

# Electromagnetic Induction

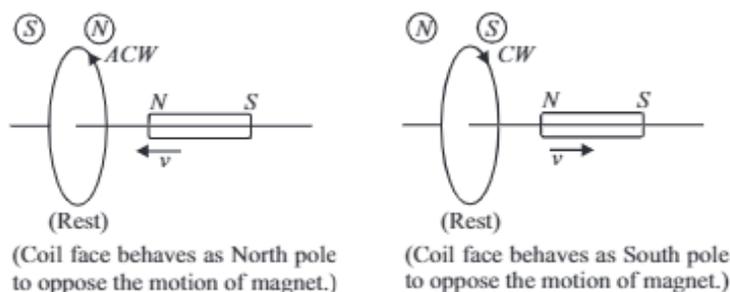
## CASE STUDY / PASSAGE BASED QUESTIONS

Questions 1-6 are Case Study based questions and are compulsory. Attempt any 4 sub parts from each question. Each question carries 1 mark.

1

### Direction of Induced Current

Lenz's law states that the direction of induced current in a circuit is such that it opposes the change which produces it. Thus, if the magnetic flux linked with a closed circuit increases, the induced current flows in such a direction that a magnetic flux is created in the opposite direction of the original magnetic flux. If the magnetic flux linked with the closed circuit decreases, the induced current flows in such a direction so as to create a magnetic flux in the direction of the original flux.

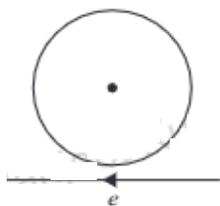


- (i) Which of the following statements is correct?
- The induced e.m.f is not in the direction opposing the change in magnetic flux so as to oppose the cause which produces it.
  - The relative motion between the coil and magnet produces change in magnetic flux.
  - Emf is induced only if the magnet is moved towards coil.
  - Emf is induced only if the coil is moved towards magnet.
- (ii) The polarity of induced emf is given by
- Ampere's circuital law
  - Biot-Savart law
  - Lenz's law
  - Fleming's right hand rule
- (iii) Lenz's law is a consequence of the law of conservation of
- charge
  - mass
  - momentum
  - energy

### Syllabus

Electromagnetic induction; Faraday's laws, induced EMF and current; Lenz's Law, Eddy currents. Self and mutual induction.

- (iv) Near a circular loop of conducting wire as shown in the figure, an electron moves along a straight line. The direction of the induced current if any in the loop is

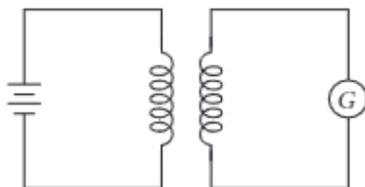


- (a) variable (b) clockwise  
 (c) anticlockwise (d) zero
- (v) Two identical circular coils *A* and *B* are kept in a horizontal tube side by side without touching each other. If the current in the coil *A* increases with time, in response, the coil *B*
- (a) is attracted by *A* (b) remains stationary  
 (c) is repelled (d) rotates

## 2

### Mutual Inductance

Mutual inductance is the phenomenon of inducing emf in a coil, due to a change of current in the neighbouring coil. The amount of mutual inductance that links one coil to another depends very much on the relative positioning of the two coils, their geometry and relative separation between them. Mutual inductance between the two coils increases  $\mu_r$  times if the coils are wound over an iron core of relative permeability  $\mu_r$ .



- (i) A short solenoid of radius  $a$ , number of turns per unit length  $n_1$ , and length  $L$  is kept coaxially inside a very long solenoid of radius  $b$ , number of turns per unit length  $n_2$ . What is the mutual inductance of the system?
- (a)  $\mu_0 \pi b^2 n_1 n_2 L$  (b)  $\mu_0 \pi a^2 n_1 n_2 L^2$  (c)  $\mu_0 \pi a^2 n_1 n_2 L$  (d)  $\mu_0 \pi b^2 n_1 n_2 L^2$
- (ii) If a change in current of 0.01 A in one coil produces a change in magnetic flux of  $2 \times 10^{-2}$  weber in another coil, then the mutual inductance between coils is
- (a) 0 (b) 0.5 H (c) 2 H (d) 3 H
- (iii) Mutual inductance of two coils can be increased by
- (a) decreasing the number of turns in the coils  
 (b) increasing the number of turns in the coils  
 (c) winding the coils on wooden cores  
 (d) none of these.
- (iv) When a sheet of iron is placed in between the two co-axial coils, then the mutual inductance between the coils will
- (a) increase (b) decrease  
 (c) remains same (d) cannot be predicted
- (v) The SI unit of mutual inductance is
- (a) ohm (b) mho (c) henry (d) none of these

