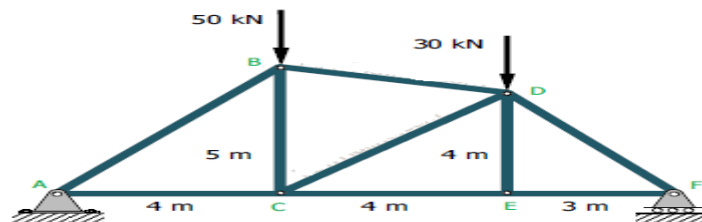
3. Find the force acting in all members of the truss shown in Figure



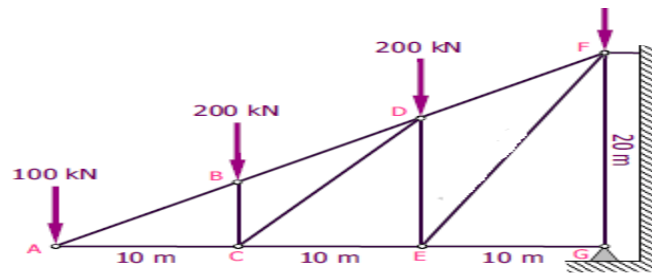
4. The structure in Fig. is a truss which is pinned to the floor at point A, and supported by a roller at point D. Determine the force to all members of the truss.



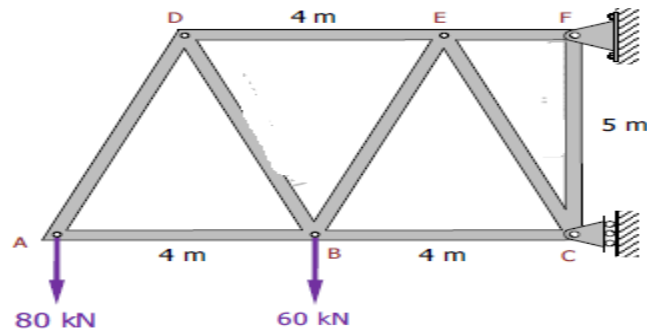
5. Compute the force in all members of the truss shown in Fig.



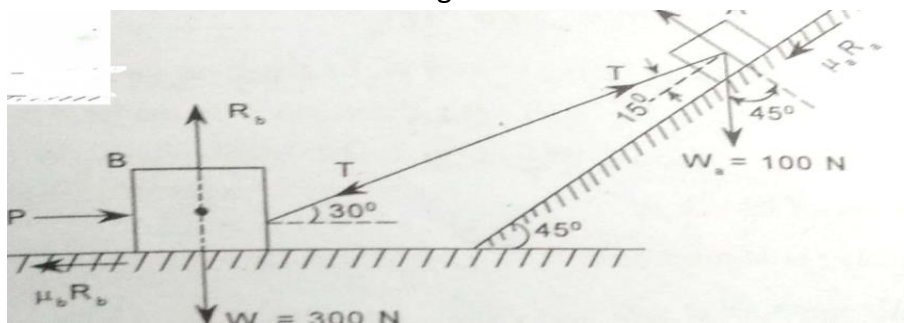
6. Use the method of sections to compute for the force in members DF, EF, and EG of the cantilever truss as shown in fig



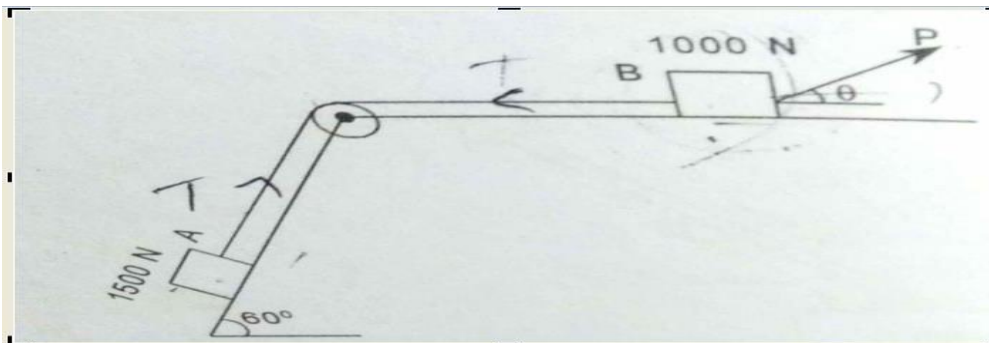
7. The truss in Fig. is pinned to the wall at point F, and supported by a roller at point C. Calculate the force (tension or compression) in members BC, BE, and DE



