Notes:

(i) From Fleming's **right**-hand rule,

- Current is anti-clockwise in the loop
- XY is the source of (induced) e.m.f.
- Y is the **positive** and X is the **negative** terminal.

(ii) Electrical energy is obtained as long as the disc rotates.

- Larger e.m.f. as rotation speed increases
- **Mechanical** energy is converted to **electrical** energy.

(iii) No e.m.f. will be induced if the contact at X is removed and made to touch a point on the rim **diametrically** opposite to Y.

(iv) An application of the Faraday's rotating disc is its use in the **car speedometer**.

- The axle of the disc is connected by a link to the driving wheels
- The faster the wheel turns, the faster the disc rotates in a magnetic field
- With the rim and axle of the disc connected to a voltmeter via carbon brushes, the meter readings, when calibrated, will indicate the speed of the car.

Example 6

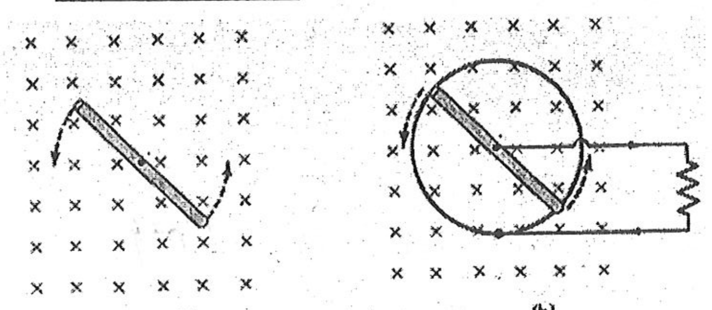
A straight metallic rod is rotating about its midpoint on an axis parallel to a uniform magnetic field. The length of the rod is $2l$, and the angular velocity of rotation is ω.

(i) What is the induced emf between the midpoint of the rod and the each end?

(ii) Indicate on the diagram the positive and negative terminals of the induced emf.

(iii) What is the induced emf between the two ends?

(i) Consider one-half of the rod, from the midpoint to one end. This piece takes a time $\frac{2\pi}{\omega}$ to sweep out the circular area πl^2. Hence the rate at which it sweeps across the magnetic flux is $\frac{l^2\omega}{2}$, i.e. induced emf = $\frac{Bl^2\omega}{2}$ between the midpoint and each end.

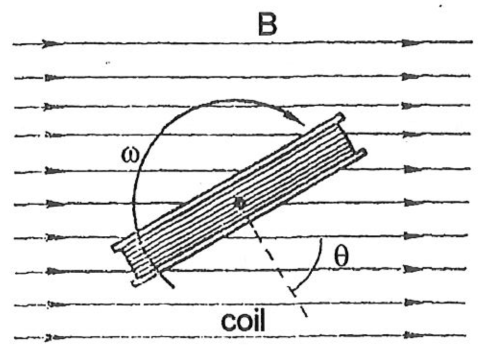


(a) (b)

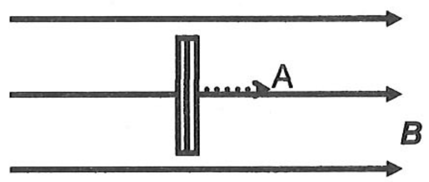
(iii) The emf between the two ends is zero because both ends act as negative terminals, i.e. the emf induced in each half of the rod is in the opposite direction.

(D) Induced e.m.f. in a rotating coil [Change in θ]

Consider a coil of N turns and area A being rotated at a constant angular velocity ω in a magnetic field of flux density B, its **axis being perpendicular to the field**.

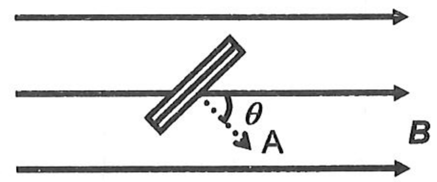


(i) At time $t = 0$



Plane of the coil is perpendicular to B, i.e. $\theta = 0°$, where θ is the angle between the **normal** to the plane of the coil and the magnetic field B.

