OCR A Physics A-level

Topic 3.2: Forces in action

Notes

Dynamics

Force

When a **resultant force**, F, acts on a body with mass m, the body will accelerate. The resultant force is related to mass and acceleration by the formula $F = ma$. The SI unit for force is kgms⁻², but the **Newton**, N, is commonly used to measure force. One Newton is defined as the force that will give a mass of 1kg an acceleration of 1 ms⁻².

The weight of an object is defined as the **gravitational force** acting upon the object. To determine the weight of an object, we can used the formula $F = ma$, where the acceleration is the **acceleration of free fall**. On Earth, this is g, but the weight of an object will change if it is taken to another location (e.g. the moon) where the acceleration of free fall is different. The formula for weight is $W = mg$, where m is the mass of the object, and g is the acceleration due to gravity.

Commonly occurring forces:

- Weight – the gravitational force acting on an object, through its centre of mass.
- Friction – the force that arises when two surfaces rub against each other.
- Drag – the resistive force on an object travelling through a fluid (e.g. water or air).
- Tension – the force within a stretched cable or rope.
- Up-thrust – the upward buoyancy force acting on an object when it is in a fluid.
- Normal Contact Force – the force arising when an object rests against another object acting at a 90° angle to the plane of contact.

Free-body diagrams

Free body diagrams can be used to **model all of the forces** that are acting on an object. Each force is represented as a **vector arrow**, scaled to the magnitude of the force they represent, and pointing in the direction that the force acts. Each arrow should be labelled with the name of the force it represents.

Free body diagrams can be used to identify which forces act in which plane, and resolve the net force in a particular direction. Each force is labelled with angles and magnitudes, and by **resolving each force** in to its horizontal and vertical components, the net force in a particular direction can be calculated.

Motion under constant force

If an object experiences a constant net force, then there must be a **resultant acceleration**, determined using F = ma. This motion can be extended to a 2-D plane, such as a slope. The weight of the object acts vertically down, the frictional force between the slope and the object acts along the plane of the slope, in the direction opposing motion, and the normal reaction force acts at a 90° angle to the plane of contact between the object and the slope. It is often easier to

resolve the forces in to the component acting **parallel** to the slope, and the component acting **perpendicular** to the slope, rather than horizontally and vertically.

Non-uniform acceleration

Drag

An object **moving through a fluid** experiences a drag force acting on it. Drag is a **frictional** force that **opposes motion**. In air, it is referred to as air resistance, but it can act in any fluid. The magnitude of the drag force depends on several factors, including the speed of the object, the object's shape and texture, and the density of the fluid. The two most significant factors are the **speed** of the object, and the object's **cross-sectional area**. Drag is proportional to the square of the speed, and it also increases as the cross-sectional area increases.

When an object is falling vertically in a uniform gravitational field, it is often modelled as having only a constant attractive force, equal to *mg,* acting on it. However, in reality there are opposing drag forces that **reduce the net force** acting on an object, and as a result reduce the magnitude of the acceleration. Because drag is proportional to the square of the speed, the drag force will increase until it is **equal in magnitude** to the weight of the object – this results in terminal velocity.

Terminal velocity

As the velocity of a falling object increases during free fall, so does the magnitude of the drag force. As the weight of the object **remains constant**, the net force on the object will be **reduced** until it is 0. Because the acceleration of the object is proportional to the net force acting on it, as the net force reduces, so does the acceleration. At the point where the drag force is equal in magnitude to the weight, and hence the net force on the object is 0, the object will **no longer accelerate** – it has reached **terminal velocity**, and it will **remain at this velocity** for the duration of the fall before reaching the ground.

Techniques to determine terminal velocity

The terminal velocity of a ball bearing in viscous fluid can be determined experimentally. Take a cylinder and fill it with a **viscous liquid**. Hold a ball bearing over the surface of the liquid, and then **release it from rest**. At the same time, start a timer, and **mark the position** of the ball bearing within the tube. When the ball bearing reaches terminal velocity, the distance it has travelled between each time interval will be the same, and so its velocity can be determined.

To increase the accuracy of this experiment, set up a **pulley system** over the tube of fluid, with the ball bearing attached on one end. On the other end, attach a **strip of tape** passing through a **ticker timer**. The ticker timer will produce 50 dots per second on the tape, which will travel at the same speed as the ball bearing. The distance between dots and the time can then be used to determine terminal velocity.

Equilibrium

Moment of a force

The moment of a force can be defined as the **magnitude of the force**, multiplied by the **perpendicular distance** from the force to the pivot, $Moment = Fx$. It is the **turning effect** of the force about an axis or pivot, is measured in Nm. The SI unit is kgm^2s^{-2}.

