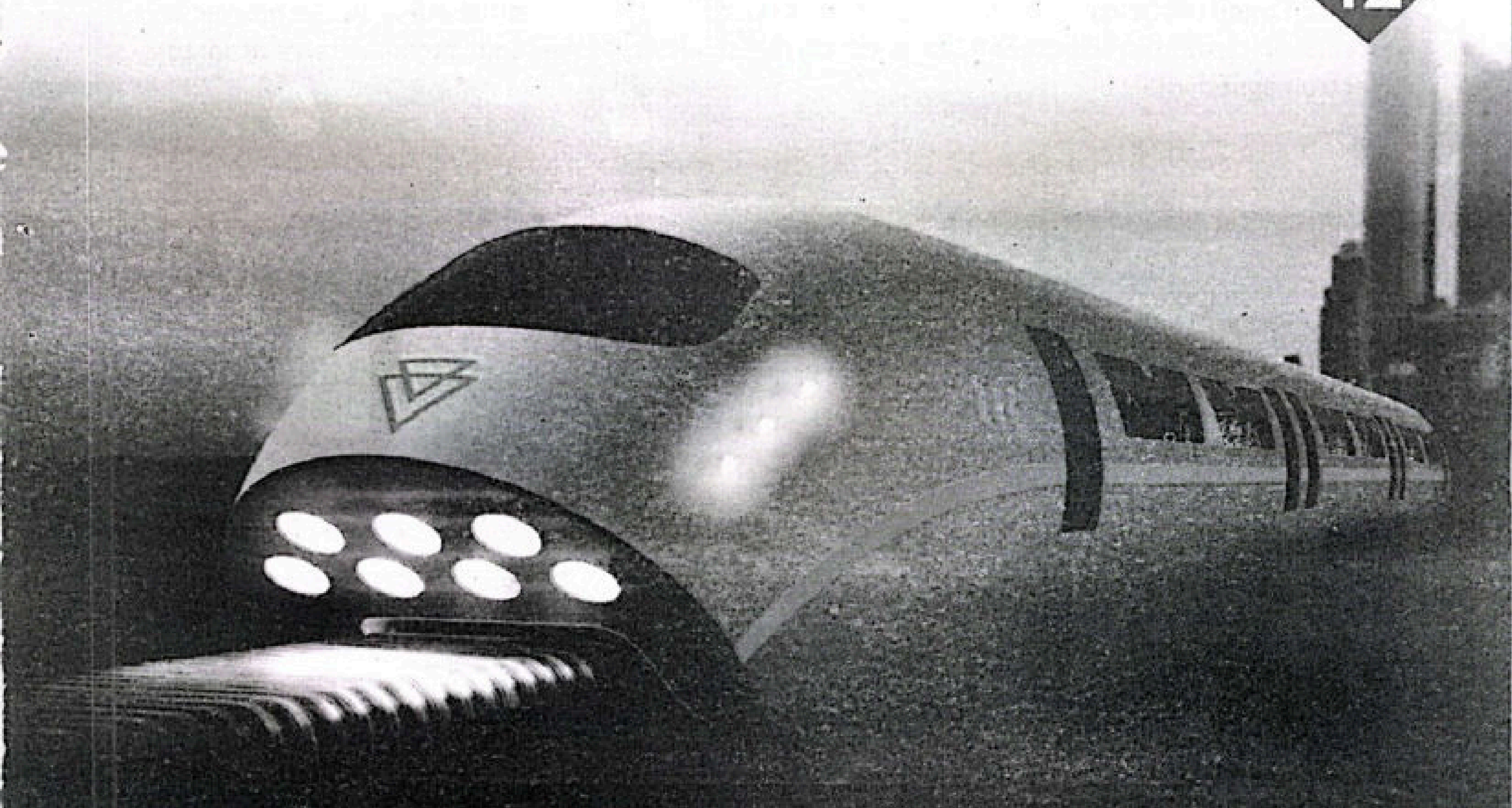
ELECTROMAGNETISM

UNIT 12



Student Learning Outcomes (SLOs)

The students will:

- Define and explain magnetic fields.
- state that a force might act on a current-carrying conductor placed in a magnetic field.
- use the equation $F = BIL \sin\theta$ [with directions as interpreted by Fleming's left-hand rule to solve problems].
- Define magnetic flux density [as the force acting per unit current per unit length on a wire placed at right angles to the magnetic field]
- use $F = BQV \sin\theta$ to solve problems.
- describe the motion of a charged particle moving in a uniform magnetic field perpendicular to the direction of motion of the particle.
- explain how electric and magnetic fields can be used in velocity selection.
- sketch magnetic field patterns due to the currents in a long straight wire, a flat circular coil and a long solenoid.
- state that the magnetic field due to the current in a solenoid is increased by a ferrous core.
- explain the origin of the forces between current-carrying conductors and determine the
- direction of the forces.
- define magnetic flux [as the product of the magnetic flux density and the cross-sectional area perpendicular to the direction of the magnetic flux density].
- use $\emptyset = BA$ to solve problems.
- use the concept of magnetic flux linkage.
- explain experiments that demonstrate Faraday's and Lenz's laws. [(a) that a changing magnetic flux can induce an e.m.f. in a circuit, (b) that the induced e.m.f. is in such a direction as to oppose the change producing it, (c) the factors affecting the magnitude of the induced e.m.f.
- Use Faraday's and Lenz's laws of electromagnetic induction to solve problems.
- explain how seismometers make use of electromagnetic induction to the earthquake detection [specifically in terms of: (i) any movement or vibration of the rock on which the seismometer rests (buried in a protective case) results in relative motion between the magnet and the coil (suspended by a spring from the frame.) (ii) the emf induced in the coil is directly proportional to the displacement associated].

Magnetism is the study of how a magnetic field, generated by a moving charged particle, affects other charged particles or permanent magnets. Electromagnetism is the study of the magnetic effects of current. In this unit, we shall study about the laws and phenomena related to electromagnetism.

12.1 MAGNETIC FIELDS

The magnetic field is the region or space surrounding a magnet in which a compass needle, a small magnet, or a piece of ferromagnetic material, and a moving charged particle can experience a magnetic force. A permanent bar magnet, a current-carrying conductor, a fluctuating electric field and a moving charge can create a magnetic field. The magnetic force between magnets acts over a distance. They apply force due to interaction of their magnetic fields (i.e. non-contact force).

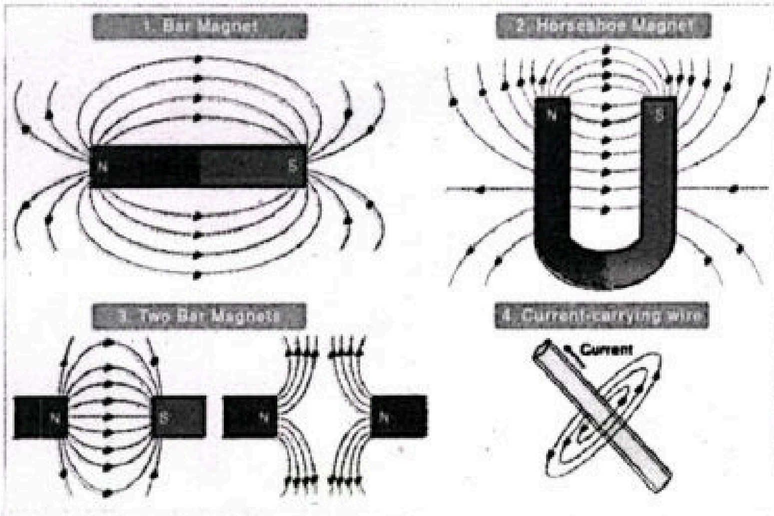


Figure 12.1 (a): Magnetic field.

Michael Faraday proposed an alternative explanation. He suggested that each magnet sets up a magnetic field in space around it, as shown in Fig. 12.1 (a). When you place another magnet in that field, it responds to the field at its own location. This interaction of fields is the cause of force between them. Interaction of field lines can be drawn in the form of picture. As we have already discussed in earlier classes, gravitational fields exert the force of gravity on other masses. An electric field exists around charges, so that other charges in this region will experience an electric force. Similarly, magnetic fields exert force on other magnets, like compass needles, magnetic materials, and moving electric charges.

For Your Information

The magnetic field was studied in 1269 by Petrus Peregrinus de Maricourt, with John Mitchell claiming magnetic poles repel each other in 1750. Charles-Augustin de Coulomb confirmed Earth's magnetic field in 1785, and Simeon Denis Poisson presented the first magnetic field model in 1824.

You can easily visualize the magnetic field of a magnet by sprinkling iron filings near the magnet, as shown in the Fig. 12.1 (b). The iron particles become magnetized in a magnetic field and stick together along magnetic field lines. One key distinction between magnetic field lines and electric field lines is that the magnetic field lines

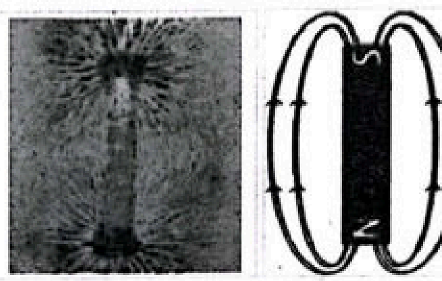
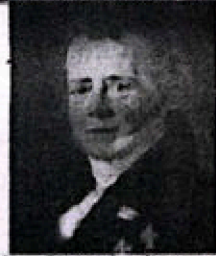


Figure 12.1 (b): Magnetic field of a magnet by sprinkling iron filings.

form complete loops. Magnetic field lines exit from the north pole and enter the south pole, as shown in Fig. 12.1 (b). But inside the magnet, the direction of magnetic field lines goes from the south pole to the north pole. This is the reason why there are no magnetic monopoles, which means tnat the North and South poles do not exist independently. The magnetic field at the poles of the bar magnet is strongest.

Hans Christian Oersted (1777-1851)



In April 1820, Orsted discovered that a magnetic needle aligns itself perpendicularly to a current-carrying wire. That was definite experimental evidence of the relationship between electricity and magnetism.

Properties of Magnetic Field Lines

1. Magnetic field lines never cross each other.
2. The density of the magnetic field lines indicates the strength of the magnetic field.
3. Magnetic field lines always form closed loops.
4. Magnetic field lines always start from the north pole and enter at the south pole.
5. Like magnetic poles repel, and unlike magnetic poles attract each other.

12.1.1 Magnetic Field Due to Current in a Long Straight Wire

In 1820, Hans Oersted first described the magnetic field due to current in a wire.

Experiment

Take a piece of copper wire that passes vertically through a horizontal piece of card board, as shown in Fig. 12.2. Place small magnetic compass needles on the card board along a circle with the centre at the wire. All the compass needles point in the direction of north-south. When a heavy current passes through a wire, the compass needles set themselves along the tangent to the circle. Circular magnetic field in anti-clockwise direction is produced around current carrying conductor, as shown in Fig 12.3 (a).

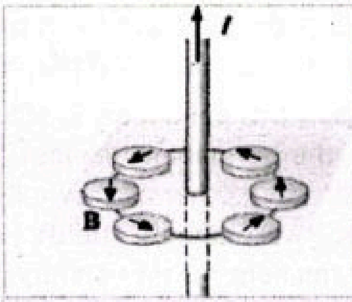


Figure 12.2: Compass needle pointing in the direction of magnetic field.