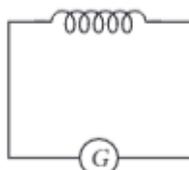
## Eddy Currents and their Effects

Currents can be induced not only in conducting coils, but also in conducting sheets or blocks. Current is induced in solid metallic masses when the magnetic flux threading through them changes. Such currents flow in the form of irregularly shaped loops throughout the body of the metal. These currents look like eddies or whirlpools in water so they are known as eddy currents. Eddy currents have both undesirable effects and practically useful applications. For example it causes unnecessary heating and wastage of power in electric motors, dynamos and in the cores of transformers.

- (i) The working of speedometers of trains is based on
- |                          |                        |
|--------------------------|------------------------|
| (a) wattless currents    | (b) eddy currents      |
| (c) alternating currents | (d) pulsating currents |
- (ii) Identify the wrong statement.
- Eddy currents are produced in a steady magnetic field.
  - Induction furnace uses eddy currents to produce heat.
  - Eddy currents can be used to produce braking force in moving trains.
  - Power meters work on the principle of eddy currents.
- (iii) Which of the following is the best method to reduce eddy currents?
- |                                 |                       |
|---------------------------------|-----------------------|
| (a) Laminating core             | (b) Using thick wires |
| (c) By reducing hysteresis loss | (d) None of these     |
- (iv) The direction of eddy currents is given by
- |                              |                          |
|------------------------------|--------------------------|
| (a) Fleming's left hand rule | (b) Biot-Savart law      |
| (c) Lenz's law               | (d) Ampere-circuital law |
- (v) Eddy currents can be used to heat localised tissues of the human body. This branch of medical therapy is called
- |                   |                    |
|-------------------|--------------------|
| (a) Hyperthermia  | (b) Diathermy      |
| (c) Inductothermy | (d) none of these. |

## Self Induction

When a current  $I$  flows through a coil, flux linked with it is  $\phi = LI$ , where  $L$  is a constant known as self inductance of the coil. Any change in current sets up an induced emf in the coil. Thus, self inductance of a coil is the induced emf set up in it when the current passing through it changes at the unit rate. It is a measure of the opposition to the growth or the decay of current flowing through the coil. Also, value of self inductance depends on the number of turns in the solenoid, its area of cross-section and the relative permeability of its core material.



- (i) The inductance in a coil plays the same role as
- |                           |                         |
|---------------------------|-------------------------|
| (a) inertia in mechanics  | (b) energy in mechanics |
| (c) momentum in mechanics | (d) force in mechanics  |

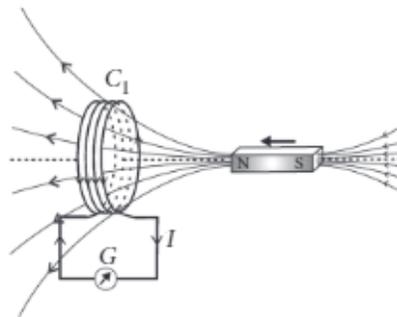
- (ii) A current of 2.5 A flows through a coil of inductance 5 H. The magnetic flux linked with the coil is  
 (a) 0.5 Wb (b) 12.5 Wb (c) zero (d) 2 Wb
- (iii) The inductance  $L$  of a solenoid depends upon its radius  $R$  as  
 (a)  $L \propto R$  (b)  $L \propto 1/R$  (c)  $L \propto R^2$  (d)  $L \propto R^3$
- (iv) The unit of self-inductance is  
 (a) weber ampere (b)  $\text{weber}^{-1}$  ampere (c) ohm second (d) farad
- (v) The induced e.m.f. in a coil of 10 henry inductance in which current varies from 9 A to 4 A in 0.2 second is  
 (a) 200 V (b) 250 V (c) 300 V (d) 350 V

## 5

### The Experiments of Faraday and Henry

In year 1820 Oersted discovered the magnetic effect of current. Faraday gave the thought that reverse of this phenomenon is also possible *i.e.*, current can also be produced by magnetic field. Faraday showed that when we move a magnet towards the coil which is connected by a sensitive galvanometer. The galvanometer gives instantaneous deflection showing that there is an electric current in the loop.

