# 2. MOTION

### Concept of Motion

In strict terms, if the position of a material system as measured by a particular observer changes with respect to time, that system is said to be in motion with respect to the observer. Absolute motion, then, has no significance, and only relative may be defined. In this context, frame of reference is a crucial concept. For instance, the relative motion of a train will seem different from the ground than from the train. It is important to know where you are.

There are various kinds of motion-one dimensional, two-dimensional and three-dimensional. A train running on a railway track, or a bus on a road, is examples of motion in one dimension. A carom coin or a billiard ball in motion; are examples of motion in two dimensions over a plane. Objects moving on the surface of the earth over distances comparable to the earth's radius are examples of motion in two dimensions, but not over a plane. Finally, the most general motions we can consider are of objects moving in space, involving all the three dimensions.

### Rectilinear Motion

If a body moves so that every particle of the body follows a straight-line path, then the motion of the body is said to be rectilinear. Rectilinear motion is an idealised form of motion which rarely, if ever, occurs in actual experience, but it is the simplest imaginable type of motion and thus forms the basis for the analysis of more complicated motions. However, many actual motions are approximately rectilinear and may be treated as such without appreciable error. For example, a ball thrown directly upward may follow for all practical purposes, a straight-line path. The motion of a high-speed rifle bullet fired horizontally may be essentially rectilinear for a short length of path, even though in its larger aspects the ideal path is a parabola. The motion of an automobile travelling over a straight section of roadway is essentially rectilinear if minor variations of path are neglected. The motion of a single wheel of the car is not rectilinear, although the motion of the centre of mass of the wheel may be displayed graphically by plotting position against time.

**Distance and Displacement.** The distance that an object moves is an important thing to know when describing motion. Displacement is the distance travelled by a body in a particular direction. Distance is simply the magnitude of the displacement.

**Speed and Velocity.** When the body covers equal distances in equal intervals of time, we say that the motion is uniform.

The speed of a body is the distance covered by it in a unit time interval.

$$\text{Speed} = \frac{\text{total distance moved by a body}}{\text{time taken}}$$

If the distance is measured in metres and time in seconds, the unit of speed will be metre/second (SI unit of speed).

We often use "speed" and "velocity" interchangeably and sometimes we are justified in doing so. However, speed is not always the same thing as velocity. Strictly speaking, *speed* measures the rate at which we travel, while *velocity* involves not only speed but also direction. In rectilinear motion, or motion in a straight line, velocity and speed are practically synonymous, since only one direction is involved. In motion along a curve, however, the direction of the velocity is always different from the actual path along which the moving object travels.

The units of velocity are the same as those of speed. Thus if a body undergoes a displacement s is a time-interval t, then its velocity v is given by $v = s/t$. The velocity of a body at a given instant of time is known as its *instantaneous velocity.* Velocity is not to be confused with speed. It includes the speed and the direction of motion at that same instant of time.

The simplest type of motion is rectilinear motion at constant speed. If the speed of an automobile is constant, and it covers 4 km in four minutes, it will have travelled at the rate of 60 km per hour at each and every moment of the hour. What we really mean is that its average speed is 60 km per hour. The average speed is equivalent to the total distance divided by the elapsed time.

$$\text{Similarly. Average velocity} = \frac{\text{total displacement}}{\text{total time taken}}$$

**Acceleration.** Changes in speed are described in terms of the rate at which we changes our speed. The velocity of a body changes due to change in its speed or direction or both.

**Acceleration** is defined as the rate of change of velocity. If the velocity of a body changes from to $u$ to $v$ in a time interval t, then its acceleration a is given by

$$a = \frac{\text{change in velocity}}{\text{time}}$$

Acceleration is a vector quantity. In general the velocity of a body can change with time. Consider the case in which velocity of the body changes at a uniform rate i.e., the amount of increase of decrease in the velocity in equal intervals of time is always the same. Such a motion is called uniformly accelerated motion. One example of uniformly accelerated motion is the motion of the cycle going down an inclined road when the rider is not pedaling and wind resistance is negligible. The change in velocity in successive equal intervals of time may not be the same and then the body is said to be in non-uniformly accelerated motion.

**Acceleration due to Gravity.** Freely falling bodies move with constant acceleration. The force bringing this about is the gravitational attraction of the earth. The force of gravitation differs at various locations. It is stronger, for example, at the poles than at the equator.