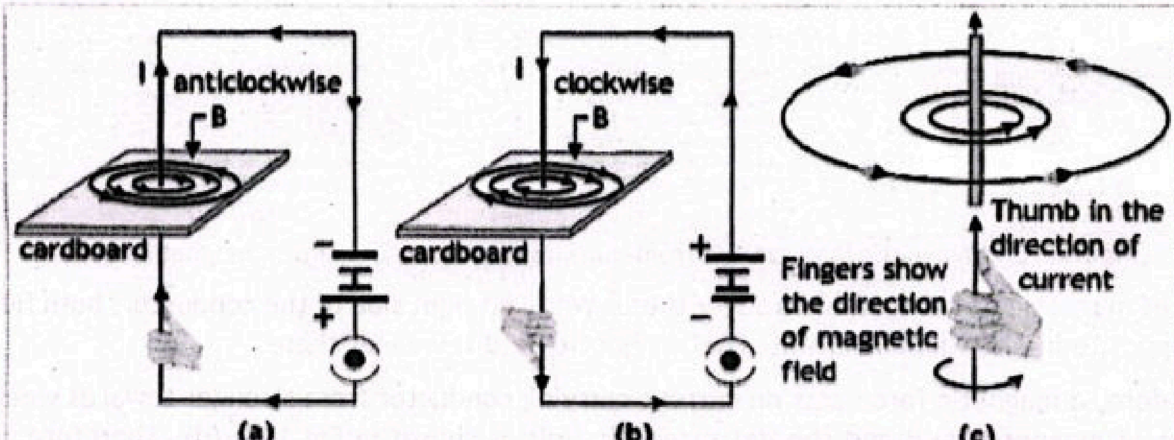


Figure 12.3: Circular magnetic field is produced around current carrying conductor.

When we reverse the direction of the current, the direction of **B** is also reversed in clockwise direction, as shown in Fig 12.3(b). If the current through the wire is stopped, all the needles will again point in the north-south direction. We conclude that

- A magnetic field is set up only around a current-carrying conductor.
- The lines of forces are circular, and their direction depends upon the direction of the current.

Direction of Magnetic Field: The direction of the magnetic field can be determined by the right-hand rule, as shown in Fig. 12.3 (c). It can be stated as:

If the wire is grasped in the fist of the right hand with the thumb pointing in the direction of (conventional) current, then the curled fingers indicate the direction of magnetic field.

12.2 MAGNETIC FORCE ON A CURRENT-CARRYING CONDUCTOR IN UNIFORM MAGNETIC FIELD

Consider a straight-current carrying conductor, as shown in Fig. 12.4 (a) having concentric circular magnetic field lines in clockwise direction due to the current flow into the page. Fig. 12.4 (b) is representing magnetic field of a permanent magnet (From North to South pole).

When this conductor is placed in external magnetic field of the permanent magnet, their magnetic fields interact with each other as shown in Fig. 12.4 (c). We can see that the two magnetic fields i.e. external magnetic field of permanent magnet and magnetic field of current carrying conductor support each other on left side of the conductor

> **For Your Information**
> A current-carrying wire in a magnetic field moves because a force acts on it. The magnetic field making the wire move is called a catapult field. The catapult field is due to the combined effect of the magnetic field of current-carrying wire and magnetic field of bar magnet. Fig. 12.4 shows the separate fluxes, and how they combine to form a catapult field.

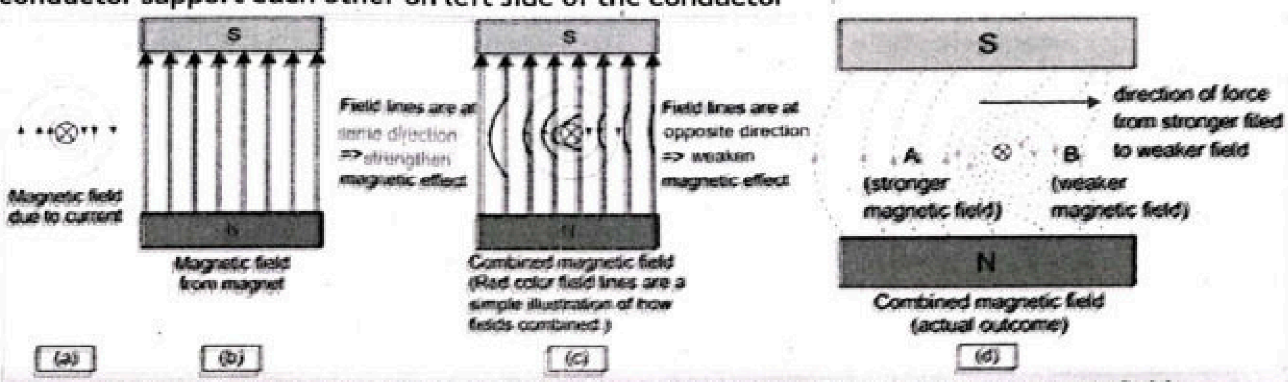


Figure 12.4: Magnetic force on a current-carrying conductor in uniform magnetic field.

and net magnetic field becomes stronger there. While on right side of the conductor, both fields are opposite in direction. Therefore, net magnetic field is weaker there.

Therefore, a magnetic force acts on current carrying conductor from stronger towards weaker region of magnetic field and the net magnetic field is shown in Fig 12.4 (d). Therefore, the conductor tends to move towards the right where the net magnetic field is weak.

The magnetic force on the conductor will be directed toward the right, perpendicular to both the length of conductor and the external magnetic field.

Derivation: Consider a conductor with length L carrying current I placed on two conducting rails in uniform magnetic field B, as shown in Fig. 12.5. When magnetic force acts on the conductor, it begins to move on the conducting rails in the direction of force. From different experiments, we conclude following points for force experienced by the conductor.

i) Magnetic force on the conductor is directly proportional to current flowing in it.

$$F \propto I$$

ii) Magnetic force on the conductor is directly proportional to it length.

$$F \propto L$$

iii) Magnetic force on the conductor is directly proportional to strength of external magnetic field.

$$F \propto B$$

iv) Magnetic force on the conductor is directly proportional to sine of angle between length of the conductor and magnetic field.

$$F \propto \sin\theta$$

Where θ is angle between B and L, combining the above four relations, we get:

$$F \propto I\,L\,B \sin\theta$$

Or $$F = K\,I\,L\,B \sin\theta$$

Where, k is the proportionality constant and in SI system its value is equal to 1.

$$F = BIL \sin\theta \quad \text{\_\_\_\_\_\_} \quad (12.1\ a)$$

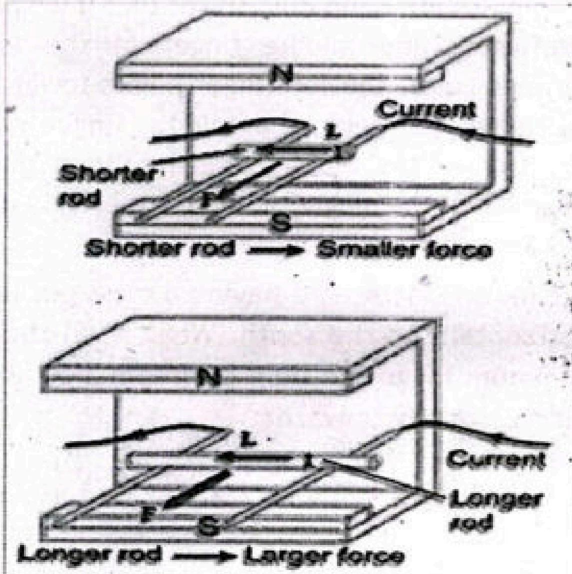


Figure 12.5: Conductor carrying a current, placed on two conducting rails in uniform magnetic field.

In vector form, it can be expressed as:

$$F = I\,L\,B \sin\theta\ \hat{n}$$

$$F = I\,(L \times B) \quad \text{\_\_\_\_\_\_} \quad (12.1\ b)$$

The magnetic force is perpendicular to both the length of the conductor and magnetic field.

Maximum Force: This magnetic force F is maximum when $\theta = 90^0$, i.e., when the conductor is placed perpendicular to the magnetic field.

Then, $$F_{max} = I\,L\,B \sin 90^0$$

$$F_{max} = I\,L\,B\,(1) = I\,L\,B$$

$$F_{max} = I\,L\,B$$

Convention to represent direction

To show the direction, sometime we use Dot (•) and cross(×):
Dot (•) represents **out of the plane.**
cross (×) represents **into the plane.**

Minimum Force: This magnetic force F is minimum (zero) when the conductor is placed parallel (i.e., $\theta = 0^o$) or antiparallel (i.e., $\theta = 180^o$) to the magnetic field.

For $\theta = 0^o$, $F_{min} = I\,L\,B \sin 0^o$

F_{min} = I L B (0) = 0

For θ = 180°, F_{min} = I L B sin180° = 0

Thus, it is concluded that a current-carrying conductor will not experience force in a magnetic field if the angle between **B** and **L** is 0° or 180°.

FLEMING'S LEFT-HAND RULE

Fleming's Left-Hand Rule states that if we position our thumb, forefinger, and middle finger of the left-hand mutually perpendicular, the forefinger points towards the direction of the magnetic field, the middle finger points towards the direction of the electric current, then thumb indicates the direction of the magnetic force experienced by the conductor, as shown in Fig. 12.6.

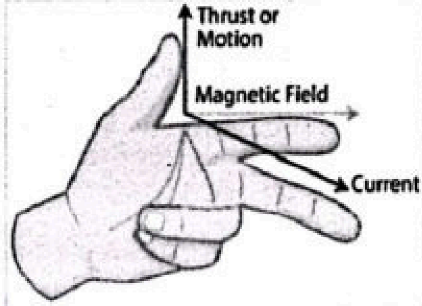
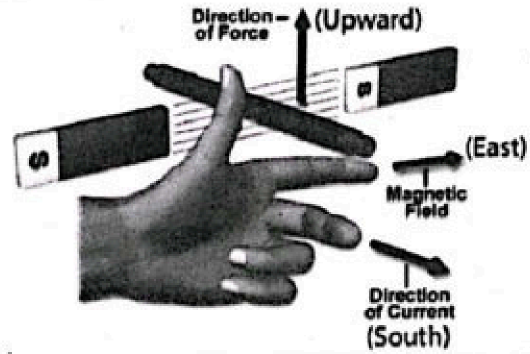


Figure 12.6: Fleming's Left-Hand Rule.

Example 12.1: A wire having a mass per unit length of 0.400 g cm^{-1} carries a 5.0 A current horizontally to the south. What is (a) the direction of force and (b) the magnitude of the minimum magnetic field perpendicular to the length of the conductor needed to lift this wire vertically upward?

Given: $\frac{m}{L}$ = 0.400 g cm^{-1} = $\frac{0.400\quad 10^{3}}{1\quad 10^{2}}$ = 0.04 kg m^{-1}

I = 5.0 A



Solution: According to given condition, the magnetic force must be upward to lift the wire. For current in the south direction, the magnetic field must be towards east to produce an upward magnetic force, as shown by the Fleming's left-hand rule in the figure.