(ii) At time t



The angle between the normal to the plane of the coil and B is θ.
Flux linking each turn is given by

$$\phi = BA\cos\theta = BA\cos\omega t$$

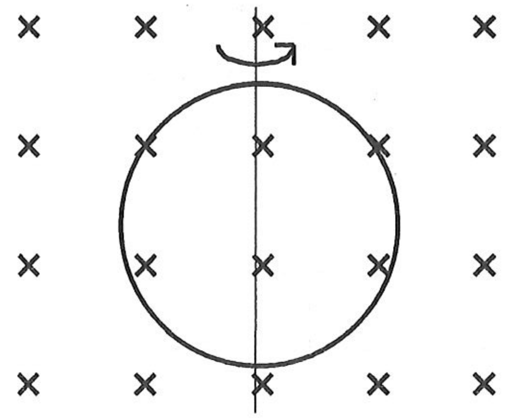
By Faraday's law,

$$E = -\frac{d}{dt}(\text{total }\phi) = -\frac{d}{dt}(N\phi) = -\frac{d}{dt}(NBA\cos\omega t)$$

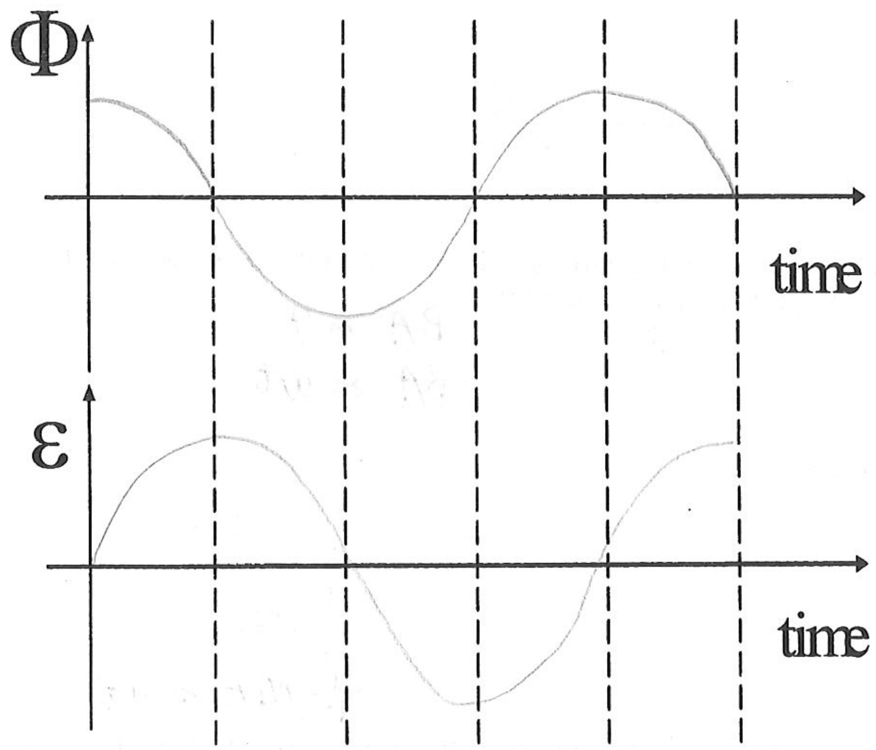
Thus, $E = NBA\omega\sin\omega t$ is a sinusoidally alternating e.m.f. induced in the rotating coil.

Note: Unlike the emf in the previous examples, this one changes with time. Its sinusoidal time dependence is in fact just like that of standard alternating emf used for household electric power. In fact, **sinusoidally varying emf** arises whenever **conducting loops** are rotated in **uniform magnetic fields.**

Example 7
Consider a circular coil rotating in a magnetic field (directed into paper).



At time $t = 0$, the plane of the coil is perpendicular to the field as shown above.
Sketch the graphs of
(a) total flux linked to the coil against time; and
(b) e.m.f. induced in the coil against time.



(a) $E = NBlv = 85 \times 1.5 \times 13 \times 10^{-12} \times 18 \times 10^{-12} = 2.98\ V$

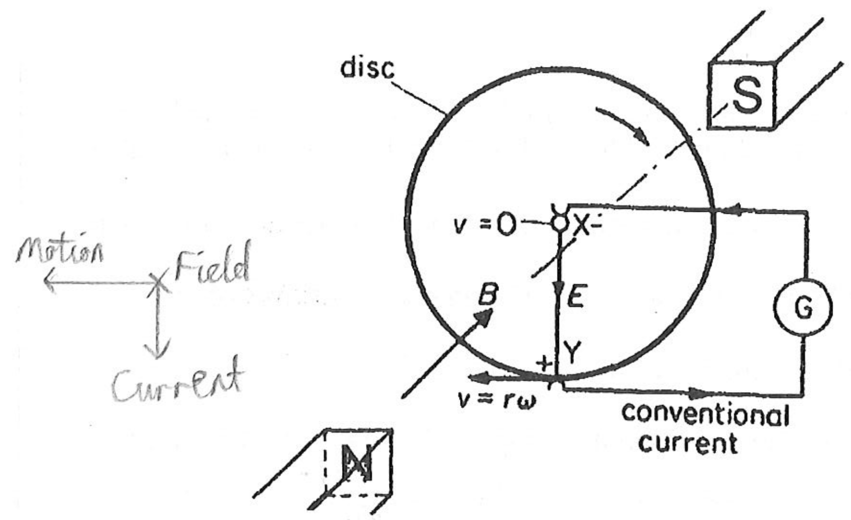
(b) $I = \frac{E}{R} = \frac{2.92}{6.2} = 0.48A$