Whenever relative motion between coil and magnet takes place an emf induced in coil. If coil is in closed circuit then current is also induced in the circuit. This phenomenon is called electromagnetic induction.



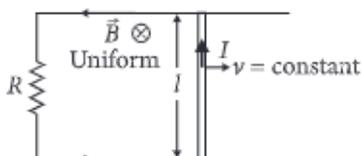
- (i) The north pole of a long bar magnet was pushed slowly into a short solenoid connected to a galvanometer. The magnet was held stationary for a few seconds with the north pole in the middle of the solenoid and then withdrawn rapidly. The maximum deflection of the galvanometer was observed when the magnet was  
 (a) moving towards the solenoid (b) moving into the solenoid  
 (c) at rest inside the solenoid (d) moving out of the solenoid.
- (ii) Two similar circular loops carry equal currents in the same direction. On moving the coils further apart, the electric current will  
 (a) remain unaltered (b) increases in one and decreases in the second  
 (c) increase in both (d) decrease in both.
- (iii) A closed iron ring is held horizontally and a bar magnet is dropped through the ring with its length along the axis of the ring. The acceleration of the falling magnet is.  
 (a) equal to  $g$   
 (b) less than  $g$   
 (c) more than  $g$   
 (d) depends on the diameter of the ring and length of magnet.
- (iv) Whenever there is a relative motion between a coil and a magnet, the magnitude of induced emf set up in the coil does not depend upon the  
 (a) relative speed between the coil and magnet (b) magnetic moment of the coil  
 (c) resistance of the coil (d) number of turns in the coil.

- (v) A coil of metal wire is kept stationary in a non-uniform magnetic field
- (a) an emf and current both are induced in the coil      (b) a current but no emf is induced in the coil  
 (c) an emf but no current is induced in the coil      (d) neither emf nor current is induced in the coil.

6

### Motional EMF from Lorentz Force

The emf induced across the ends of a conductor due to its motion in a magnetic field is called motional emf. It is produced due to the magnetic Lorentz force acting on the free electrons of the conductor. For a circuit shown in figure, if a conductor of length  $l$  moves with velocity  $v$  in a magnetic field  $B$  perpendicular to both its length and the direction of the magnetic field, then all the induced parameters are possible in the circuit.



- (i) Direction of current induced in a wire moving in a magnetic field is found using
- (a) Fleming's left hand rule      (b) Fleming's right hand rule  
 (c) Ampere's rule      (d) Right hand clasp rule
- (ii) A conducting rod of length  $l$  is moving in a transverse magnetic field of strength  $B$  with velocity  $v$ . The resistance of the rod is  $R$ . The current in the rod is
- (a)  $\frac{Blv}{R}$       (b)  $Blv$       (c) zero      (d)  $\frac{B^2v^2l^2}{R}$
- (iii) A 0.1 m long conductor carrying a current of 50 A is held perpendicular to a magnetic field of 1.25 mT. The mechanical power required to move the conductor with a speed of  $1 \text{ m s}^{-1}$  is
- (a) 62.5 mW      (b) 625 mW      (c) 6.25 mW      (d) 12.5 mW
- (iv) A bicycle generator creates 1.5 V at 15 km/hr. The EMF generated at 10 km/hr is
- (a) 1.5 volts      (b) 2 volts      (c) 0.5 volts      (d) 1 volt
- (v) The dimensional formula for emf  $\epsilon$  in MKS system will be
- (a)  $[\text{ML}^2\text{T}^{-3}\text{A}^{-1}]$       (b)  $[\text{ML}^2\text{T}^{-1}\text{A}]$       (c)  $[\text{ML}^2\text{A}]$       (d)  $[\text{MLT}^{-2}\text{A}^{-2}]$

### ASSERTION & REASON

For question numbers 7-20, two statements are given-one labelled Assertion (A) and the other labelled Reason (R). Select the correct answer to these questions from the codes (a), (b), (c) and (d) as given below.

