MECHANICS II: Physics Notes

Table of Contents

3. Projectiles 3.1 Concept of projectiles 3.2 Motion of a projectile 3.3 Summary
4. Equilibrium of Forces 4.1 Concept of equilibrium 4.2 Resultant and equilibrant of forces 4.3 Equilibrium of three forces acting at a point 4.4 Moment of a force 4.5 Condition of equilibrium under the action of parallel coplanar forces 4.6 Condition of equilibrium under the action of non-parallel coplanar forces 4.7 Centre of gravity 4.8 Stability of objects 4.9 Equilibrium of bodies in liquids 4.10 Flotation 4.11 Density and relative density 4.12 Hydrometer 4.13 Summary
5. Simple Harmonic Motion (SHM) 5.1 Definition of simple harmonic motion (SHM) 5.2 Simple harmonic motion from circular motion 5.3 Speed and acceleration of SHM 5.4 Energy of SHM 5.5 Forced vibration and resonance 5.6 Summary
6. Linear Momentum 6.1 Impulse and momentum 6.2 Newton's laws of motion 6.3 Conservation of linear momentum 6.4 Collisions 6.5 Applications of Newton's and conservation of momentum laws 6.6 Inertial mass and weight 6.7 Summary
7. Mechanical Energy 7.1 Work 7.2 Mechanical energy 7.3 Conservation of mechanical energy 7.4 Machines 7.5 Types of machine 7.6 Summary
8. Heat Energy: Temperature and its Measurements 8.1 Heat and temperature 8.2 Methods of measuring temperature 8.3 Good temperature and temperature scales of thermometers 8.4 Types of thermometers 8.5 Molecular explanation of temperature 8.6 Summary
9. Measurement of Heat Energy 9.1 Specific heat 9.2 Change of state; latent heat 9.3 Evaporation 9.4 Boiling 9.5 Summary
Detailed Notes

3. Projectiles

3.1 Concept of Projectiles

- **Definition:** A projectile is any object that is thrown or projected into the air, subject only to the force of gravity (neglecting air resistance).
- **Examples:** A thrown ball, a fired bullet, water from a hose, a long jumper.

3.2 Motion of a Projectile

- **Key Idea:** Projectile motion can be analyzed by separating it into two independent components: horizontal and vertical motion.
    - **Horizontal Motion:** Constant velocity (assuming no air resistance). The horizontal acceleration is zero.
    - **Vertical Motion:** Constant acceleration due to gravity (g), acting downwards.
- **Trajectory:** The path followed by a projectile is typically a parabola.
- **Formulas (basic):**

- Formulas (basic):
  - Horizontal distance: $x = v_x t$
  - Vertical distance: $y = v_y t - \frac{1}{2} g t^2$

    (upwards positive) or $y = v_y t + \frac{1}{2} g t^2$

    (downwards positive)
  - Vertical velocity: $v_y = u_y - gt$

3.3 Summary

- Projectiles are objects moving under gravity only.
- Motion is analyzed in independent horizontal (constant velocity) and vertical (constant acceleration) components.

4. Equilibrium of Forces

4.1 Concept of Equilibrium

- **Definition:** An object is in equilibrium if it is either at rest (static equilibrium) or moving with a constant velocity (dynamic equilibrium). This means the net force acting on the object is zero.
- **Condition:** Sum of all forces acting on the object in any direction is zero. ΣF= 0.

4.2 Resultant and Equilibrant of Forces

- **Resultant Force:** A single force that has the same effect as all the individual forces acting on an object.
- **Equilibrant Force:** A single force that is equal in magnitude and opposite in direction to the resultant force. When an equilibrant is applied, the object will be in equilibrium.

4.3 Equilibrium of Three Forces Acting at a Point

- **Lami's Theorem:** If three coplanar forces acting at a point are in equilibrium, then each force is proportional to the sine of the angle between the other two forces.

- For forces F1, F2, F3 and angles α, β, γ opposite to them respectively:

$$\frac{F_1}{\sin\alpha} = \frac{F_2}{\sin\beta} = \frac{F_3}{\sin\gamma}$$

- **Triangle of Forces:** If three forces acting at a point are in equilibrium, they can be represented in magnitude and direction by the three sides of a closed triangle taken in order.

4.4 Moment of a Force (Torque)

- **Definition:** The turning effect of a force about a pivot or fulcrum.
- **Formula:** Moment = Force × Perpendicular distance from the pivot to the line of action of the force.
- **Unit:** Newton-metre (Nm).
- **Principle of Moments:** For an object to be in rotational equilibrium, the sum of clockwise moments about any point must be equal to the sum of anticlockwise moments about the same point.

4.5 Condition of Equilibrium Under the Action of Parallel Coplanar Forces

- For parallel forces to be in equilibrium:
    1. The vector sum of forces in one direction equals the vector sum of forces in the opposite direction.
    2. The sum of clockwise moments equals the sum of anticlockwise moments about any point.