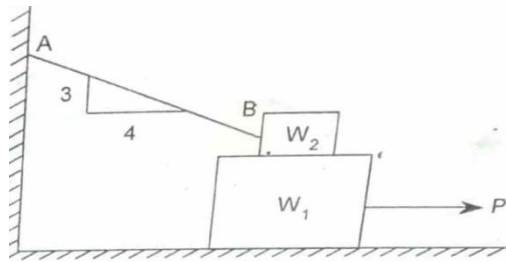
8. A uniform bar AB 10 m long and weighing 280N is hinged at B and rests upon a 400 N block as shown in figure. If the coefficient of friction is 0.4 for all contact surfaces. Find the horizontal force P required to start moving the 400 N block



9. Referring the blow figure determine the least value of the force P to cause motion to impend rightward. Assume the coefficient of friction under the blocks to be 0.2 and the pulley to be frictionless

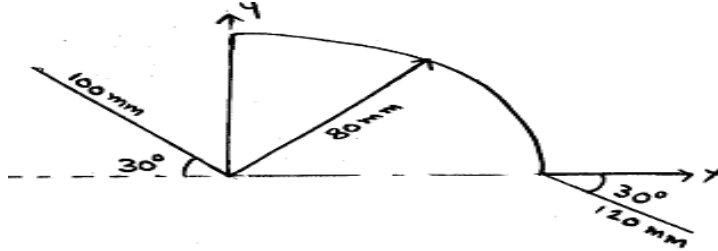


10. A block of weight $W_1 = 1290$ N on a horizontal surface and supports another block of weighing $W_2 = 570$ N on the top of its as shown in figure. The block of weight W_2 is attached to a vertical wall by an inclined string AB. Find the force P applied to the lower block that will be necessary To cause slipping to impend. the Coefficient of friction between block 1 and 2 is 0.25 and between block 1 and horizontal surface is 0.4

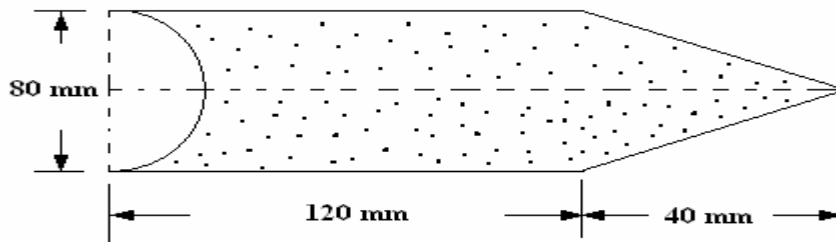


UNIT III

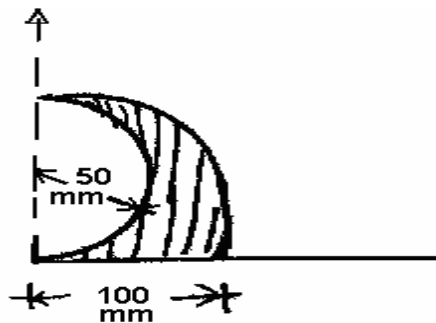
1. Locate the centroid of the wire bent as shown in figure



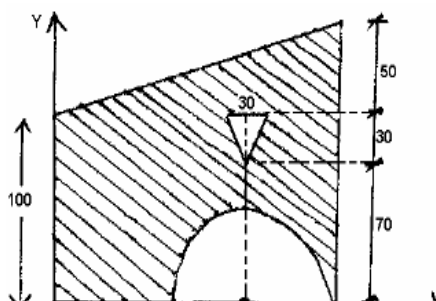
2. Find the Centroid for the shaded area about y – axis. As shown in the Figure[4]

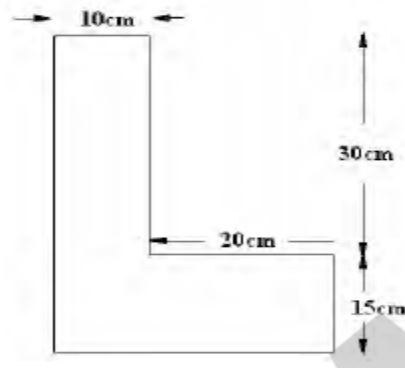


3. State and prove Pappus theorem
4. Locate the centroid of the shaded area shown in figure

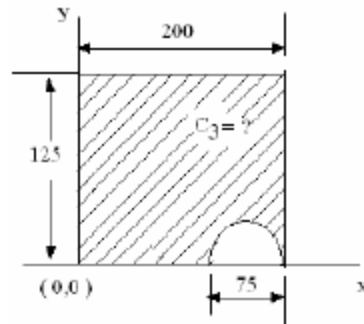


5. Find the centroid of Quarter circle having the radius R
6. Determine the centre of gravity of solid cone of base Radius 'R' and height 'h'
7. Locate the centroid of the shaded area and also find the moment of inertia about horizontal centroidal axis shown in figure. All dimensions in mm.