- (a) Both A and R are true and R is the correct explanation of A  
 (b) Both A and R are true but R is NOT the correct explanation of A  
 (c) A is true but R is false  
 (d) A is false and R is also false
7. **Assertion (A)** : When two coils are wound on each other, the mutual induction between the coils is maximum.  
**Reason (R)** : Mutual induction does not depend on the orientation of the coils.
8. **Assertion (A)** : An induced emf is generated when magnet is withdrawn from the solenoid.  
**Reason (R)** : The relative motion between magnet and solenoid induces emf.

9. **Assertion (A)** : An induced current is developed when the number of magnetic lines of force associated with conductor is changed.  
**Reason (R)** : An induced current develop in a conductor moved in a direction parallel to the magnetic field.
10. **Assertion (A)** : A copper sheet is placed in a magnetic field. If we pull it out of the field or push it into the field, we experience an opposing force.  
**Reason (R)** : According to Lenz's law, eddy current produced in sheet opposes the motion of the sheet.
11. **Assertion (A)** : Changing magnetic flux can produce induced e.m.f..  
**Reason (R)** : Faraday established induced e.m.f. experimentally.
12. **Assertion (A)** : Induced e.m.f. depends on number of turns and area of the coil.  
**Reason (R)** : Induced e.m.f. increases with increase in number of turns of coil.
13. **Assertion (A)** : Inductance coil are made of copper.  
**Reason (R)** : Induced current is more in wire having less resistance.
14. **Assertion (A)** : Self-inductance is called the inertia of electricity.  
**Reason (R)** : Self-inductance is the phenomenon, according to which an opposing induced e.m.f. is produced in a coil as a result of change in current or magnetic flux linked with the coil.
15. **Assertion (A)** : When number of turns in a coil doubled, coefficient of self inductance of the coil becomes four times.  
**Reason (R)** : Coefficient of self inductance is proportional to the square of number of turns.
16. **Assertion (A)** : The coil in the resistance boxes are made by doubling the wire.  
**Reason (R)** : Thick wire is required in resistance box.
17. **Assertion (A)** : The resistance of a coil for direct current is 5 ohms. An alternating current is sent through it. The resistance will remain same.  
**Reason (R)** : The resistance of a coil does not depend upon nature of current.
18. **Assertion (A)** : Acceleration of a magnet falling through a copper ring decreases.  
**Reason (R)** : The induced current produced in a circuit always flow in such direction that it opposes the change or the cause that produced it.
19. **Assertion (A)** : An artificial satellite with a metal surface is moving above the earth in a circular orbit. A current will be induced in satellite if the plane of the orbit is inclined to the plane of the equator.  
**Reason (R)** : The current will be induced only when the speed of satellite is more than 8 km/sec.
20. **Assertion (A)** : An aircraft flies along the meridian, the potential develops at the ends of its wings.  
**Reason (R)** : Whenever there is change in the magnetic flux e.m.f. induces.

## HINTS & EXPLANATIONS

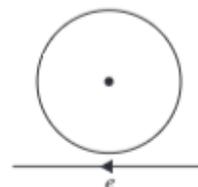
1. (i) (b): The relative motion between the coil and the magnet produces change in the magnetic flux in the coil. The induced emf is always in such a direction that it opposes the change in the flux.

(ii) (c)

(iii) (d)

(iv) (a) : When an electron is moving from right to left, the flux linked with loop (which is going into the page) will first increase and then decrease as the electron

passes by. So the induced current  $I_i$  in the loop will be first clockwise and will change direction (*i.e.* will become anticlockwise) as the electron passes by.



(v) (c) : When current in coil A increases with time, there will be a change of flux in coil B which will induce a current in B. Now, according to Lenz's law, the direction of induced current in B will be opposite

to the direction of current in A. Thus, if two loops carry current in opposite direction they will repel each other.

2. (i) (c) : The mutual inductance of the system is  

$$M = \mu_0 n_1 n_2 \pi a^2 L$$

(ii) (c) : Here,  $\phi_B = 2 \times 10^{-2}$  Wb,  $I = 0.01$  A  
 As  $\phi_B = MI$

$\therefore$  Mutual inductance between two coils is

$$M = \frac{\phi_B}{I} = \frac{2 \times 10^{-2} \text{ Wb}}{0.01 \text{ A}} = 2 \text{ H}$$

(iii) (b) : Mutual inductance of coils,  $M = \frac{\mu_0 \mu_r N_1 N_2 A}{l}$

It is clear that mutual inductance of coils can be increased by increasing the number of turns in the coils.