The gravitational attraction of the earth causes all objects to fall with an acceleration of about 9.8 metres per second per second ($9.8 m/s^2$). The exact rate will depend on the gravitational force at a given part of the earth's surface. Suppose we drop a ball from the top of a skyscraper. At the end of 1 second, the ball will have attained a velocity of 9.8 metres per second. At the end of 2 seconds, the velocity will be 19.6 metres per second, at the end of 3 seconds, 29.4 metres per second, and so on. In this case, of course, we have positive acceleration. Actually, the velocity in each case would not be quite so great as we have indicated, because the air resistance would hold the ball back by a slight amount. If an object is cast straight up in the air, the force of gravity will decelerate it (decrease its velocity) at the rate of 9.8 metres per second per second.

**Equations of Motion.** There exist some relations between velocity, acceleration and the time intervals during which we study the motion of a body. These relations are called equations of motion.

Let a body be moving with initial velocity, u, under a uniform acceleration, a. Suppose it undergoes a displacement, s, in a time interval, t. At the end of the time interval, let its velocity be v. The relationship between *u, v, a, s* and *t* can be given by the following equations.

| | |
|---|---|
| $v = u + at$ | u = initial velocity (m/s) |
| $s = \frac{1}{2}(v + u)\,t$ | v = final velocity (m/s) |
| $s = ut + 1/2at^2$ | a = acceleration ($m/s^2$) |
| $v^2 = u^2 + 2as\ t$ | s = displacement (m) |
| | t = time taken (s) |

If the values of three of the quantities u, v, s, a and t are known, you can calculate the value of fourth quantity by substituting the numbers in appropriate equation.

**Motion in two and three dimension**

**Vectors and Scalars** When we want to describe the motion of objects over two-dimensional plane or in three dimensional space, the idea of direction becomes more important than in one dimension. This is because there are many more directions in two and three dimensions than just the two possibilities in one dimension. To deal with position, velocity and acceleration in two and three dimensions, new mathematical quantities called *vectors* have to be used.

- Those quantities that have magnitude and direction are called vector quantities or vectors. Example-displacement, acceleration, force, etc.
- Those quantities that have magnitude only, are called scalar quantities or scalars. Example–distance, area, work, etc.

**Vector and Scalar Addition**

**Scalar quantities** A scalar quantity has size but no direction. Examples include mass, volume, temperature, time wavelength and speed. Scalar quantities are added just as any two numbers can be added.

**Vector quantities** A vector quantity has size and direction. Examples include velocity, force, acceleration, momentum and weight. When several vectors act together from a point, their combined effect is called their resultant. The resultant is a single vector that can replace those several vectors. For example, two forces of 3 N and 4 N can pull in the same direction, oppose one another or work together at a certain angle.

In (a) the resultant is 1 N :

In (b) the result is 7 N

The vectors in (c) cannot be added together in such a simple way. We use the parallelogram low.

**Force**

The word force generally denotes a push or a pull. Let us see what a force can do. In a hockey match a player hits a stationary ball with his stick and the ball starts moving in straight line. Another player deflects the moving ball in another direction and yet another player stops the ball. Sometimes a player simply pushes the moving ball to increase its speed without changing its direction. In all the cases the player apply force with their sticks. Thus we can say that force produces (or tends to produce) change in a body's state of rest or of uniform motion in a straight line.

Consider what happens when more than one force are exerted on a body. If two persons pull an object in the same direction with equal force, the object will have twice the acceleration than if one pulled alone. If, however, the two pulled with equal force but in opposite directions, the object will not accelerate because the oppositely directed equal forces cancel one another and the **net force** in zero.

It should be noted that zero net force, and therefore, zero acceleration does not necessarily imply zero velocity. Zero acceleration means that the object maintains its velocity, neither increasing nor decreasing. If the object is at rest, it remains at rest under the action of zero net force.

**NEWTON'S LAWS OF MOTION**

**Force and Inertia** It is an observable fact that inanimate objects at rest do not start moving of their own accord. Effort is required to move them. When we push or pull a table, for instance, we are exerting a force on the table. It is the force exerted by a bat that makes the ball move.

**Inertia** is the inherent property of objects to remain at rest unless acted upon by a force. Also the property of a body to keep moving with constant velocity in the absence of any force acting on it is its inertia. Gelileo discovered the law of inertia. Bodies moving with uniform velocity would maintain this state of motion forever in the absence of forces acting upon them. Continuing his investigations on the basis of Galileo's findings, Issace Newton formulated his three laws of motion which form the foundation of mechanics.