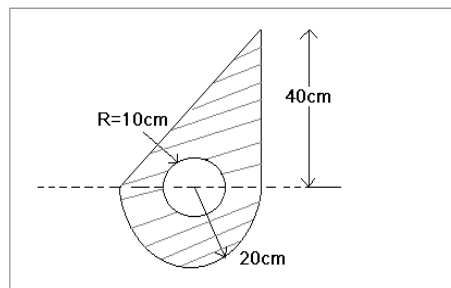
9. Determine the centroid of the shaded area as shown in figure



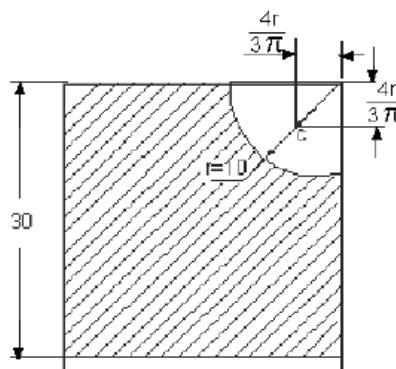
10. Determine the centre of gravity of right solid circular arc of radius R and height h

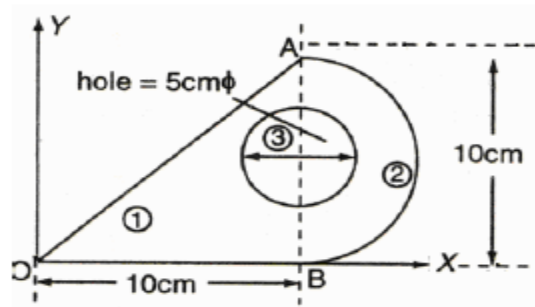
UNIT IV

1. From first principles deduce an expression to determine the Moment of Inertia of a triangle of base ' b ' and height ' h '
2. Find the moment of inertia about the horizontal centroidal axis.



3. Determine the mass moment of inertia of sphere about its diametrical axis
4. Determine moment of inertia of a quarter circle having the radius ' r '
5. Locate the centroid and calculate moment of inertia about horizontal and vertical axis through the centroid as shown in figure
6. Find the Moment of inertia of the shaded area shown in figure about Centroidal X and Y axis. All dimensions are in cm.





8. Find the mass moment of inertia of a circular plate about centroidal axis
9. Determine the Mass moment of inertia a solid sphere of Radius R about its diametrical axis
10. Determine the mass moment of Inertia of Rod of Length L

UNIT V

1. Derive the Expression for the Equations of motion of the body when it is accelerated uniformly.
2. A particle under a constant deceleration is moving in a straight line and cover a distance of 20 m in first 2 seconds and 40 m in next 5 seconds. Calculate the distance it covers in the subsequent 3 seconds and the total distance covered before it comes to rest
3. State and Explain D'Alemberts principle
4. The motion of a particle in a rectilinear motion is defined by the relation $s = 2t^3 - 9t^2 + 12t - 10$ Where s is metres and t in seconds
 - i) Find the acceleration of the particle when velocity is zero
 - ii) the position and total distance travelled when the acceleration is zero
5. With an initial velocity of 126 m/s, a bullet is fired upwards at an angle of elevation of 35° from a point on a hill and strikes the target which is 100 m lower than the point of projection. Neglecting the air resistance calculate
 - i) The maximum to which it will rise above the horizontal plane from which it is projected
 - ii) Velocity with which it will strike the target
6. A stone is dropped into a well while splash is heard after 4.5 seconds. Another stone is dropped with an initial velocity, v and the splash is heard after 4 seconds. If the velocity of the sound is 336 m/s, determine the initial velocity of second stone
7. A motorist is travelling at 90 kmph, when he observes a traffic light 250 m ahead of him turns red. The traffic light is timed to stay red for 12 sec. If the motorist wishes to pass the light without stopping, just as it turns green. Determine
 - i) The required uniform deceleration of motor and
 - ii) The speed of the motor as it passes the traffic light
8. Two bodies of weights 40 N and 25 N are connected to the two ends of a light in extensible spring passing over a smooth pulley. The weight of 40 N is placed on a rough horizontal surface while the weight of 25 N is hanging free in air. The angle of plane is 15° . Determine
 - a) the acceleration of the system
 - b) The tension ($\mu = 0.2$) in the string.
 - c) The distance moved by the weight 25 N in 3 seconds starting from rest