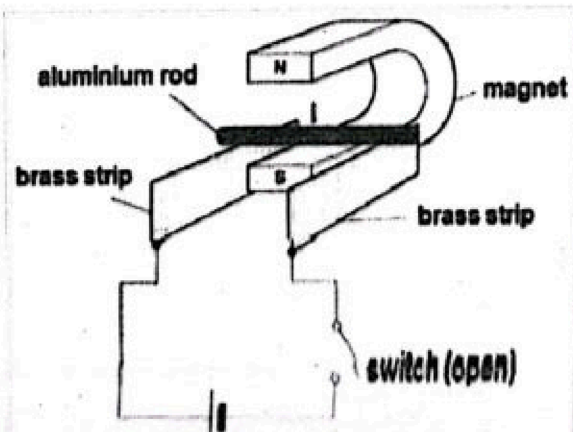
$F_B = ILB\sin\theta$ with $w = mg$

In order to lift the wire, the magnetic force must be equal to the weight of the wire.

$$F_B = F_g$$

$$ILB\sin\theta = mg \quad \text{or} \quad B = \left(\frac{m}{L}\right)\frac{g}{I\sin\theta}$$

$$B = (0.04)\left(\frac{9.8}{5.0\,A \times \sin 90^\circ}\right) = 0.0784\ T$$



Assignment 12.1

The figure shows a light aluminium rod resting between the poles of a magnet. A current is passed through the rod from two brass strips connected to a power supply. (a) On the figure, draw the direction of the current when the switch is closed (b) State which way the rod

moves when the switch is closed. Give a reason for your answer. (c) State the effect on the movement of the rod when:
(i) the current is increased.
(ii) the current is reversed.

12.3 MAGNETIC INDUCTION or MAGNETIC FLUX DENSITY

A current-carrying conductor positioned at right angle to a magnetic field will experience a magnetic force that can be used to quantify magnetic flux density.

The formula $B = \frac{F}{IL}$ determines the flux density B for a uniform magnetic field. Where F is the force acting on a current carrying conductor, I is the magnitude of current, and L is the length of the conductor in the uniform magnetic field with magnetic flux density B.

The SI unit of magnetic flux density (or) magnetic induction is tesla (T).

Since $B = \frac{F}{IL}$ and $1\,T = = \frac{1N}{(1A)(1m)\sin 90^0}$

If a 1 m-long conductor carrying a current of 1 A, placed perpendicular to a magnetic field, experiences a force of 1 newton, then the magnetic induction is one tesla.

Another CGS unit used for B is gauss (G). The relation between tesla and gauss is

$1\,T = 10000\,G$ OR $1\,T = 10^4\,G$ OR $1\,G = 10^{-4}\,T$

Magnetic field is a vector quantity.

12.4 MAGNETIC FORCE ACTING ON MOVING CHARGE IN UNIFORM MAGNETIC FIELD

It is experimentally verified that moving charges produce magnetic fields around them. When moving charged particles enter in an external magnetic field of the permanent magnet, the magnetic field of the moving charge interacts with the magnetic field of the permanent magnet. Due to interaction of both fields, net magnetic field becomes stronger on one side of the charge than its other side (just like explained earlier for force on current carrying conductor placed in magnetic field). Therefore, magnetic force acts on the moving charge particle from stronger to weaker magnetic field region and deflect from its path, as shown in Fig 12.7. It has been seen that the charged particle deflects from its path, perpendicular to both magnetic fields and velocity, because a net force is acting on it perpendicular to B and v. When a charge enters into the magnetic field, it experiences a force, provided that the following conditions are fulfilled:

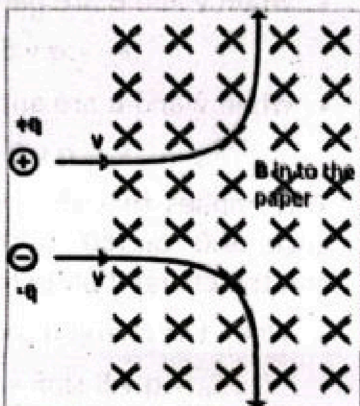


Figure 12.7: Trajectories of charged particles in a magnetic field.

- The charge must be moving, because no magnetic force acts on a stationary charge.
- The velocity of the moving charge must have a component that is perpendicular to the direction of the magnetic field.

Consider a positive point charge '+q' moving with velocity 'v' making an angle 'θ' with the magnetic field 'B', as shown in the Fig. 12.8.

The *force experienced* by a positive point charge is mathematically expresses as:

$$F_B = q\,(v \times B) \qquad \text{\_\_\_\_\_\_\_\_} \ (12.2)$$

Magnetic force F_B acting on negative charge is:

$$F_B = -\,q\,(v \times B) \qquad \text{\_\_\_\_\_\_\_\_} \ (12.3)$$

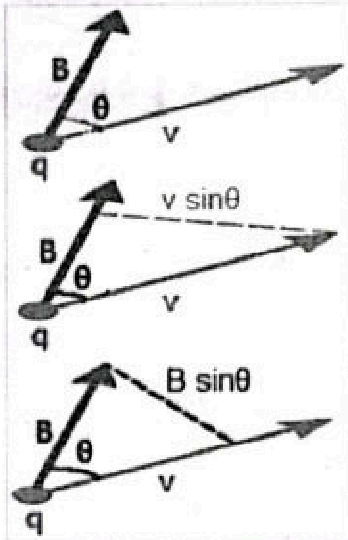


Figure 12.8: Velocity of charge is making an angle 'θ' with the magnetic field.

The negative sign in equation (12.3) shows that the direction of magnetic force acting on negative charge is opposite to that of the positive charge. The magnitude of magnetic force acting on a charge 'q' moving with velocity 'v' in the magnetic field of strength 'B' is given by:

$$F_B = q\,v\,B\,\sin\theta$$

Where θ is angle between **v** and **B**.

Maximum Force: The force will be maximum when the charged particle moves perpendicular to B (θ= 90°).

$$F_B = q\,v\,B\,\sin 90^\circ$$

$$F_{B(max)} = q\,v\,B$$

F_B is maximum and charged particle moves in circular path.

Minimum Force:

- When **v** and **B** are parallel, (θ = 0°)

$$F_B = q\,v\,B\,\sin 0^\circ = q\,v\,B\,(0) = 0$$

- When **v** and **B** are anti-parallel (θ =180°)

$$F_B = q\,v\,B\,\sin 180^\circ = q\,v\,B\,(0) = 0$$

This implies that the charged particle moves at an angle of 0° or 180° to the magnetic field, then F = 0 and the charged particle moves in a straight path.

- When the charged particle is at rest (v = 0)

$$F_B = q\,v\,B\,\sin\theta = q\,(0)\,B\,\sin\theta = 0$$

- If q = 0, then $F_B = (0)\,v\,B\,\sin\theta = 0$

If the angle between magnetic field B and the velocity v of charged particle is other than 0°, 90° and 180° then charged particle moves in helical path (spiral path), as shown in Fig. 12.9. This particle's motion has both parallel and perpendicular components.

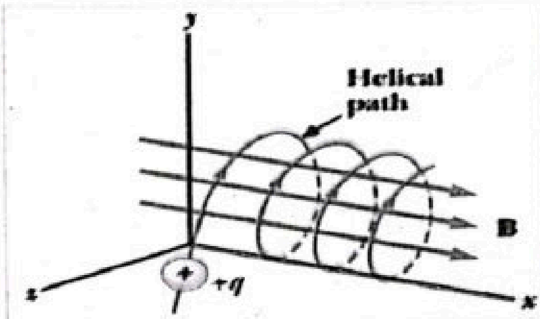


Figure 12.9: Other than angle 0°, 90°, 180° Charged particle move in helical path.

The direction of the force experienced by the moving charge is perpendicular to the both magnetic field B and its velocity v. For a positive charge, Right-Hand Rule-II and Fleming's Left-Hand Rule for force on a current-carrying conductor are used to determine the direction of force. where the direction of current is replaced by the velocity of the charged particle.

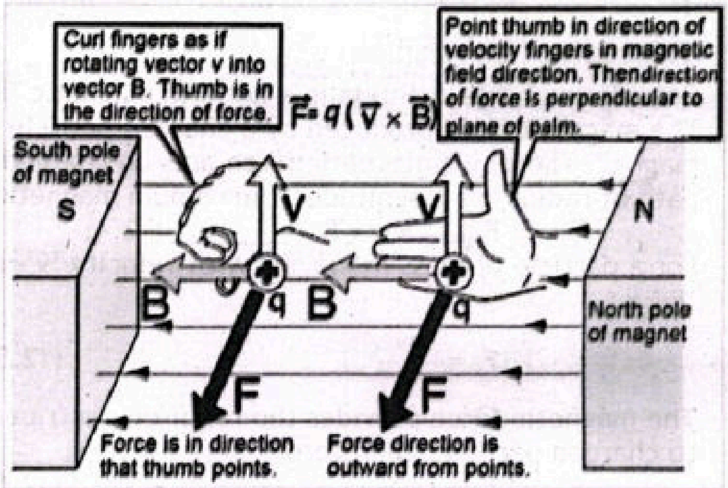


Figure 12.10: Magnetic force on a moving charged particle has a direction perpendicular to both velocity and magnetic field.

For instance, if a positive particle moves from the bottom of the setup shown in Fig. 12.10, an outward force acts on the charged particle. The direction of magnetic force on negatively charged particles will be inward. Magnetic force on a moving charged particle has a direction perpendicular to both velocity and magnetic field B.

Example 12.2: An electron is accelerated through 3600 V from rest and then enters a uniform 2.70 T magnetic field. What are (a) the maximum and (b) the minimum values of the magnetic force this particle experiences?

Given: $\Delta V = 3600$ V $\qquad$ B = 2.70 T

To Find: $F_{B_{max}} = ?$ $\qquad$ $F_{B_{min}} = ?$

Solution: For Speed of electron: $\frac{1}{2}$ m v² = e ΔV $\qquad$ or $\qquad v = \sqrt{\frac{2e\Delta V}{m}}$

Putting values, we get: $\qquad v = \sqrt{\frac{2 \times 1.6 \times 10^{-19} \times 3600}{9.1 \times 10^{-31}}} = 3.556 \times 10^7 \text{ m s}^{-1}$

(a) $\quad F_{B_{max}} = $ e v B $= (1.60 \times 10^{-19}\text{ C})(3.556 \times 10^7\ m/s)(2.70\text{ T}) = 1.54 \times 10^{-11}$ N

(b) $\quad F_{B_{min}} = $ e v B sin0° = 0 $\qquad$ or $\qquad F_{B_{min}} = $ e v B sin180° = 0

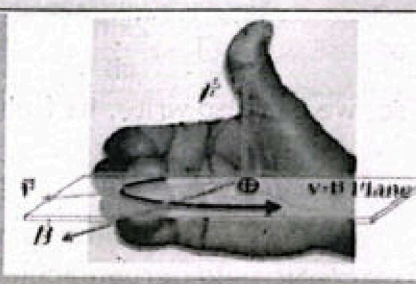
Assignment 12.2

Prove that magnetic force is not responsible to do work on a charged particle moving in circular path in a magnetic field.