4.6 Condition of Equilibrium Under the Action of Non-parallel Coplanar Forces

- For non-parallel forces to be in equilibrium:
    1. The vector sum of all forces is zero (resolved into horizontal and vertical components, $\Sigma F_x = 0$ and $\Sigma F_y = 0$.
    2. The sum of clockwise moments equals the sum of anticlockwise moments about any point.

4.7 Centre of Gravity (CG)

- **Definition:** The point where the entire weight of an object appears to act.
- For a uniform object, the CG is at its geometric centre.
- It's the point where the object can be balanced.

4.8 Stability of Objects

- **Stability:** The ability of an object to return to its original position after being slightly displaced.
- **Types of Equilibrium:**
    - **Stable Equilibrium:** CG is low, base is wide. When tilted, CG is raised. (e.g., a pyramid)
    - **Unstable Equilibrium:** CG is high, small base. When tilted, CG is lowered. (e.g., a cone balanced on its tip)
    - **Neutral Equilibrium:** CG remains at the same height when tilted. (e.g., a ball on a flat surface)
- An object is more stable if it has a lower centre of gravity and a wider base.

4.9 Equilibrium of Bodies in Liquids

- When an object is immersed in a liquid, it experiences an upward force called upthrust (or buoyant force).
- For a floating object, the upthrust equals the weight of the object.
- For a submerged object that is in equilibrium, the upthrust balances the weight of the object, or it rests on the bottom if its weight is greater than upthrust.

4.10 Flotation

- **Archimedes' Principle:** When an object is wholly or partially immersed in a fluid, it experiences an upthrust equal to the weight of the fluid displaced.
- An object floats if its density is less than or equal to the density of the fluid it is in.

4.11 Density and Relative Density

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- **Density (ρ):** Mass per unit volume. $\rho = \frac{m}{V}$.

  Unit: kg/m³ or g/cm³.

- **Relative Density (Specific Gravity):** The ratio of the density of a substance to the density of a reference substance (usually water at 4°C). It has no units.
  - Relative Density = $\frac{\text{Density of substance}}{\text{Density of water}}$

4.12 Hydrometer

- **Function:** An instrument used to measure the relative density of liquids.
- **Principle:** It floats deeper in less dense liquids and shallower in more dense liquids (due to Archimedes' principle).

4.13 Summary

- Equilibrium means net force and net moment are zero.
- Moments cause turning effects.
- Centre of gravity and base area affect stability.
- Archimedes' principle explains flotation and upthrust.
- Density and relative density are crucial for understanding floating and sinking.

5. Simple Harmonic Motion (SHM)

5.1 Definition of Simple Harmonic Motion (SHM)

- **Definition:** A type of periodic motion where the restoring force is directly proportional to the displacement from the equilibrium position and acts in the opposite direction to the displacement.
- **Key Characteristics:**
  - Periodic (repeats at regular intervals)
  - Oscillatory (moves back and forth about an equilibrium position)
  - Restoring force/acceleration is proportional to displacement ($F \propto -x$ or $a \propto -x$).

5.2 Simple Harmonic Motion from Circular Motion

- SHM can be seen as the projection of uniform circular motion onto a diameter. This analogy helps derive the equations for SHM.

5.3 Speed and Acceleration of SHM

- Displacement (x): $x = A\sin(\omega t)$ or $x = A\cos(\omega t)$, where A is amplitude, ω is angular frequency.
- Velocity (v): $v = \frac{dx}{dt} = A\omega\cos(\omega t)$ (maximum at equilibrium position, zero at extreme ends).
- Acceleration (a): $a = \frac{dv}{dt} = -A\omega^2\sin(\omega t) = -\omega^2 x$ (maximum at extreme ends, zero at equilibrium position).

5.4 Energy of SHM

- **Total Energy (E):** In SHM, total mechanical energy (Kinetic Energy + Potential Energy) is conserved.
- **Kinetic Energy (KE):** $KE = \frac{1}{2} mv^2$ (maximum at equilibrium, zero at extreme ends).
- **Potential Energy (PE):** $PE = \frac{1}{2} kx^2$ or $PE = \frac{1}{2} m\omega^2 x^2$ (maximum at extreme ends, zero at equilibrium).
- $E = \frac{1}{2} kA^2 = \frac{1}{2} m\omega^2 A^2$

5.5 Forced Vibration and Resonance

- **Free Vibration:** An oscillation where the system oscillates at its natural frequency without any external force.
- **Forced Vibration:** An oscillation where an external periodic force is applied to a system, causing it to vibrate at the frequency of the applied force.
- **Resonance:** A phenomenon that occurs when the frequency of the applied forced vibration matches the natural frequency of the oscillating system, resulting in a large amplitude of vibration.
    - **Examples:** Breaking a wine glass with sound, Tacoma Narrows Bridge collapse.

5.6 Summary

- SHM is a specific type of oscillation with a restoring force proportional to displacement.
- Its motion can be derived from circular motion.
- Energy in SHM is conserved, converting between KE and PE.
- Resonance occurs when the driving frequency matches the natural frequency, leading to large amplitudes.