(c) $F = NBIl = 85 \times 0.481 \times 13 \times 10^{-12} \times 1.5 = 8.0N$

(d) Rate at which work must be done = $Fv = 9.38 \times 10^{-2} \times 18 \times 10^{-2}$
$= 1.7 \times 10^{-2}\ W$

(C) Induced e.m.f. in a spinning disc (Faraday's rotating disc) [Flux-cutting]

In 1831, Michael Faraday performed the following experiment which had far-reaching consequences for electrical technology. He had invented a means by which electricity could be generated by moving conductors through magnetic fields.



(i) A metal disc of radius r is rotated at a steady speed in a perpendicular magnetic field B.
(ii) Sliding contacts are made at the rim (Y) and axle (X).
(iii) As the disc rotates, the radius of the disc between the contacts at any instant is cutting the magnetic flux at a steady rate, inducing an e.m.f. between X and Y. A current then flows in the direction indicated.

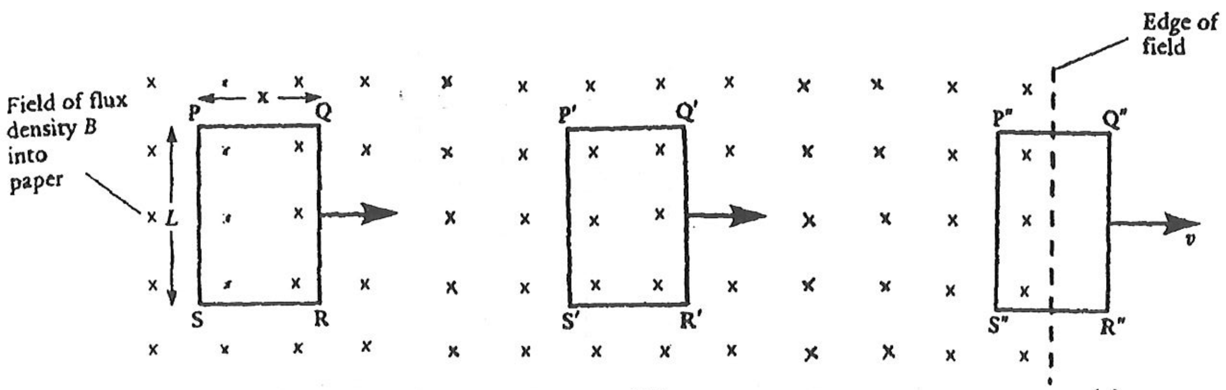
If the disc makes f revolutions per second,

then the area swept over per second $= \frac{d}{dt}(A) =$ $\pi r^2 f$

$\therefore$ Flux cutting per second $= = B\frac{d}{dt}(A) = B\pi r^2 f$.

E.m.f. induced between the axle and the rim is $\boldsymbol{E = B\pi r^2 f}$

(B) Induced e.m.f. in a rectangular coil [Flux-Cutting]



(a) $\varepsilon = 0$

(b) $\varepsilon = 0$

(c) $\varepsilon = Blv$

Figures (a) and (b)

(i) Sides PQ and RS move parallel to its length, hence no. emf is induced in them.

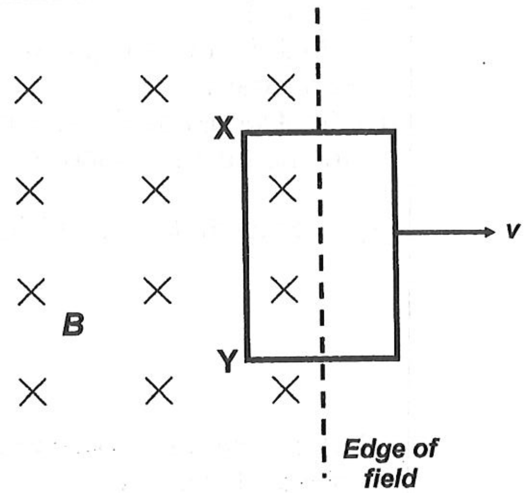
(ii) Sides PS and QR cut across the field lines, so that equal and opposite e.m.f.s are induced in them.
Thus, the net e.m.f. in the coil is zero.