For your information

Right hand rule to find direction of magnetic force on charged particle in magnetic field:

Place the velocity and magnetic field vectors in one plane and sweep from velocity towards magnetic field vector with right hand through smaller angle then magnetic force on charge is directed towards the thumb and perpendicular to the plane of velocity and magnetic field.



12.5 MOTION OF A CHARGED PARTICLE IN A UNIFORM MAGNETIC FIELD

Consider a charge q enters in a uniform magnetic field B with velocity v, as show in Fig. 12.11. The magnetic field produced by a charged particle interacts with magnetic field of permanent magnet. Thereby a magnetic force acts on charged particle and it begins to move in a circular path of radius 'r'. Magnitude of maximum magnetic force is:

$$F_{B(max)} = q\,v\,B \qquad \text{\_\_\_\_\_\_\_\_ (12.4)}$$

For a particle of mass m moving with velocity 'v' in a circle of radius 'r' the centripetal force 'F_c' is:

$$F_c = \frac{mv^2}{r} \qquad \text{\_\_\_\_\_\_\_\_ (12.5)}$$

The magnetic force provides the required centripetal force to charged particle, therefore,

$$F_c = F_{B(max)} \qquad \text{\_\_\_\_\_\_\_\_ (12.6)}$$

Putting values from equations (12.4) and (12.5) in (12.6):

$$\frac{mv^2}{r} = q\,v\,B$$

$$\frac{mv}{r} = q\,B \qquad \text{\_\_\_\_\_\_\_\_ (12.7)}$$

Radius of circular path is $r = \dfrac{mv}{qB}$ ________ (12.8)

Putting v = rω in equation (12.7):

$$\frac{mr\omega}{r} = q\,B \quad \text{or} \quad m\,\omega = q\,B$$

$$\omega = \frac{qB}{m} \qquad \text{\_\_\_\_\_\_\_\_ (12.9)}$$

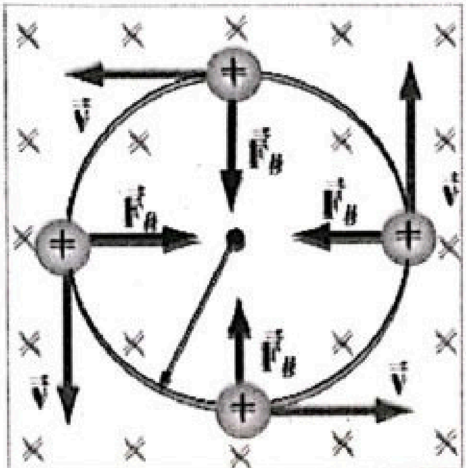


Figure 12.11: A magnetic force acts on charged particle and move it into a circular path.

This is the cyclotron frequency of a charge particle moving in a circle in a magnetic field in terms of angular motion. The time period T of the charged particle is:

$$T = \frac{2\pi}{\omega} \qquad \text{\_\_\_\_\_\_\_\_ (12.10)}$$

Putting value of ω from equation (12.9) in (12.10), we get: $T = \dfrac{2\pi}{qB/m}$

or $$T = \frac{2\pi m}{qB} \qquad \text{\_\_\_\_\_\_\_\_ (12.11)}$$

so, we can also write, its frequency as:

$$f = \frac{qB}{2\pi m} \qquad \text{\_\_\_\_\_\_\_\_ (12.12)}$$

Example 12.3: A proton is moving in a circular orbit of radius 12 cm in a uniform 0.40 T magnetic field perpendicular to the velocity of the proton. Find the speed of the proton.

Given: Radius = r = 12 cm = 0.12 m Uniform magnetic field= B= 0.40 T

Charge of proton= e = 1.60×10^{-19}C Mass of proton = $m_p = 1.67 \times 10^{-27}\ kg$

To Find: Velocity of proton = v = ?

Solution: As, $$v = \frac{eBr}{m_p}$$

Substitute numerical values: $$v = \frac{(1.6\quad 10^{\ 19})(0.040)(0.12)}{1.67\quad 10^{\ 27}}$$

$$v = 4.59\times10^{6}\ \mathrm{m\ s^{-1}}$$

Assignment 12.3

In a uniform magnetic field with a strength of 1.20×10^{-3} T, calculate the radius of an orbit of circular path of an electron moving at a speed of 2.0×10^{7} m s^{-1}.

12.6 VELOCITY SELECTOR METHOD

Velocity selector is a device used as velocity filter for charged particles. It has mutually perpendicular electric and magnetic fields. When charged particle enters with velocity v perpendicular to both electric and magnetic fields then both electric and magnetic forces act on charged particle. At a particular velocity the electric and magnetic force acting on charged particle are equal in magnitude but opposite in direction cancel out their net effect and charged particle moves in straight path undeflected, as shown in Fig 12.12.

then $F_E = F_B$

Putting F_E = q E and F_B = q v B,

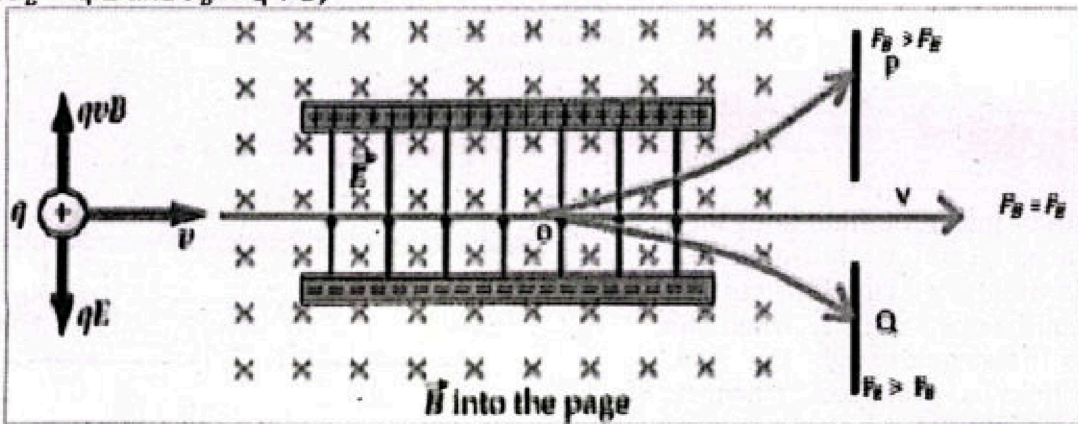


Figure 12.12: No net force acting on the charge particle.

Therefore, q E = q v B

or $$v = \frac{E}{B} \qquad \text{\_\_\_\_\_\_\_\_ (12.13)}$$

If the beam of charged particles, moving at different velocities, passes through the velocity selector, only those particles will pass straight through the device, which have velocities equal to the ratio of the electric field to the magnetic field. Particles moving slower than this speed will be deflected in the direction of electric force because magnetic force will be less than electric force on it. On contrary, those charge particles having greater speeds will be deflected in the direction of magnetic force because magnetic force will be greater than electric force on it.

The vector sum of electric and magnetic forces acting on a charged particle in electric and magnetic fields applied in same region is called Lorentz force.

$$F = F_E + F_B$$
$$F = qE + q(v \times B)$$

12.7 MAGNETIC FIELD PATTERNS

12.7.1 Magnetic Field Due to Current Carrying Straight Conductor

The electric current flowing through a wire produces a magnetic field around it in the form of concentric circle, as shown in Fig. 12.13. The strength of the magnetic field depends upon the magnitude of the current and the distance of the point from the current-carrying conductor. The strength of the magnetic field produced by current in a long, straight wire is given by:

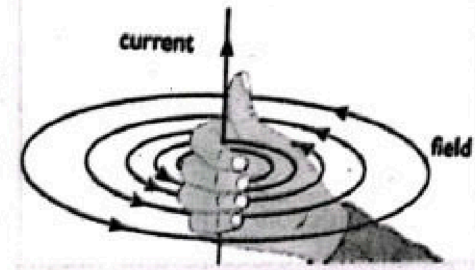


Figure 12.13: Magnetic field lines for a current carrying straight wire.

$$B = \frac{\mu_0 I}{2\pi r}$$

Where 'I' is the current and 'r' is the distance of any point from the wire, and the constant is $\mu_0 = 4\pi \times 10^{-7}$ Wb $A^{-1}\, m^{-1}$.

12.7.2 Magnetic Field Due to Current Carrying Flat Circular Coil

The pattern of magnetic field lines for a current carrying coil is shown in Fig. 12.14. Consider a circular current carrying coil having radius r. When the current is passing through the coil, magnetic field is produced. Magnetic field at the center of the single current carrying circular loop is given by:

$$B = \frac{\mu_0 I}{2r}$$

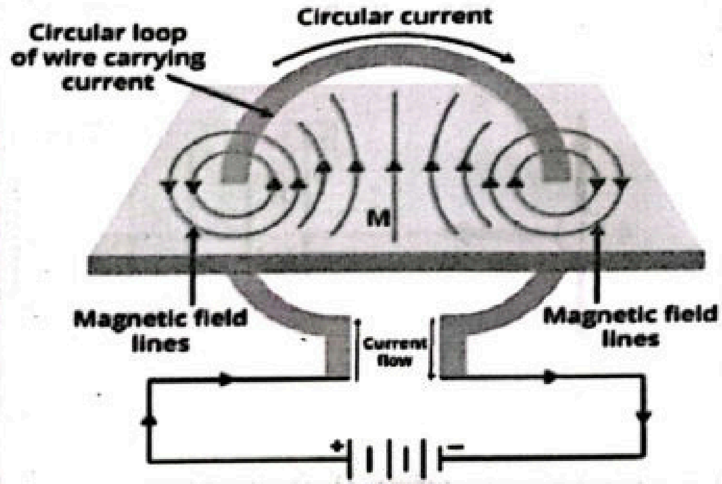


Figure 12.14: Magnetic field lines for a current carrying coil.

12.7.3 Magnetic Field Due to Current Carrying Solenoid

A solenoid is a current-carrying coil that produces magnetic field, as shown in Fig. 12.15. The magnetic field of a solenoid is similar to the magnetic field of a bar magnet, with the north pole at one end of the coil and the south pole at the other end, depending on the direction of current 'I'. The field inside the solenoid is strong and uniform as compare to the outside. The mathematical expression for magnetic field of solenoid is given by:

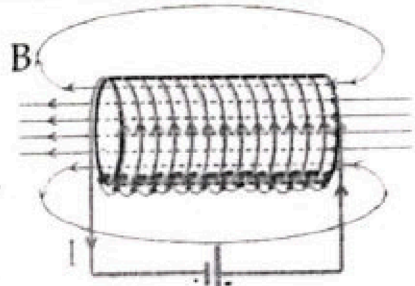


Figure 12.15: Solenoid.

$$B = \mu_0 n I$$

Where n is number of turns (N) per unit length (L) of solenoid, (i.e., $n = N/L$).

Right-Hand Rule for a Solenoid: Curl the fingers of right hand in the direction of current, the erect thumb will point in the direction of north pole.