(iv) (a) : We know that the mutual inductance depends (directly proportional) on the permeability of the medium surrounding the coils. When the permeability of the medium is increased by inserting a sheet of iron, then the mutual inductance between the coils also increases.

(v) (c)

3. (i) (b) : The working of speedometers is based on eddy currents.

(ii) (a)

(iii) (a) : To reduce the eddy currents in the metal armature of motors, wire is wrapped around a number of thin metal sheets called lamination.

(iv) (c) : Eddy currents also oppose the change in magnetic flux, so their direction is given by Lenz's law.

(v) (c)

4. (i) (a) : The inductance in a coil plays the same role as inertia in mechanics.

(ii) (b) : Here,  $I = 2.5$  A,  $L = 5$  H

Magnetic flux linked with the coil is

$$\phi_B = LI = (5 \text{ H})(2.5 \text{ A}) = 12.5 \text{ Wb}$$

(iii) (c) : The inductance of a solenoid is

$$L = \mu_0 n^2 Al$$

where  $A$  is the area of cross-section of the solenoid,  $l$  its length and  $n$  is the number of turns per unit length. As  $A = \pi R^2$ , where  $R$  is the radius of the solenoid.

$$\therefore L = \mu_0 n^2 \pi R^2 l \Rightarrow L \propto R^2$$

(iv) (c) : The magnitude of induced emf is

$$|\epsilon| = L \frac{dI}{dt} \Rightarrow L = \frac{|\epsilon| dt}{dI}$$

$$\text{or, } L = \frac{\text{volt} \times \text{second}}{\text{ampere}} = \text{ohm second}$$

(v) (b) : Here  $L = 10$  henry  $I_1 = 9$  A,  $I_2 = 4$  A and  $\Delta t = 0.2$  second

Then induced e.m.f.

$$\epsilon_1 = -L \frac{dI}{dt} = -L \frac{(I_2 - I_1)}{\Delta t} = \frac{-10 \times (4 - 9)}{0.2} = \frac{50}{0.2} = 250 \text{ V}$$

5. (i) (d) : More rapid is the movement of bar magnet, more is the deflection observed in the galvanometer.

(ii) (c) : Two circular loops carrying current in the same direction will attract each other. If they are now separated, induced currents will try to keep status quo, by increasing the current in both the coils.

(iii) (b) : Acceleration of the magnet will not be equal to  $g$ . It will be less than  $g$ . This is because, as the magnet falls, amount of magnetic flux linked with the ring changes.

An induced emf is developed in the ring which opposes the downward motion of the magnet.

(iv) (c) : The magnitude of induced emf set up in the coil does not depend upon the resistance of the coil whereas induced current set up in the coil depend upon the resistance of the coil.

(v) (d) : As long as a coil of metal is kept stationary in a magnetic field, even if it is non-uniform, unless it is changing with respect to time, there will be no induced emf or current in the coil.

6. (i) (b) : Direction of current induced in a wire moving in a magnetic field is found by using Fleming's right hand rule.

(ii) (a) : Induced e.m.f,  $\epsilon = Blv$

$$\text{Current in the rod, } I = \frac{\epsilon}{R} = \frac{Blv}{R}$$

(iii) (c) : Here,  $l = 0.1$  m,  $v = 1$  m s<sup>-1</sup>

$$I = 50 \text{ A, } B = 1.25 \text{ mT} = 1.25 \times 10^{-3} \text{ T}$$

The induced emf is,  $\epsilon = Blv$

The mechanical power is

$$P = \epsilon I = BlvI = 1.25 \times 10^{-3} \times 0.1 \times 1 \times 50 = 6.25 \times 10^{-3} \text{ W} = 6.25 \text{ mW}$$

(iv) (d) : Emf induced,  $\epsilon = Blv$

Here,  $\vec{B}$ ,  $\vec{l}$  and  $\vec{v}$  are mutually perpendicular

For given  $B$  and  $l$ ,  $\epsilon \propto v$ .