6. Linear Momentum

6.1 Impulse and Momentum

- **Momentum (p):** A measure of the "quantity of motion" of an object. It's the product of mass and velocity.
    - **Formula:** p = mv. Unit: kg m/s or Ns.
    - Momentum is a vector quantity.
- **Impulse (J):** The change in momentum of an object. It's also defined as the product of force and the time interval over which the force acts.
    - **Formula:** J = Δp = FΔt. Unit: Ns or kg m/s.

6.2 Newton's Laws of Motion

- **Newton's First Law (Law of Inertia):** An object at rest stays at rest and an object in motion stays in motion with the same speed and in the same direction unless acted upon by an unbalanced force.
- **Newton's Second Law:** The acceleration of an object is directly proportional to the net force acting on it and inversely proportional to its mass. The direction of the acceleration is in the direction of the net force.
    - Formula: $F = ma$. Alternatively, $F = \frac{\Delta p}{\Delta t}$ (Rate of change of momentum).
- **Newton's Third Law:** For every action, there is an equal and opposite reaction. Forces always occur in pairs.

6.3 Conservation of Linear Momentum

- **Principle:** In an isolated system (where no external forces act), the total linear momentum of the system remains constant.
    - **Formula:** Total momentum before interaction = Total momentum after interaction.
    - m1u1 + m2u2 = m1v1 + m2v2

6.4 Collisions

- **Types of Collisions:**
    - **Elastic Collision:** Both momentum and kinetic energy are conserved. Objects bounce off each other.
    - **Inelastic Collision:** Momentum is conserved, but kinetic energy is *not* conserved (some is converted to heat, sound, deformation). Objects may stick together.
    - **Perfectly Inelastic Collision:** Objects stick together after collision, moving as a single mass. Kinetic energy loss is maximum.

6.5 Applications of Newton's and Conservation of Momentum Laws

- **Rocket Propulsion:** Based on Newton's third law and conservation of momentum (expulsion of hot gases in one direction creates thrust in the opposite).
- **Recoil of a Gun:** When a bullet is fired, the gun recoils backward due to conservation of momentum.
- **Impact Forces:** Understanding impulse helps in designing safety features (e.g., airbags, crumple zones) by increasing the time of impact to reduce the force.

6.6 Inertial Mass and Weight

- **Inertial Mass:** A measure of an object's resistance to changes in its state of motion (its inertia). It's the 'm' in F=ma.
- **Weight:** The force of gravity acting on an object.
    - **Formula:** W = mg, where g is acceleration due to gravity.
    - Weight is a force and depends on gravity; mass is an intrinsic property of the object.

6.7 Summary

- Momentum is mass times velocity, a vector quantity.
- Impulse is change in momentum, also force times time.
- Newton's Laws describe motion and force interactions.
- Conservation of momentum is a fundamental principle, especially for collisions.
- Mass is a measure of inertia, while weight is the force of gravity.

7. Mechanical Energy

7.1 Work

- **Definition:** Work is done when a force causes a displacement of an object in the direction of the force.
- **Formula:** W = Fd cosØ, where Ø is the angle between the force and displacement.
- **Unit:** Joule (J). 1 Joule = 1 Newton-metre (Nm).
- **Conditions for Work Done:**
    1. A force must be applied.
    2. There must be displacement.
    3. The force must have a component in the direction of displacement.

7.2 Mechanical Energy

- **Definition:** The energy associated with the motion and position of an object. It is the sum of kinetic energy and potential energy.
- **Kinetic Energy (KE):** Energy possessed by an object due to its motion.
    - **Formula:** KE = ½mv².
- **Potential Energy (PE):** Stored energy due to an object's position or state.
    - **Gravitational Potential Energy (GPE):** Energy due to an object's height in a gravitational field.
        - **Formula:** GPE = mgh.
    - **Elastic Potential Energy:** Energy stored in a stretched or compressed elastic material (e.g., spring).

7.3 Conservation of Mechanical Energy

- **Principle:** In a closed system where only conservative forces (like gravity or spring force) are doing work, the total mechanical energy (KE + PE) remains constant.
    - KEi + PEi = KEf + PEf

7.4 Machines

- **Definition:** A device that helps us do work more easily or conveniently. They can:
    - Multiply force (e.g., lever, jack)
    - Change the direction of force (e.g., pulley)
    - Change the speed of operation (e.g., gears)
    - Transfer force (e.g., hydraulic press)

7.5 Types of Machine

- **Simple Machines:** Basic mechanical devices for applying force.
  - **Lever:** A rigid bar that pivots about a fixed point (fulcrum). Classes 1, 2, 3.
  - **Pulley:** A wheel with a grooved rim over which a rope or cable passes. Can be fixed or movable.
  - **Inclined Plane:** A flat surface set at an angle to the horizontal.
  - **Wedge:** Two inclined planes joined together.
  - **Screw:** An inclined plane wrapped around a cylinder.
  - **Wheel and Axle:** A large wheel attached to a smaller axle, rotating together.
- **Compound Machines:** Combinations of two or more simple machines.

7.6 Summary

- Work is done when force causes displacement.
- Mechanical energy is the sum of kinetic and potential energy.
- Conservation of mechanical energy applies in ideal systems.
- Machines make work easier by modifying force, direction, or speed.