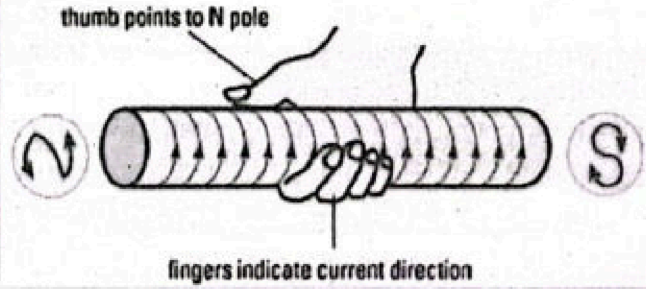


Figure 12.16: Right hand rule for solenoid.

Example 12.4: A horizontal power line carries a current of 100 A in an east to west direction. What is the magnitude and direction of the magnetic field due to the current 2.0 m below the line?

Given: $I = 100$ A, $R = 2.0$ m, $\mu_o = 4\pi \times 10^{-7}$ Wb/A m

To Find: Magnetic field (B) = ?

Solution: By using formula $B = \dfrac{\mu_o I}{2\pi r}$

$$B = \frac{4\pi \times 10^{-7} \times 100}{2\pi \times 2} = 1.0 \times 10^{-5} T$$

By using the right-hand thumb rule, we can infer that magnetic field B acts in south direction.

Assignment 12.4

A 15.0 cm long solenoid has 300 turns of wire and 5.0 A current flow through it. How strong a magnetic field is there inside the solenoid?

12.8 MAGNETIC FIELD DUE TO THE CURRENT IN A SOLENOID IS INCREASED BY A FERROUS CORE

Ferrous materials are those that contain iron. The term "ferrous" comes from the Latin word "ferrum," which means iron. Iron can be easily magnetized when placed in external magnetic fields.


Figure 12.17: solenoid

In the absence of a core, the magnetic lines of forces start to diverge by curving sharply and immediately outside the coil.

If a ferrous material (such as iron rod) is placed inside the solenoid (Fig.12.17), the strength of the magnetic field increases significantly. This occurs because the ferrous core becomes magnetized due to the magnetic field generated by the solenoid. This process is called induction. If wire of solenoid is tightly wound on the iron core, then magnetic field at the cross section remain parallel and close to each other, that's why new magnetic field is uniform and strong there.

The relative permeability μ_r of a ferrous core (iron core) is very high. Therefore, when iron core is inserted in solenoid, it increases the strength of magnetic field many times, given by the formula

$$B_{(\text{Iron cored solenoid})} = \mu_r B_{(\text{air cored})} = \mu_r \mu_0 n I$$

Common ferrous materials used in cores include iron, silicon steel, and various iron alloys. Each of these materials has its own characteristic relative permeability.

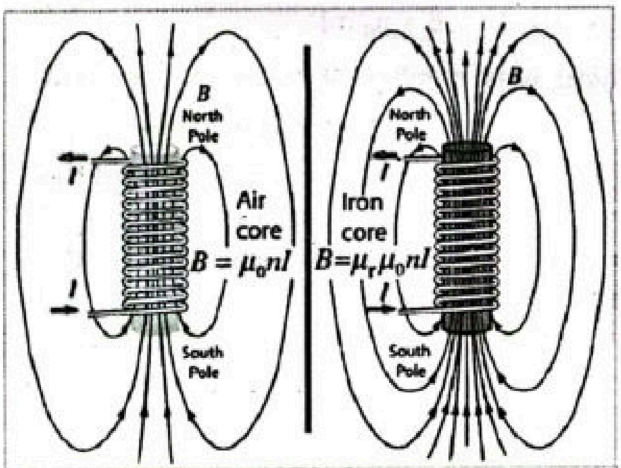


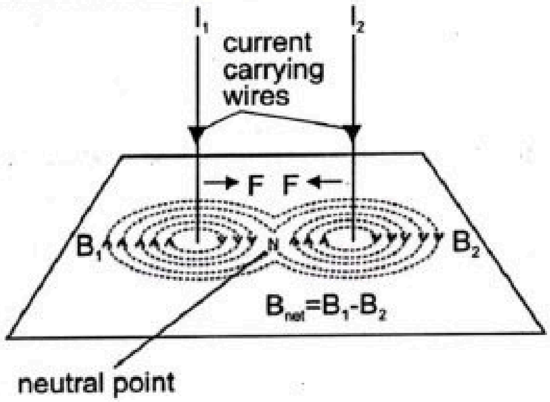
Figure 12.18: Magnetic field of solenoid with iron core is stronger.

12.9 MAGENATIC FORCES BETWEEN CURRENT-CARRYING CONDUCTORS

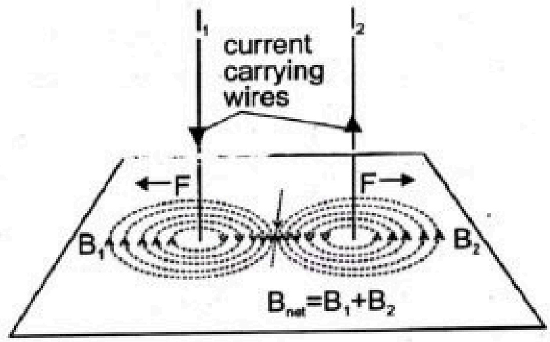
The attractive force between the two parallel wires carrying current in the same direction is magnetic in nature. When two parallel current-carrying conductors are placed close to each other, each conductor produces its own magnetic field. Each wire is in the magnetic field of the other, causing them to experiences a force that is at the right angle to both the current and the magnetic field. In the region between two parallel wires, the magnetic fields orient in opposite directions, which weakens the net magnetic field.

Whereas, the magnetic field on the outer sides of wires is stronger than in between the wires. Therefore, magnetic force acts on the current-carrying conductor from a stronger to a weaker magnetic field region, and two wires attract each other, as shown in Fig. 12.19 (a).

Note that, in the case of attractive force (currents in the same direction), there is a neutral point between the wires where the magnetic fields are equal in magnitude but opposite in direction. If the currents in two



(a) currents in same direction - attractive forces



(b) currents in opposite direction - repulsive forces

Figure 12.19: Interaction of two current-carrying conductor.

wires are equal in magnitude, the neutral point will be located midway between the wires (assuming the medium has uniform permeability). Otherwise, the neutral point would be closer to the wire with the smaller current.

The magnetic force acting per unit length on each current-carrying wire is repulsive in nature when current flowing in both wires is in the opposite direction.

In between two parallel wires carrying current in opposite directions, as shown in Fig. 12.19 (b), the magnetic fields of the two wires are in the same direction and support each other; therefore, the net magnetic field is stronger. The magnetic field on the outer sides of the wire is weaker as compared to the field in between the wires. Therefore, magnetic force acts on the current-carrying conductor from a stronger to a weaker magnetic field region, and two wires repel each other. Consider two wires of length L, carrying currents I_1 and I_2 placed at distance r from each other. Each wire is in the magnetic field of the other, as shown in Fig. 12.19 (c).

Magnetic field of 1st wire is given by:

$$B_1 = \frac{\mu_0 I_1}{2\pi r} \quad \text{\_\_\_\_\_\_\_} \quad (12.14)$$

Magnetic field of 2nd wire is given by:

$$B_2 = \frac{\mu_0 I_2}{2\pi r} \quad \text{\_\_\_\_\_\_\_} \quad (12.15)$$

Force exerted by first wire on the second wire is:

$$F_{12} = B_1 I_2 L \quad \text{\_\_\_\_\_\_\_} \quad (12.16)$$

Putting value from equation (12.14) in (12.16), we get:

$$F_{12} = \left(\frac{\mu_0 I_1}{2\pi r}\right) I_2 L$$

$$\frac{F_{12}}{L} = \frac{\mu_0 I_1 I_2}{2\pi r} \quad \text{\_\_\_\_\_\_\_} \quad (12.17)$$

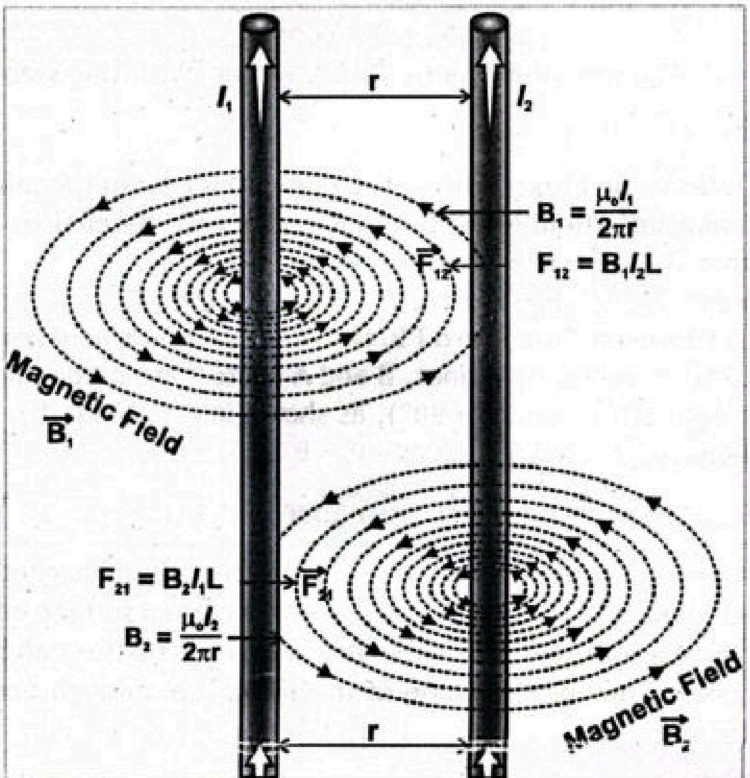


Figure 12.19 (c): Magnitude of force between two current-carrying conductor.

This is the expression for magnetic force acting per unit length of a current carrying conductor.

Similarly, force exerted by 2[nd] wire on the first wire is given by:

$$F_{21} = B_2 I_1 L \quad \text{\_\_\_\_\_\_\_} \quad (12.18)$$

Putting value from equation (12.15) in (12.18), we get:

$$F_{21} = \left(\frac{\mu_0 I_2}{2\pi r}\right) I_1 L \qquad \text{or} \qquad \frac{F_{21}}{L} = \frac{\mu_0 I_1 I_2}{2\pi r}$$

So, these forces make the action and reaction pair.

12.10 MAGNETIC FLUX

The number of magnetic lines of force passing through certain element of area is called magnetic flux.

Magnetic flux Φ_B is the scalar product of uniform magnetic field **B** and vector area **A**.

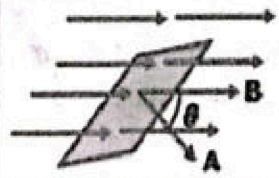


Figure 12.20 (a): Magnetic Flux.

Mathematically: $\Phi_B = \mathbf{B.A}$

If θ is angle between magnetic field B and vector area A, as shown in Fig 12.20 (a), then magnitude of magnetic flux is:

$$\Phi_B = B\,A\cos\theta$$

Unit: The unit of magnetic flux is weber (Wb). One weber is given by 1 Wb = 1 N m A^{-1}.