**Newton's First Law of Motion** Newton's first law of motion is a reformulation of Galileo's law of inertia and states: *Every body continues in its state of rest of uniform motion in a straight line unless compelled by some external force to act otherwise.*

The state of rest and that of uniform motion are both examples of zero acceleration. They are, as a matter of fact, the only examples of zero acceleration. The first law tells us therefore that in order to change such a state of motion we need a force. If a body is at rest, we will have to apply a force on it to make it move. If a body is moving with constant speed in a straight line and if we want to change its speed, we will have to apply a force on it to make it move. If body is moving with constant speed we will have to apply a force in the direction of motion. If we just want to change the direction of motion, we still need a force acting normal to this direction.

**Momentum** The momentum of an object is defined as follows:

momentum = mass X velocity

With mass measured in kg and velocity in m/s, momentum is measured in kg m/s. like force and velocity, momentum is a vector quantity.

**Force and momentum** There is an important relationship between momentum and force. It emerges if you consider the equation *F=ma* in more detail. Take the case of the spacecraft.

To begin with, the spacecraft has a velocity *u*. its rocket motor is fired briefly, so that a force *F* acts on the spacecraft for a time t. As a result, the velocity is increased to *v*.

Then, the acceleration a of the spacecraft

$= \frac{\text{gain in velocity}}{time}$

$= \frac{v-u}{t}$

So : *F* = *ma* can be written $F = m\left(\frac{v-u}{t}\right)$

Multiplying out the brackets : $F = \left(\frac{mv-mu}{t}\right)$

*mu* is the momentum the spacecraft had originally; *mv* is the momentum it ends up with after the force has acted. The equation above can therefore be expressed in words:

$\text{force} = \frac{\text{gain in momentum}}{\text{time}}$

or force = rate of change of momentum

It follows, for example, that a force of 1 N, applied to an object, will make its momentum increase by 1 kg m/s, each second.

**Newton's Second Law of Motion** Force acting on a body causes changes in its position or state of uniform motion; the acceleration produced is the effect. Newton's second law of motion relates these two quantities–force and acceleration. It states that the force as an object is directly proportional to the product of the mass of the object and its acceleration.

The law is also stated as: The rate of change of momentum of an object is directly proportional to the force acting, and takes place in the direction in which the force acts.

If a constant force is being considered, the law can be written in the following form:

The above proportions show that there are two ways of regarding a force. There are also two ways of defining the newton: 1 newton is the force which gives a mass of 1kg an acceleration of 1 $m/s^2$ or 1 newton is the force which cause an object to gain momentum at the rate of 1kg m/s per second [1kng $m/s^2$].

**Impulse**

As: force =

It follows that : force X time = gain in momentum

In symbols: Ft = mv-mu

When a force acts for a given time, the quantity force X time is called an Impulse. If force is measured in N and time in s, impulse is measured in Ns or kg m/s – both amount to the same thing.

Newton observed that when a given force acted for a given time on any object, a larger mass gained less velocity than a smaller one, but the quantity mass X velocity increased by the same amount in every case. It was this observation that led him to define momentum (though he called it a 'quantity of motion') and to put forward his second law of motion.

**Newton's Third Law of Motion** Newton's third law of motion states : To every action there is always an equal and opposite reaction. It may be noted that action and reaction which occur in pairs act on different bodies. If they acted on the same body, the resultant force would be zero and there could never be accelerated motion.

When one body exerts a force on a second body, the second body at the same time exerts a force on the first body. It is impossible to have a single isolated force. Furthermore, the above two forces are found to be equal in magnitude and opposite in direction. For example, if we try to push a heavy door the force we exert on it accelerates it as it opens. Simultaneously we feel the force exerted by the door on us impeding our movement.

**Conservation of Momentum** An important consequence of Newton's third law, in combination with the second, is the law of conservation of momentum which states: When two or more bodies interact with one another, their total momentum remains constant, provided no external forces are acting.

**Rocket propulsion** One of the spectacular instances in which Newton's third law or the momentum of conservation manifests itself is the flight of a rocket. Here gases produced by the combustion of fuel are ejected and the reaction to this generates the thrust on the rocket. Here is an example in which the mass of the body keeps changing, as the gas escapes from the rocket. The exhaust gases move with an approximately constant velocity with respect to the rocket. If the rate of ejection of gas is constant during firing, then the rate of change of momentum will also be constant. However, as the mass of the rocket keeps decreasing due to the escaping mass of the gases, the acceleration will not remain constant. Both the velocity and the acceleration of the rocket will increase.