OR Since there is no change in flux through the coil as it moves (same area within constant B field), net e.m.f. is zero.

Figure (c)

When the side Q"R" leaves the field B, induced e.m.f. appears across P"S" only and the coil therefore has a net e.m.f. $E = Blv$.
A current flows clockwise in the coil.

Example 5
[*Compare with* figure (c) above.]
A rectangular loop is pulled out of the magnetic field B at a constant speed v.
Suppose the loop is a tightly wound coil of 85 turns, made of copper wire.
XY = 13 cm, B = 1.5 T, resistance of the loop R is 6.2 Ω, and v = 18 cms^{-1}.
(a) What induced e.m.f. appears in the coil?
(b) What is the induced current?
(c) What force must you exert on the coil to pull it along?
(d) At what rate must you do work to pull the coil along?



(E) Induced e.m.f. in a stationary coil [Change in *B*]

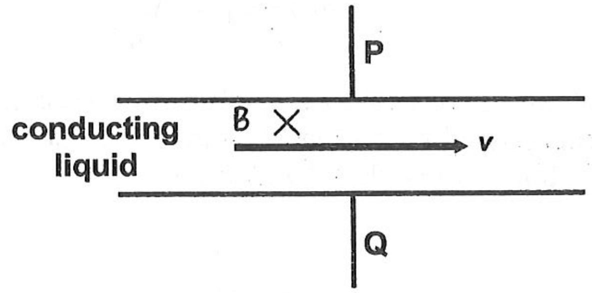
Example 8
Refer to Pg 3 and 4 on "Experiments on Electromagnetic Induction".

For (i), as the magnet moves closer to the coil, the coil will experience an increasing magnetic flux as flux density is larger nearer to the pole of a bar magnet. This is a case of a change in magnetic flux due to a change in the flux density, leading to an induced e.m.f. in the coil.

For (ii), as the switch is turned on, coil B will experience an increasing magnetic flux as the flux density of coil A will increase from zero to a maximum value. Hence, this is also a case of a change in magnetic flux due to a change in the flux density, leading to an induced e.m.f. in the coil.

(F) Induced e.m.f. in a conducting liquid

Example 9



An electromagnetic flow meter consists of a measuring instrument connected to two electrodes P and Q on diametrical ends of a pipe which carries a conducting liquid.
If a magnetic field B = 0.010 T is directed into the plane of the paper at the conducting liquid in the region of the electrodes, determine
(i) which electrode is at a higher potential; and
(ii) the volume rate of flow of the liquid (in m^3s^{-1}) if the diameter of the pipe is 50 mm and the e.m.f. generated between P and Q is 0.25 mV.

(i) Using Fleming's right-hand rule, P is at a higher potential.

(ii) Generation of e.m.f. between P and Q establishes an electric field which produces an electric force opposing the magnetic force, i.e.

$E = Bl v$

$V = \frac{E}{Bl} = \frac{0.25 \times 10^{-3}}{0.01 \times 50 \times 10^{-3}} \times 0.5\ ms^{-1}$

∴ Volume flow rate = Av = $9.8 \times 10^{-4}\ m^3 s^{-1}$

7 Appendices

Use of a Search Coil to Measure Flux Density

- Flux Linkage and Charge

When the flux linking a closed circuit changes, a current flows. During this process, a quantity of charge passes.

Consider the case in which the flux linking a coil of N turns changes at a steady rate from $\Phi 1$ to $\Phi 2$ in time t. A steady emf E is induced given by

$$E = \frac{N(\Phi_2 - \Phi_1)}{t}$$

If the circuit has a resistance R, the steady current that flows is

$$I = \frac{E}{R}$$

Hence, the quantity of charge Q which flows in a time t is given by

$$Q = It = \frac{Et}{R}$$

$$= \frac{N(\Phi_2 - \Phi_1)}{R} = \frac{N\Delta\Phi}{R}$$

If the change of flux is brought about rapidly, Q may be measured by a ballistic galvanometer. For a ballistic galvanometer, Q is directly proportional to the first deflection of the galvanometer, i.e.

$$Q \propto \theta$$

$$Q = c\theta$$

where θ is the first deflection of the galvanometer and c is a proportionality constant.