Special Cases

(i) Maximum Flux: If the surface (plane) is held perpendicular to magnetic field lines, **B** and **A** vectors are parallel to each other (i.e., $\theta = 0^o$), as shown in Fig. 12.20 (b).

Then, $\Phi_B = B\,A\cos 0^0 = B\,A\,(1) = B\,A$

(ii) Minimum Flux (Zero Flux): If the surface is held parallel to the magnetic field lines, **B** and **A** vectors are perpendicular to each other (i.e., $\theta = 90^o$), as shown in Fig. 12.20 (b).

Then, $\Phi_B = B\,A\cos 90^0 = B\,A\,(0) = 0$

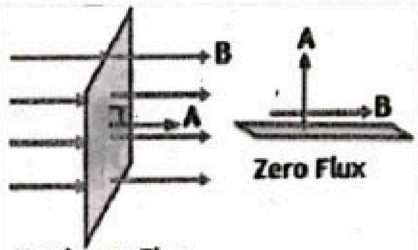


Figure 12.20 (b): Maximum and minimum magnetic flux.

Magnetic Flux Through Curved Surface or Non-Uniform Magnetic Field

When a curved surface is placed in a non-uniform magnetic field (Fig. 12.20 c), then, we divide the curved surface into a number of small elements. The net magnetic flux can be found by adding the value of magnetic flux through each element.

Thus $\Phi_B = \Sigma \mathbf{B}.\Delta\mathbf{A}$

Magnetic Flux Density: Magnetic flux density (B) is also defined as:

Maximum magnetic flux per unit area is called magnetic flux density.

$$B = \frac{\Phi}{A}$$

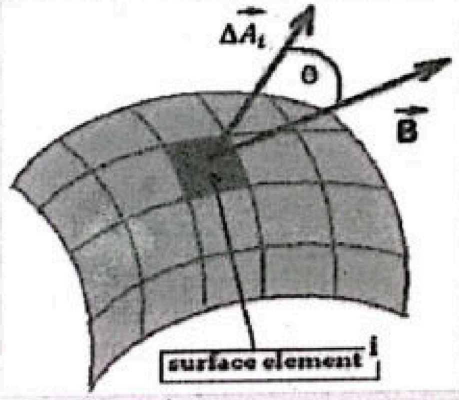


Figure 12.20 (c): Magnetic flux through curved surface.

Unit of magnetic flux density is Wb m^{-2} which is equal to tesla (T).

Example 12.5: In a certain region, the magnetic field is given by B = $(4\,\hat{\imath} + 6\,\hat{k})$ Wb m^{-2}. How much magnetic flux passes through a 2.0 m^2 area loop in this region if the loop lies flat in the x y-plane?

Given: Magnetic induction = B = $(4\,\hat{\imath} + 6\,\hat{k})$ Wb m^{-2} Area of the loop = ΔA = $(2.0\,\hat{k})$ m^2

To Find: Magnetic flux = Φ_B = ?

Solution: As we know that: $\Phi_B = \mathbf{B} \cdot \Delta\mathbf{A}$

Putting the values, we get: $\Phi_B = (4\,\hat{\imath} + 6\,\hat{k}) \cdot (2\,\hat{k})$ = 12 Wb

Assignment: 12.5

A magnetic field of 0.8 T passes perpendicular to a disc with a radius of 2 cm. Find the magnetic flux through the disc.

12.11 MAGNETIC FLUX LINKAGE

Magnetic flux linkage is defined as:

The product of the magnetic flux and the number of turns of the coil.

It is a quantity commonly used for solenoids and coils, which are made of N turns of wire. The magnetic flux density by a single wire is usually very low. Magnetic flux of single turn can be increased by increasing magnetic flux density and by increasing area of loop.

The magnetic flux linkage refers to the number of turns (N) on a coil multiplied by the magnetic flux (Φ) of one turn. This gives the equation:

$$N\Phi = NBA$$

If the cross-sectional area (A) of loop and magnetic flux density (B) are not perpendicular, the equation becomes:

$$\text{Magnetic flux linkage} = BAN\cos\theta$$

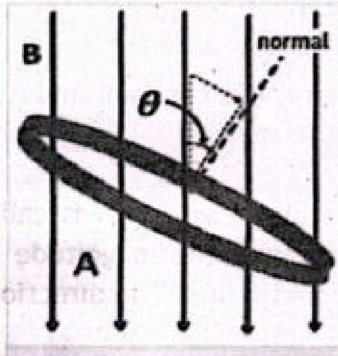


Figure 12.21: Magnetic flux linkage.

Where, θ is the angle between the vector area (A) and the magnetic flux density (B), as shown in Fig. 12.21.

Units: The flux linkage ΦN has the units of Weber turns (Wb turns).

Example 12.6: A solenoid with a circular cross-sectional area of 0.80 m^2 and 300 turns is facing perpendicular to a magnetic field with magnetic flux density of 4 mT. Determine the magnetic flux linkage for this solenoid.

Given: Cross-sectional area, A = 0.80 m^2 Magnetic flux density, B = 4 mT= 4×10^{-3} T

Number of turns of the coil, N = 300 turns

To Find: ΦN = ?

Solution: Using the formula ΦN = BAN

Substitute in values: $\Phi N = (4 \times 10^{-3}\ \text{T}) \times 0.80\ m^2 \times 300 = 0.96$ Wb turns

Assignment 12.6

A solenoid contains 200 turns of wire. Each piece of wire has a cross-sectional area of $0.004\ m^2$ If the magnetic flux density is 12.0 mT calculate the magnetic flux linkage.

12.12 FARADAY'S LAW

The phenomenon in which the change in magnetic flux causes an induced emf in a conductor is called electromagnetic induction.

The basic requirement for electromagnetic induction is the change in magnetic flux linking the conductor (or coil).

Faraday's Laws of Electromagnetic Induction

It states that:

The average e.m.f induced in a conducting coil of N turns is directly proportional to the rate of change of magnetic flux through the conductor.

If N is the number of turns of the coil and ε is the induced e.m.f. then:

$$\text{Induced e.m.f} \propto \text{rate of change of magnetic flux}$$

$$\text{Induced e.m.f} \propto \frac{\textit{Total change in magnetic flux}}{\textit{Total time}}$$

For N turns of coil:

$$\text{Induced e.m.f} \propto N\frac{\Delta\phi}{\Delta t}$$

$$\varepsilon = kN\frac{\Delta\phi}{\Delta t}$$

Where, k is constant and its value is '1' in SI units. So,

$$\varepsilon = N\frac{\Delta\phi}{\Delta t}$$

The above equation is called Faraday's law of electromagnetic induction, and it is used to determine the magnitude of induced emf. The induced emf always opposes the change in magnetic flux. The direction of induced emf is given by **Lenz's law.**

$$\varepsilon = -N\frac{\Delta\phi}{\Delta t}$$

The negative sign indicates that the direction of the induced current is such that it opposes the change in flux. Faraday's law is the fundamental law that describe the production of emf due to change of magnetic flux in various circuits and devices. For example, AC devices like induction motors, induction generators or transformers, as well as DC devices like DC motors, DC generators.

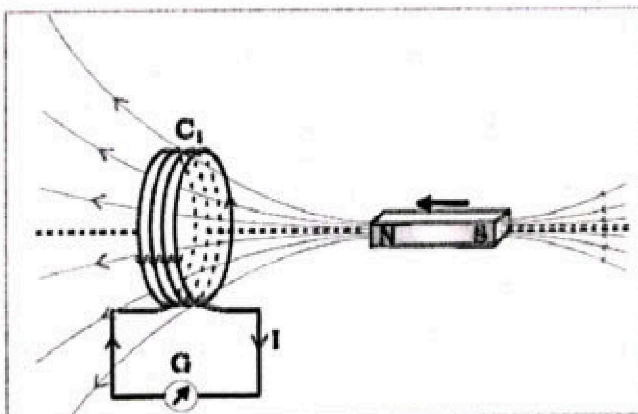


Figure 12.22: Magnet is moving and coil is at rest.

Experiment 1: In this experiment, we use a bar magnet and a coil connected to a sensitive galvanometer, as shown in the Fig. 12.22.

Case I: When there is no relative motion between the magnet and coil, the galvanometer shows no current.

Case II: When the bar magnet is moved towards the coil, the magnetic flux changes and induces emf. As a result, induced current flows in the coil.

Case- III: When the bar magnet is moved away from the coil, the magnetic flux again changes, inducing an emf and an induced current flow in the coil but in the opposite direction.

Experiment 2: Emf is Induced by relative motion of a coil with respect to magnetic field. In this experiment, the coil is rotated in a magnetic field. As the change in magnetic flux is given by:

$$\Delta\Phi = \Delta B(A\cos\theta)$$

During the rotation of the coil, the angle θ between the magnetic field and the vector area A of the coil changes. Therefore, the magnetic flux of the coil changes, inducing an emf in the coil. The induced current flows through the circuit, and which produces deflection in the galvanometer. This is the basic principle of an electric generator (Fig. 12.23).

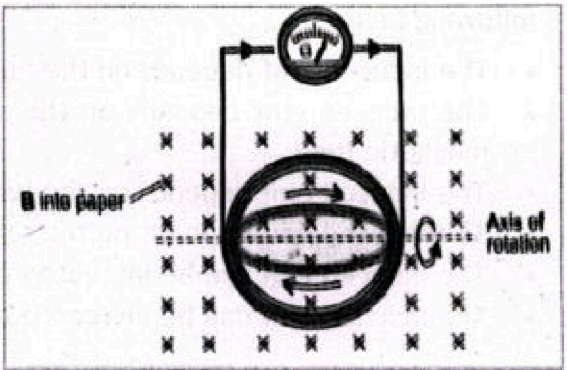


Figure 12.23: Coil is rotated in magnetic field.

Experiment 3: Emf is also Induced by changing a magnetic field (the transformer effect). In this experiment, two coils are placed closed to each other.

The primary coil 'P' is connected in series with the battery through a switch and rheostat, while the secondary coil S is connected only to a galvanometer. If the switch of coil P is closed, a momentary current is induced in the coil S. When the switch P is opened, a current is produced in the coil S in opposite direction. When we open or close the switch then there will be a change of current, which causes to changing magnetic field of coil P and the magnetic flux through coil S changes. The changing magnetic flux induces emf in coil S, as shown in Fig. 12.24.

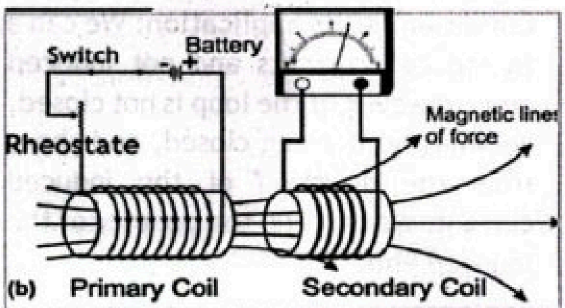


Figure 12.24: By changing magnetic field of primary coil, the magnetic flux through secondary coil changes.

If the current in the primary coil is varied with the help of a rheostat, then the magnetic field of coil P and the magnetic flux through coil S change. The changing magnetic flux induces the emf in it. The induced emf and induced current will remain in the coil as long as the magnetic flux through it changes. This is the basic principle of the working of a transformer.