**Newton's Laws and Circular Motion** The third law of Newton always applies to curvilinear motion. When we whirl a stone around by a string, our hand exerts an inner pull–a centripetal force—upon the stone to keep it moving around in a curve. Centripetal force is the inward force required to keep a particle or an object moving in a circular path. It can be shown that a particle moving in a circular path has an acceleration towards the centre of the circle along a radius. This radial acceleration, called the centripetal acceleration, is such that, if a particle has a tangential velocity *v* when moving in a circular path of radius R, the centripetal acceleration is $v^2/R$. If the particle undergoing the centripetal acceleration has a mass M, then by Newton's second law of motion the centripetal force $F_c$ in the direction of the acceleration is expressed by the equation below,

$$F_c = Mv^2/R = MRù^2$$

**Satellites in orbit** Gravitational pull provides the centripetal force needed to make a satellite follow a circular path around the Earth. When a satellite is put into a circular orbit, its speed is carefully chosen so that its weight supplies exactly the right amount of centripetal force to keep it in that particular orbit. For a satellite orbiting the Earth just above the atmosphere, the orbital speed required is about 8000m/s (29000 kilometres per hour), and the 'burn time' of the launch vehicle's engines has to be controlled very accurately so that the correct speed is achieved.

## FRICTION

Friction is the name given to the force that tries to stop materials sliding across each other. There is friction between your hands when you rub them together, and there is friction between your shoes and the ground when you walk along. Friction is caused in two ways. First, rougher surfaces have ridges and bumps which catch in each other. Second, all materials are made up of tiny particles called molecules, and these have a tendency to stick to each other when materials are pressed together.

**Static and Dynamic Friction** When a side way force is applied to the block placed on the bench, we see that as the force is increased the friction between the block and the bench rises, reaching its greatest value just as the block is about to slide. This steady speed, the friction is slightly less than before, since the sliding or dynamic friction is less than the static friction. It is easier to slide two surfaces across each other than it is to start them sliding in the first place.

**Fluid Friction.** Gases and liquids are called fluids. There is friction whenever an object moves through a fluid. Air resistance is an example of fluid friction. When a car is travelling fast on a motorway, air resistance is the largest of all the frictional forces opposing its motion. Nowadays, car bodies are designed so that air resistance is reduced to a minimum.

**Rolling Friction** The wheel has been considered one of the greatest inventions. It is much easier to cart a heavy load on a trolley with wheels than to push it. Wheels are used extensively in our daily lives for transportation, since they save labour to a great extent. This is because of the reduced friction during rolling as compared to sliding. When a body rolls over a surface the frictional force developed is known as the rolling friction.

**Importance of Friction** Many everyday activities like walking or gripping objects are carried out through friction, and most people have experienced the problems that arise when there is too little friction and conditions are slippery. However, friction is serious nuisance in devices that move continuously, like electric motors or railroad trains, since it constitutes a dissipation of energy, and a considerable proportion of all the energy generated by humans is wasted in this way. Most of this energy loss appears as heat, while a small proportion induces loss of material from the sliding surfaces, and this eventually leads to further waste, namely, to the wearing out of the whole mechanism.

**The Moment of a Force** An object is accelerated when acted upon by an unbalanced force and the acceleration is in the direction of the applied force. However, there are situations when a body may be fixed at a point (a door hinged along one side) or along an axis (a wheel free to rotate about a fixed axis). We find that the turning effect of a force increases as the distance of the point of its application from the axis of rotation increases. The turning effect of a force depends upon (i) the perpendicular distance between the point of application of the force and the axis of rotation, called the force-arm or the lever-arm; (ii) the magnitude of the applied force. The turning effect of a force is called moment of the force or torque. The moment of the force is given by the product of the magnitude of the force and the length of the corresponding force-arm. The SI unit of torque is newton- metre. If $F$ be the magnitude of the force and $l$ be the length of the force-arm, than the moment of force is given by $F X l$. If a force $F_1$ acting at a distance $l_1$, from the point of rotation is balanced by a force $F_2$, acting at a distance $l_2$ then

$$F_1 X l_1 = F_2 X l_2.$$

This principle of moments is utilised in the construction of physical balances. The turning effect of a small force can be increased by applying it at a large distance.

Two equal and opposite forces acting at different points of a body are said to form a couple. The moment of a couple is given by the magnitude of the force and the perpendicular distance between them. The action of a couple tends to rotate the object in one direction. If two equal and opposite couples act simultaneously on an object, they balance each other and no rotation is produced. This is similar to the case in linear motion when two equal and opposite forces acting at a point produce a zero resultant.