A search coil, connected to a ballistic galvanometer, is placed with its plane perpendicular to a magnetic field B.

The initial flux Φ linked with the search coil is given by

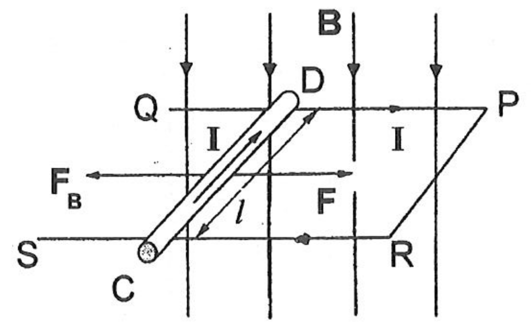
$$\Phi = BAN$$

The coil is given a sharp pull downwards out of the magnetic field and the first deflection θ of the galvanometer is noted.

The charge through the galvanometer is

$$Q = \frac{BAN}{R} = c\theta$$

Method II: Using law of conservation of energy



Consider CD being pulled by an external agent with a force F along the metal rails PQ and RS at a steady velocity v across the B field.
CD cuts the magnetic flux and causes a change of flux linkage in the area PRCD.
An e.m.f. is induced in the circuit. The induced e.m.f. will drive a current clockwise (by Fleming's **right**-hand rule) in the circuit.
This causes a magnetic force F_B to act (to the left by Fleming's **left**-hand rule) on the conductor opposing F.
When the conductor CD moves with uniform velocity v, we have

$$F = F_B = BIl$$

By the law of conservation of energy,
rate of work done by external agent = rate at which electrical energy is generated

$$BIlv = IE$$

Hence, $E = Blv$

Example 4
An aeroplane with a wingspan of 50 m flies horizontally with a speed of 180 ms^{-1} at a location where the vertical component of the Earth's magnetic field is 3.5 x 10^{-5} T.
(a) What is the magnitude of the e.m.f. induced across the aeroplane's wingspan?
(b) What would be the reading on a voltmeter connected between the ends of the aeroplane's wings?

(a) Magnitude of e.m.f. induced $= Blv$
$= 3.5 \times 10^{-5} \times 50 \times 180$
$= 0.32\,V$

(b) The voltmeter would read 0V. The reason will be discussed in the next section.

6 Applications of the Laws of Electromagnetic Induction

We will consider the induced e.m.f.s in following types of conductor:

(A) In a straight conductor

(B) In a rectangular coil

(C) In a spinning disc (Faraday's rotating disc)

flux cutting

(D) In a rotating coil θ changes

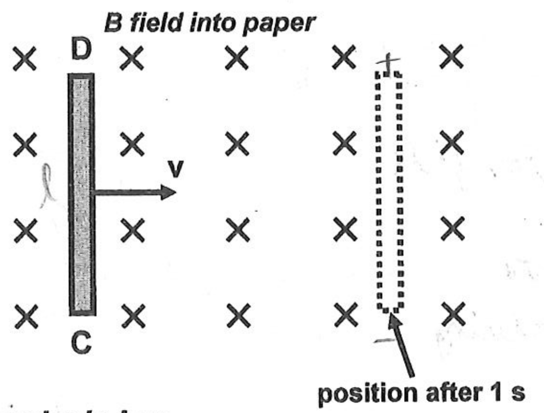
(E) In a stationary coil B changes

(F) In a conducting liquid flux cutting

Take note of the way that the flux changes in each of these cases.

(A) Induced e.m.f. in a straight conductor [Flux-cutting]

Consider a straight conductor of length l moving with a velocity v at right angles to a uniform magnetic field B.



Method I: Using Faraday's law

Area swept out by CD in 1 s = lv

Flux cut by CD in 1 s = Blv (since B is directed perpendicular to area swept out)

Across the ends CD,
induced e.m.f. E = rate of flux cutting = Blv

In general, $$E = Blv$$

Using Fleming's right-hand rule, the end D is at a higher electric potential than C.
If a stationary wire outside the field is connected across the conductor, a current would flow out from D and into C.