- The electromotive force, or emf is induced when the magnetic flux linking with a coil changes (the magnetic flux either increases or decreases).
- A constant magnetic flux cannot produce emf in a conductor. The cause of induced emf is a change in magnetic flux.

- The magnitude of induced emf depends on the rate of change of magnetic flux.
- The induced emf is independent of the resistance and resistivity of the circuit and depends *only on the rate of* change of the magnetic flux through the conductor.
- Induced current ($I = \varepsilon/R$) depends on the resistance and resistivity of the circuit.
- When the magnetic flux through a conductor changes, an induced emf always produces, but induced current only flows when the circuit is closed.

Factors Affecting the Magnitude of the Induced emf: The induced emf is affected by the following factors:

- The induced emf depends on the number of turns in a coil.
- The induced emf depends on the speed of the movement of the conductor through the magnetic field.
- The induced emf depends on the length of the conductor inside the magnetic field.
- The induced emf depends on the rate of change of magnetic flux through the conductor.
- The induced emf can be increased by increasing the strength of external magnetic field.
- The induced emf can be increased by increasing the area of coil.

12.13 LENZ'S LAW

In 1834, Russian physicist Heinrich Lenz discovered that the polarity of induced emf always leads to an induced current that opposes the change which induces the emf.

The direction of the induced current is always such as to oppose the change that causes the current.

Condition for its application: We can apply Lenz's law directly to closed loops because it refers to induced currents and not induced emf. However, if the loop is not closed, we imagine it being closed, and then, from the direction of the induced current, we can find the polarity of the induced emf.

Explanation: When a bar magnet is pushed towards a coil connected to a galvanometer then emf is induced due to change in its magnetic flux and induced current flows through it, as shown in Fig. 12.25 (a).

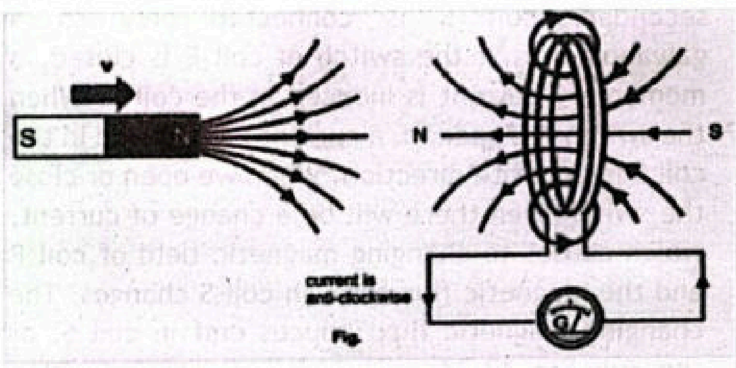


Figure 12.25 (a): The bar magnet is pushing towards the coil.

Direction of current in the coil is determined by Lenz' s law. It tells us that induced current opposes its cause. In this experiment, cause of induced current is push of the N- pole of magnet towards the coil (Which increases the magnetic flux through the coil). Induced current of the coil induces such magnetic field which opposes the push of the magnet towards the coil and hence oppose the increase of magnetic flux through the coil. It will be only possible if left side of the coil acts as N-pole and right side acts as S-pole of a bar magnet, as shown in Fig. 12.25(a). Now, by applying Right Hand Rule, we see that direction of current in the coil is anti-clockwise.

Similarly, if we 'pull' the magnet away from the coil, the induced current opposes the 'pull' by creating the south pole towards the bar magnet according to Lenz's law, as shown in Fig. 12.25 (b). When a magnet is moved away from the coil, flux decreases through the coil. To oppose this pull of the magnet and decrease in magnetic flux through the coil, the coil induces such current in it that attracts the bar magnet. For this, the left side of the coil acts as the S-pole and the right-side acts as N-pole. The S-pole of the coil attracts the N-pole of the bar magnet and opposes its motion. For this, direction of induced current in the coil reverses, i.e., current flows clockwise as according to Right Hand Rule.

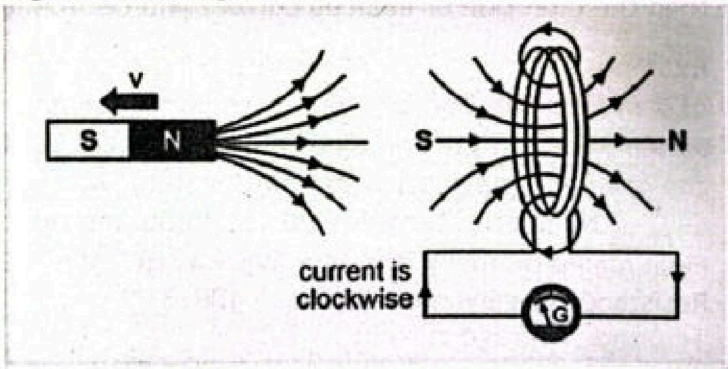


Figure 12.25 (b): The bar magnet is pulling away from the coil.

Lenz's Law and Law of Conservation of Energy

The law of conservation of energy states that energy can neither be created nor destroyed, but it can be changed from one form to another.

Lenz's law states that the direction of current is such that it opposes the change in the magnetic flux. So, an effort is required to do work against opposing forces. This work leads to changes in magnetic flux; hence, electric current is induced. Thus, mechanical energy is converted into equivalent amount of electrical energy, which is in accordance with the law of conservation of energy.

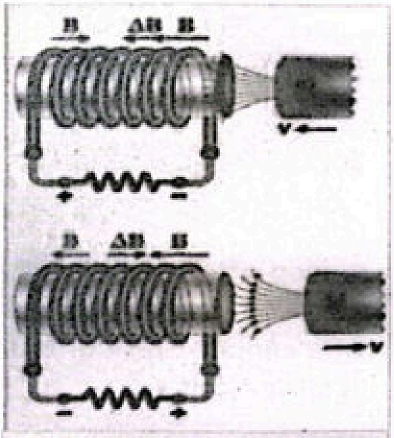


Figure 12.26: Lenz's law.

Let's exaplain further with the help of an example: consider that N-pole of a magnet is approaching the coil, as shown in Fig. 12.26, the repulsive force acts on the bar magnet due to the current induced in the coil. The result is that the motion of the magnet is opposed. The mechanical energy spent in overcoming this opposition is converted into electrical energy, which appears in the coil. We have to spend mechanical energy to induce electrical energy. Thus, Lenz's law is in accordance with the law of conservation of energy.

Fleming's Right Hand Rule: To find the direction of the induced current, Fleming's right-hand rule may be used, as shown in Fig. 12.27. It is stated as:

Stretch out of forefinger, middle finger and thumb of your right hand so that they are at right angles to one another.

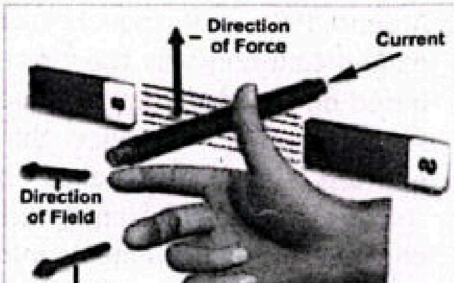


Figure 12.27: Fleming's right-hand rule to find the direction of the induced current.

If the forefinger points in the direction of magnetic field, thumb in the direction of motion of the conductor, then the middle finger will point in the direction of induced current.

When the conductor moves upwards at right angle to a stationary magnetic field then the direction of induced current is from right to left. If the motion of the conductor is downward, then the direction of induced current will be from left to right.

Example 12.7: A coil of resistance 50 Ω is placed in magnetic field and initial magnetic flux of 2 m Wb. The coil has 50 turns and a galvanometer of 100 Ω resistance is connected in series with it. Find the average emf and the current if the coil is moved in 1/10th s from the given magnetic field to another field where final magnetic flux of 4 m Wb.

Given: Number of turns N = 50 Initial magnetic flux = Φ_1 = 2m Wb = 2×10^{-3} Wb

Final magnetic flux = Φ_2 = 4 m Wb = 4×10^{-3} Wb Resistance of coil = R_1 = 50 Ω

Resistance of galvanometer R_2 = 100 Ω Time taken for change Δt = 1/10 s = 0.1 s

To Find: Average current I = ?

Solution: By Faraday's law magnitude of induced emf is

$$\varepsilon = N\frac{\Delta\phi}{\Delta t} \quad \text{or} \quad \varepsilon = N\left(\frac{\phi_2 - \phi_1}{\Delta t}\right)$$

Putting values: $$\varepsilon = 50 \times \left(\frac{4\times10^{-3} - 2\times10^{-3}}{0.1}\right) = 1\text{ V}$$

As, galvanometer is connected in series. So $R_{eq} = R_1 + R_2$

$$R_{eq} = 50 + 100 = 150\ \Omega$$

So, $$I = \frac{V}{R_{eq}} = \frac{\varepsilon}{R_{eq}} \quad \text{or} \quad I = \frac{1}{150} = 6.67\times10^{-3}\text{ A} = 6.67\text{ mA}$$

Assignment 12.6

A loop of wire is placed in a uniform magnetic field that is perpendicular to the plane of the loop. The strength of the magnetic field is 0.6 T. The area of the loop begins to shrink at a constant rate of 0.8 $m^2 s^{-1}$. What is the magnitude of emf induced in the loop while it is shrinking?

12.14 SEISMOMETER

Around 1906, a Russian Empire nobleman and inventor named Gallitzin was the first to create a seismometer based on Faraday's law of electromagnetic induction. A seismometer is a device that records seismic waves emitted during earthquakes, explosions, or other earth-shaking events. Electromagnetic sensors in seismographs convert ground movements into electrical signals.

A frame is made on which wire is wound and the ends of this frame are connected with springs tied with side walls, as shown in Fig. 12.28. A permanent magnet is placed between this frame and its coil in such a way that coil can oscillate freely.

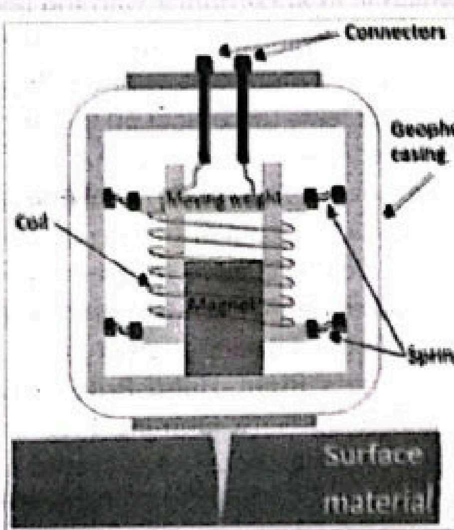


Figure 12.28: Seismometer.

When the Earth vibrates due to earthquake, there is relative motion between magnet and the coil. This causes change in magnetic flux through the coil. It induces emf and current in the coil according to Faraday's law of electromagnetic induction. This induced current is given to external circuit where values are recorded and graph is plotted.

During a high-intensity earthquake, the relative velocity between the coil and magnet increases, and the amplitude of the vibration of the coil increases.
The induced emf in the coil is directly proportional to the displacement of the coil within the magnetic field.
When the coil moves faster, the rate of change of displacement of the coil in a magnetic field increase; as a result, the rate of change of magnetic flux of the coil increases, and induced emf increases.