$$\therefore \frac{\epsilon_1}{\epsilon_2} = \frac{v_1}{v_2}$$

$$\text{Here, } \epsilon_1 = 1.5 \text{ V, } v_1 = 15 \text{ km/hr} = 15 \times \frac{5}{18} \text{ ms}^{-1}$$

$$v_2 = 10 \text{ km/hr} = 10 \times \frac{5}{18} \text{ ms}^{-1}, \epsilon_2 = ?$$

$$\text{So, } \frac{1.5}{\epsilon_2} = \frac{15 \times \frac{5}{18}}{10 \times \frac{5}{18}} = \frac{3}{2}; \quad \epsilon_2 = 1 \text{ V}$$

$$(v) (a): \epsilon = \frac{[W]}{[q]} = \frac{ML^2T^{-2}}{AT} = ML^2T^{-3}A^{-1}$$

7. (c): The manner in which the two coils are oriented, determines the coefficient of coupling

$$\text{between them i.e., } K = \sqrt{\frac{M}{L_1 L_2}}$$

where  $L_1$  and  $L_2$  are self inductance of two coils. When the two coils are wound on each other, the coefficient of coupling is maximum and hence mutual inductance between the coil is maximum.

8. (a): According to Faraday's law of electromagnetic induction, induced emf will be generated in the solenoid because of the relative motion between magnet and solenoid.

9. (a): An induced current develop in a conductor cannot moved in a direction parallel to magnetic field. This is because when the conductor moved in a direction parallel to magnetic field, amount of flux linked with the conductor does not change. Thus the induced current develops only when conductor cuts the lines of magnetic force. The direction of flow of induced current can also be found by applying Fleming's right hand rule, when the direction of motion of conductor inside the magnetic field and the

motion of conductor inside the magnetic field and the direction of magnetic field action on it are known.

10. (a): When we pull a copper plate out of the magnetic field or push it into the magnetic field, magnetic flux linked with the plate changes. As a result of this eddy currents are produced in the plate which oppose its motion (according to Lenz's law).

11. (b): E.m.f. induces, when there is change in magnetic flux. The magnitude of induced e.m.f. depends upon the rate at which the magnetic flux changes. When magnetic flux is steady or constant no e.m.f. is induced. Faraday did experiment in which, there is relative motion between the coil and magnet, the flux linked with the coil changes and e.m.f. induces.

12. (b): According to Faraday's law, the induced e.m.f.

$$(\epsilon) \text{ is given by } \epsilon = \frac{-d(N\phi)}{dt} = -\frac{d(NBA)}{dt} = -NA \frac{dB}{dt}.$$

Thus the induced e.m.f. depends on the rate of change of magnetic flux, number of turns of coil and area of the coil. If any of these factor increases (or decreases) then induced e.m.f. also increases (or decreases).

13. (a): The inductance coils made of copper will have very small ohmic resistance. Due to change in magnetic flux a large induced current will be produced in such an inductance, which will offer appreciable opposition to the flow of current.

14. (a): Self-inductance of a coil is its property by virtue of which the coil opposes any change in the current flowing through it. It is because, the induced emf produced opposes the change in current. For this reason, self induction is called inertia of electricity.

15. (a): The coefficient of self inductance of the coil is given by  $L = \frac{\mu_0 N^2 A}{l}$

where  $N$  is number of turns,  $l$  is length of the coil and  $A$  is area of coil, so  $L \propto N^2$ .

16. (c): The coil in the resistance boxes are made from double wire. Due to this current in two wires flows in opposite directions i.e., magnetic flux linked with the each coil cancel each other. Thus, no e.m.f. is induced in the resistance.

17. (d): Both assertion and reason are false. When an alternating current is sent through the coil then effective resistance of the coil will be  $\sqrt{R^2 + (\omega L)^2}$  while it was only  $R$  for direct current i.e., effective resistance of coil will increases for A.C.

18. (a): Both the assertion and reason are true and reason is the correct explanation of assertion.

reason is the correct explanation of assertion. When the magnet falls, the magnetic flux through the copper ring increases and induced e.m.f. is produced in the ring. The induced emf so produced, opposes the motion of falling magnet. Therefore, the acceleration of the falling magnet will be less than that due to gravity.

19. (c): When the satellite move in inclined plane with equatorial plane the value of magnetic field will change both in magnitude and direction. Due to this, the magnetic flux through the satellite will change and hence induced currents will be produced in the metal of the satellite. But no current will induce if satellite orbits in the equatorial plane because the magnetic flux does not change through the metal of the satellite in this plane.

20. (a): As the aircraft flies, magnetic flux changes through its wings due to the vertical component of the earth's magnetic field. Due to this, induced emf is produced across the wings of the aircraft.