Hence, $$B = \frac{c\theta R}{AN}$$

where c = a predetermined constant of the galvanometer
R = total resistance of the circuit
A = area of the search coil
N = number of turns in the search coil
θ = first deflection of the galvanometer

Eddy Currents

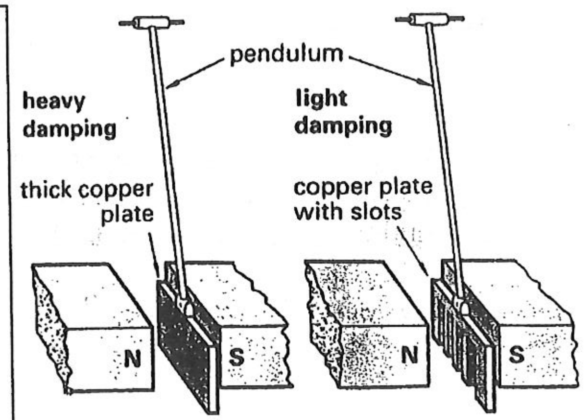
- Our discussion of induced currents has centred on conducting loops. But induced currents also appear in solid conductors through which magnetic flux is changing, e.g. in the iron core of an a.c. transformer
- Lenz's law shows that the **direction** of eddy currents in the conductor tend to *retard the motion* of the conductor in the magnetic field

  OR

  to *oppose the change of flux* through a stationary conductor

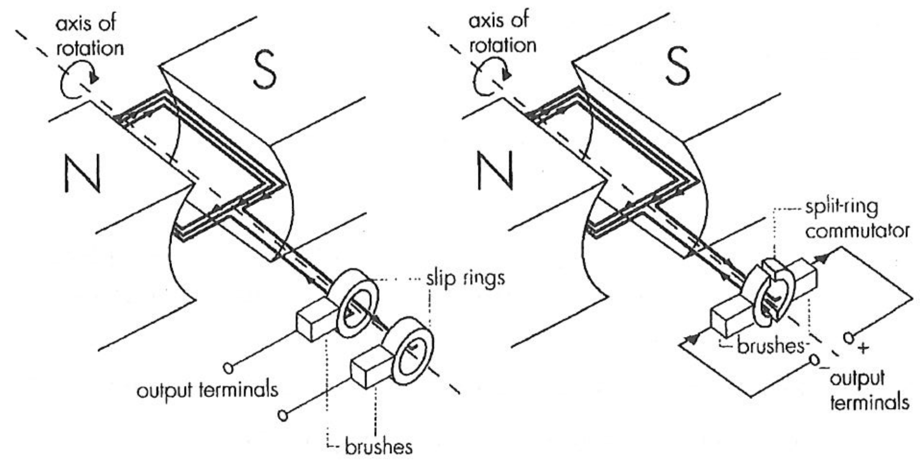
  (electromagnetic damping)
- Eddy currents also give rise to a **heating effect**.
- Electromagnetic damping effect is being used in **moving coil meters** so that the coil takes up its deflected position quickly without oscillating about its final reading.
- **Mechanical energy** is being transformed into **electrical energy** of the eddy currents which in turn is transformed into **internal energy**, thus warming the conductor.
- To minimize this energy loss through eddy currents in iron-cored instruments (e.g. motors, generators and transformers), **laminated** sheets of iron are used.
- This increases the resistance of the eddy current paths.
- Laminations are intended to break the paths for eddy current flow.
  When a thick copper plate is made to swing into a magnetic field, eddy currents are produced in the metal, by **Faraday's law**.

QUESTION By **Lenz's law**, these currents set up a magnetic field to oppose the field of the magnet, leading to retardation of the plate's motion.
Large induced currents may be reduced by creating slots in the plate. Why?
The slots increases the resistance of the eddy current paths.



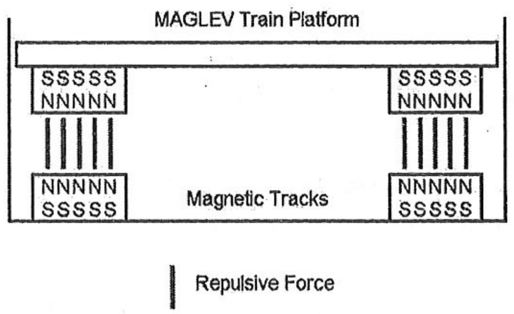
8 Applications of Electromagnetic Induction