SUMMARY

- The force on a charge moving inside a magnetic field result from interaction between the magnetic field produced by the moving charge (which is equivalent to current) and the applied magnetic field.
- When a charge moves in magnetic field in circular path, its speed and K.E remain same but its velocity and momentum change due to change in direction of motion
- For a point on the axis of a circular coil carrying current, magnetic field is maximum at the centre of the coil.
- The magnetic field is the region or space surrounding a magnet in which a compass needle, a small magnet, another ferromagnetic material, and a moving charged particle experiences a magnetic force.
- Magnetic flux linkage is defined as the product of the magnetic flux and the number of turns of the coil.
- Faraday's law states that 'the magnitude of induced e.m.f. is directly proportional to the rate of change of magnetic flux linking the coil and the number of turns of the coil N.
- Lenz's Law states that the direction of the induced current is always such as to oppose the change that causes the current.

EXERCISE

Multiple Choice Questions

Encircle the correct option.

1) Which of the following is the SI unit of magnetic induction?

A. henry B. tesla C. weber D. farad

2) A 0.5 m long straight wire carrying a current of 3.2 A kept at right angle to a uniform magnetic field of 2.0 tesla. The force acting on the wire will be:

A. 2 N B. 2.4 N C. 1.2 N D. 3.2 N

3) An electron and proton enter a magnetic field with same velocity, which of the following is the ratio of their acceleration?

A. $\frac{m_e}{m_p}$ B. $\frac{m_p}{m_e}$ C. $\left(\frac{m_e}{m_p}\right)^{\frac{1}{2}}$ D. $\left(\frac{m_p}{me}\right)^{\frac{1}{2}}$

4) If charge particle enters a magnetic field an angle 60^o, then its path will be:
A. elliptical B. straight line C. helical D. circular

5) An electron is revolving in circular path of radius r in a magnetic field. If the magnetic field is halved, then new radius will be:
A. r/2 B. r/4 C. 2r D. 4r

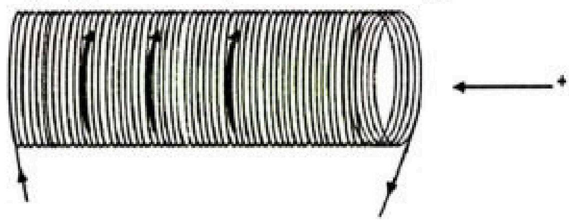
6) Which of the following particles in motion cannot be deflected by magnetic field?
A. electron B. proton C. alpha-particle D. neutron

) A proton and an α-particle moving with same velocity enter a magnetic field perpendicularly. Which one of the following is the ratio of radius of circular path of proton to α-particle?
A. 1/2 B. 1 C. 2 D. 4

8) A charged particle is moving in uniform magnetic field in a circular path. The radius of circular path is R. If the energy of the particle is doubled, then the new radius will be:
A. $\frac{R}{\sqrt{2}}$ B. $\frac{R}{2}$ C. $\sqrt{2}\,R$ D. 2R

9) A positively charged particle moving with velocity of 3.1×10^5 m/s normal to uniform magnetic field of magnitude $5.4\times 10^{-5}\,T$. Particle experiences force of 8.1×10^{-16} N, the charge on particle is:
A. 4.8×10^{-10} C B. 1.6×10^{-19} C C. 6.4×10^{-17} C D. 4.8×10^{-17} C

10) A proton is moving along the axis of a solenoid carrying a current, as shown in figure. The magnetic force on proton will be:



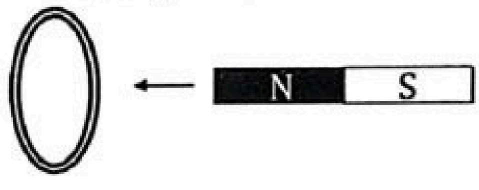
A. radially inward. B. radially outward.
C. no force acts. D. radially outward.

11) Magnetic flux will be maximum when:
A. magnetic field is perpendicular to the plane area.
B. magnetic field lies parallel to the plane area.
C. area is held at an angle of 45^o.
D. area is held at an angle of 60^o.

12) The cause of induced emf is:
A. constant magnetic flux. B. increase in magnetic flux only.
C. decrease in magnetic flux only. D. change in magnetic flux.

13) Lenz's law is in accordance with the law of conservation of:
A. charge B. energy C. momentum D. angular momentum

14) A metallic circular ring is suspended by a string and is kept in a vertical plane. When a magnet is pushed towards the ring, then it will:



A. get displaced towards the magnet.
B. remains stationary.
C. get displaced away from the magnet.
D. nothing can be said.

Short Questions

Give short answers of the following questions.

12.1 What are the various ways to create a magnetic field.

12.2 In what way is a magnetic field different from an electric field?

12.3 Why does a current carrying conductor may experience force in magnetic field?

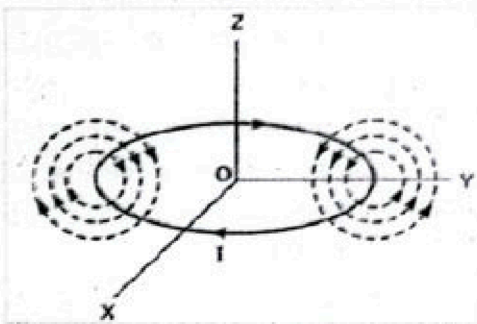
12.4 Can a charged particle move in a straight line through some region of space, in which magnetic field is non-zero? Explain.

12.5 When is the magnetic force on a moving charge in a magnetic field maximum, and when is it minimum?

12.6 In a region with a homogeneous magnetic field B directed normal to the plane into the paper, an alpha particle and a proton are travelling in its plane. What will be the ratio of the radii of the two particles' field trajectories if they have equal linear momenta?

12.7 The kinetic energy of a charged particle moving in uniform magnetic field does not change. Why? Explain

12.8 Describe the changes in the magnetic field inside a solenoid carrying a constant current I under the conditions of (a) doubling the length of the solenoid while maintaining the same number of turns, and (b) doubling the number of turns while maintaining the same length.



12.9 Explain how 1 ampere is defined using concept of force between two long parallel current-carrying wires.

12.10 A circular loop of radius R carrying current I lies in the XY-plane with its centre at origin (as shown in figure). What is the magnetic flux through the XY-plane?

12.11 A suspended magnet is vibrating freely in a horizontal plane. When a metal plate is brought beneath the magnet, the oscillations of the magnet are significantly dampened. Describe the cause of damping by using Lenz's law.

12.12 A thin metallic ring is dropped into a vertical bar magnet. Does current in the ring flow clockwise or counterclockwise when seen from above?

12.13 Show that ε and $\frac{\Delta\phi}{\Delta t}$ have the same units.

Comprehensive Questions

Answer the following questions in detail.

12.1 Explain that magnetic field is an example of a field of force produced either by current-carrying conductors or by permanent magnets.

12.2 Explain that a magnetic force act on a current-carrying conductor placed in a magnetic field. Derive an expression for it.

12.3 Explain that a magnetic force act on a charged particle in a uniform magnetic field.

12.4 Describe the concept of magnetic flux (Φ_B) as scalar product of magnetic field (B) and area (A) using the relation $\Phi_B = B.A$

12.5 Describe quantitatively the path followed by a charged particle shot into a magnetic field in a direction perpendicular to the field.

12.6 Describe the concept of magnetic force between current-carrying conductors. Derive an expression for the magnetic force acting per unit length on each current-carrying parallel conductor when current is flowing through them.

12.7 State and explain Faraday's law of electromagnetic induction.

12.8 Describe how the direction of an induced current can be predicted by Lenz's law and how Lenz's law obeys the principle of conservation of energy.

Numerical Problems

12.1 A horizontal power line carries a current of 600 A from south to north. Earth's magnetic field $5\times 10^{-5}T$ is directed toward the north and inclined downward at 70° to the horizontal. Find the magnitude of the magnetic force on 100 m of the line due to Earth's magnetic field.

(Ans: 2.82 N)

12.2 A proton is accelerated in a cyclotron in which the magnetic induction is 0.75 Wb m^{-2}. Find the cyclotron frequency. **(Ans: 11.4×10^6 Hz)**

12.3 A velocity selector consists of electric and magnetic fields described by the expressions $E = E\hat{k}$ and $B = B\hat{j}$. With B = 18.0 mT. Find the value of E such that electron of energy 850 eV moving in the negative x direction is undeflected. **(Ans: 311×10^3 N C^{-1})**

12.4 Two long straight parallel wires are 0.6 m apart and carry current 4 A and 8 A. Find the point lying between two wires at perpendicular distance where resultant magnetic field will be zero (neutral point). **(Ans: 0.2 m and 0.4 m respectively)**

12.5 A coil of wire has 100 loops. Each loop has an area of $2.0 \times 10^{-3}\, m^2$. A magnetic field is perpendicular to the surface of each loop at all times. If the magnetic field is changed from 0.2 T to 0.6 T in 0.1 s, find the average emf induced in the coil during this time. **(Ans: 0.8 V)**

12.6 A 2 m long wire carrying a current of 15 A is placed in a uniform magnetic field of 0.50 T. If the wire makes an angle of 60° with the direction of magnetic field, find the magnitude of the magnetic force acting on the wire. **(Ans: 12.99 N)**

12.7 A particle carrying a charge of $1\,\mu C$ and moving with velocity of 2×10^6 m s^{-1} enters in a magnetic field of 0.5 T at angle of 60^0 with the field. Calculate the magnitude of magnetic force acting on it. **(Ans: 0.866 N)**

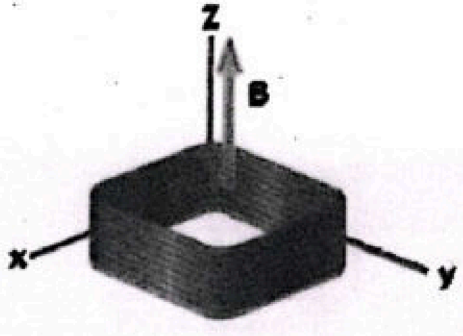
12.8 A single circular loop has radius 2 cm. The plane of the loop lies at 40° to a uniform magnetic field of 0.2 T. Find the magnitude of the magnetic flux through the loop.

(Ans: 1.62×10^{-4} Wb)

12.9 Find the magnetic force acting on a charged particle of charge $2\,\mu C$ in a magnetic field of 2 T acting in y-direction when particle velocity is $(2\hat{i} + 3\hat{j}) \times 10^6 m s^{-1}$.

(Ans: 8 N, +ve Z-axis)

12.10 A coil with 25 turns of wire is wrapped on a frame with a square cross section 1.80 cm on a side. Each turn has the same area, equal to that of the frame, and the total resistance of the coil is 0.350 ohm. An applied uniform magnetic field is perpendicular to the plane of the coil, as in the Fig. (a) Applying Faraday's law find the induced emf in the coil when the magnetic field is changing uniformly from zero to 0.50 T in 0.80 s. (b) find the magnitude of induced current and (c) Applying Lenz's law find the direction of the induced current in the coil while the field is changing.



(Ans: 5.06×10^{-3} V, 1.45×10^{-2} A, clockwise)