The distance to be used is the perpendicular distance between the **pivot point** and the **line of action** of the force. It may be necessary to resolve the force or the distance to find the perpendicular component, if the force is not acting perpendicular to the pivot. If the force is acting parallel to the pivot, or on the pivot, it will not produce a moment.

Couple and torque

A couple is a pair of forces, that have **equal magnitude** and **opposite direction**, which are applied to a body **in parallel** with each other and along different lines. They act on the body in order to produce a **rotational force** about the central pivot point. There is **no translational movement**.

The torque of a couple is defined as the product of the magnitude of one of the forces, and the perpendicular separation between the forces. This is equal to the **total moment of the couple**, as each force has a moment of its magnitude multiplied by the perpendicular distance between it and the central pivot, which is half of the total distance between the two forces.

The principle of moments

When a body is in **equilibrium**, the net force acting on it is 0, and its net moment is also 0. The principle of moments is the requirement for the net moment to be 0. It is written as *for a body in equilibrium, the sum of the clockwise moments about any point is equal to the sum of the anti-clockwise moments about the same point*. These two conditions for a body in equilibrium can be used to work out unknown forces or distances.

To do this, first resolve all forces acting on the object in to their horizontal and vertical components. The net force in each direction must be 0. If there are three coplanar forces acting on the body, a triangle of forces can be used. Then, determine the total clockwise and anti-clockwise moment in each direction. Using letters to represent unknown forces or distances, Pythagoras' theorem and the sine and cosine rules can then be used to determine the unknown values.

Centre of mass and centre of gravity

The centre of mass of an object is the point where the **entire weight** of the object appears to act. The centre of mass is the point through which the application of an external force produces **only motion in a straight lin**e, with no rotation. As long as the object is within an external gravitational field, the centre of mass and centre of gravity **coincide**.

A freely suspended object will come to rest with its centre of mass **vertically below** its suspension point, so a plumb line can be used to determine the centre of mass of an object. The object is **suspended at a point**. A plump bob is suspended from a string directly in front of the object, and a straight line along the string is drawn on to the object. The object is then suspended from another point, and another line is drawn. The **intersection** of these lines is the centre of mass of the object.
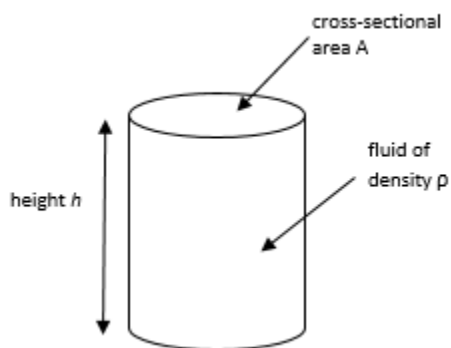
Density and Pressure

Density

The density, ρ, of a substance is defined as the mass per unit volume, $\rho = \frac{m}{V}$. The SI unit for density is kgm^{-3}. When determining the density of an object, scales can be used to measure the mass. The method for measuring volume differs depending on the object. For a liquid, a **cylinder** can be used. For a regular solid, such as a cube, **Vernier callipers** can be used to take accurate measurements of each **side length**, and the volume calculated using the volume formula for that object's shape. For an irregular solid, the object can be placed in water inside a measuring cylinder. The **change in volume** when the object is **fully submerged** is equal to the volume of the object.

Pressure

Pressure, p, is the **normal force** exerted on a surface per unit cross sectional area, $p = \frac{F}{A}$. It is measured in Nm^{-2}, which is called the Pascal (Pa).

An object immersed in a column of fluid experiences pressure due to the weight of the fluid. The pressure at the base of a column of fluid is the same in all directions, and the formula for it is pressure = height of fluid column x density of fluid x acceleration of free fall, $p = h\rho g$. This can be derived by considering a column of fluid and the equation $p = \frac{F}{A}$.

cross-sectional area A

fluid of density ρ

height h

Pressure at base = weight of column / cross-sectional area
$$p = \frac{mg}{A}$$

The mass of fluid in the column equals density x volume,
$$p = \frac{(\rho V)g}{A}$$
and as the height of the column is equal to the column's volume divided by its cross-sectional area, $h = V/A$, this can be substituted in to produce $p = h\rho g$.

Archimedes' principle

When an object is submerged in a fluid, it experiences an **upwards force**, called upthrust. This is because the pressure at the bottom surface of the object is greater than at its top surface.

Archimedes' principle is: *The upthrust exerted on a body immersed in fluid, whether partially or fully submerged, is equal to the weight of the fluid that the body displaces.*

An object will sink if the upthrust acting up is smaller than the weight acting down. For a **floating object**, the **weight is equal to the upthrust**, so the object's weight is equal to the weight of the fluid it displaces.