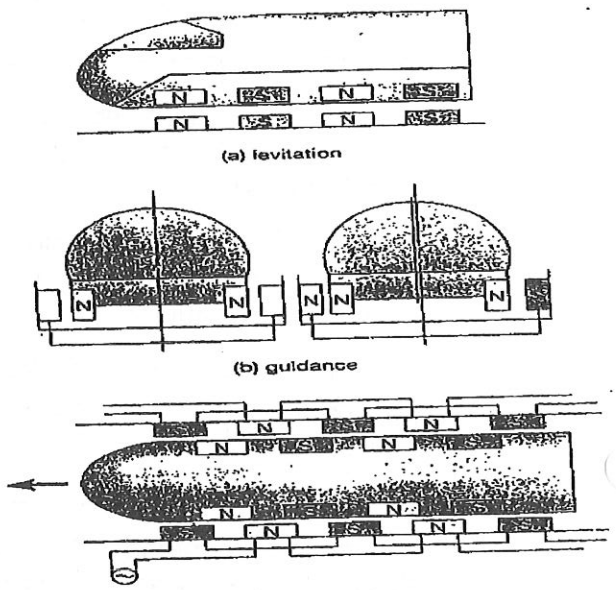
1 a.c. and d.c. generators (see reference 1, p.336)



2 In the levitation and guidance of the MagLev train which levitates a centimetre or two above the track and travels at 480 kmh^{-1}

Magnetic Levitation Trains





3 Electric guitars (see reference 3, p. 880)
4 Metal detectors (see reference 3, p. 910)
5 Induction stove (see reference 3, p. 882)

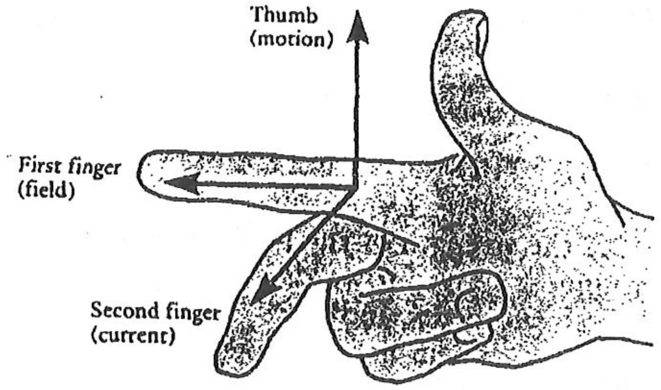
References

Books

1 Physics, Robert Hutchings (2000), pp. 330 – 342.
2 Physics in Focus, Michael Brimicombe (1990), pp. 424 – 431.
3 Fundamentals of Physics, Halliday, Resnick & Walker (1993), pp. 874 – 883.
4 Physics, Patrick Fullick (1994), pp. 454 – 463, 468 – 475.

- **Fleming's Right Hand Rule (dynamo rule)**

Useful for straight wires



Recall Fleming's rules:

RIght = Induction
LeFt = Force

- **Maxwell's Right-hand Corkscrew Rule**

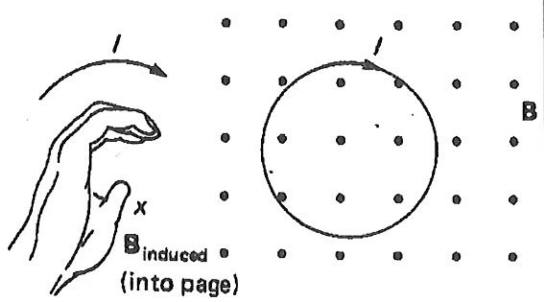
Useful for coils

Example 3

Figure shows a wire loop in a magnetic field that points out of the page. Suppose the field is *increasing in strength*. What is the direction of the induced current that flows in the loop?

By Lenz's Law, the induced current must be flowing in a direction to oppose the change that causes it, i.e. *strengthening of the field*.

Hence the field due to the induced current points *into* the page within the loop, thus *reducing* the net field strength.



From the Right-hand rule, the loop current is *clockwise*.

QUESTION

If the magnetic field points into the page and is decreasing. What is the direction of the induced current flow? *Clockwise*

Example 2
A 20-turn circular coil of diameter 4.0 cm is at right angles to a magnetic flux density of 50 mT. The flux density is then reduced steadily to zero in 10 s. What is the magnitude of the e.m.f. induced in the coil?

Magnitude of induced e.m.f. in the coil, according to Faraday's law, is

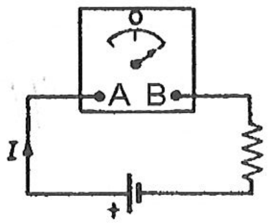
$$E = \frac{dN\phi}{dt} = \frac{N(\phi_i - \phi_f)}{t} = \frac{NBA - 0}{t} = \frac{NBA}{t}$$

where N = no. of turns of coil;
B = magnetic flux density; and
A = area of coil.

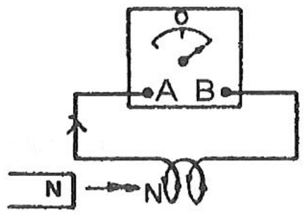
$$= \frac{20 \times 50 \times 10^{-3} \times \frac{\pi}{4}(4.0 \times 10^{-2})^2}{10} = 1.3 \times 10^{-4}\ V$$

- **Demonstration of Lenz's Law**

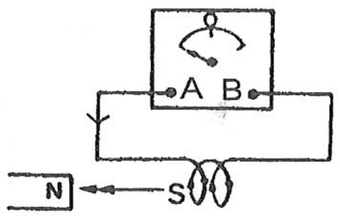
(a) Cell drives current to flow from **A** to **B**. The pointer deflects towards **B**.



(b) The "N" pole of a magnet is made to approach one end of a coil, producing an induced current in the coil which flows from **A** to **B** so that a magnetic "N" pole is produced at this end of the coil. The approaching magnet is thus repelled, hence "opposing" its motion that is causing the current. The pointer deflects towards **B**.



(c) The "S" pole of the magnet is made to approach the coil, producing an induced current in the coil which flows from **B** to **A** so that the end facing the receding magnet becomes magnetic "S" pole (to attract the magnet, hence "opposing" its motion again.) The pointer deflects towards **A**.



- **Lenz's Law and the Principle of Conservation of Energy**

Consider in the case where a North pole is induced at the end of a solenoid facing a magnet when the magnet's North pole is moved towards the solenoid. The presence of the induced North pole means that work has to be done to move the magnet against the repulsive force between the North pole of the magnet and the induced North pole. The mechanical work done is converted to electrical energy. This is consistent with the principle of conservation of energy.

i.e. **Mechanical** work expended in pushing the magnet is transformed into induced current (**electrical** energy)

Electromagnetic Induction Tutorial

Self-Attempt Exercises

S1 The magnetic flux through a coil changes uniformly from 5.00×10^{-4} Wb to 2.50×10^{-3} Wb in 2.00×10^{-2} s. Find the induced e.m.f. in the coil.

S2 An aeroplane has a wing span of 10 m and is flying at a speed of 250 ms^{-1}. What is the induced e.m.f. between the ends of the wings, if the vertical component of the Earth's magnetic field is 5×10^{-5} T?

S3 A rectangular coil of 6.00 cm by 8.00 cm is located in a uniform magnetic field B of 0.250 T. Find the flux through the coil when the plane of the coil is
(a) perpendicular to B;
(b) parallel to B; and
(c) makes an angle of 60° with B.

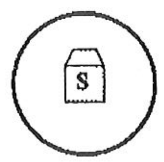
$20\ cm^2 = 2cm \times 10cm = 0.02 \times 0.1$
$2 \times 10^{-3}\ m^2$

S4 A coil with 475 turns and cross-sectional area of 20 cm^2 rotates at 600 revolutions per minute in a uniform magnetic field of 0.01 T. What is the peak value of the e.m.f. induced in the coil?

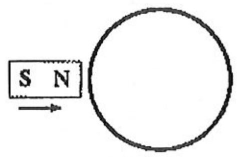
S5 In which of the following scenarios will a current be induced?
(i) A magnet moving away from a coil of wire.
(ii) A loop of wire ritating along the axis perpendicular to its plane so that it is spinning like a CD. This axis is parallel to the magnetic field lines.
(iii) A loop of wire rotating along an axis in the plane of the coil, which is perpendicular to the magentic field lines.
(iv) A solenoid rotating about an axis in the plane of the coil, which is parallel to the magnetic field lines.
(v) A single loop of wire moing across a uniform magnetic field, so that its normal is parallel to the magnetic field lines.

Discussion Questions

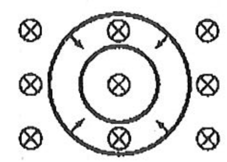
D1 Lenz's Law
In which direction is the current induced in the loop for each situation below?



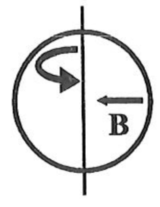
(a)
N magnetic pole moving toward loop into the page



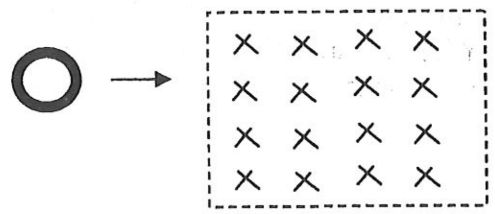
(b)
N magnetic pole moving toward the loop in the plane of the page



(c)
Shrinking a loop in a magnetic field pointing into the page



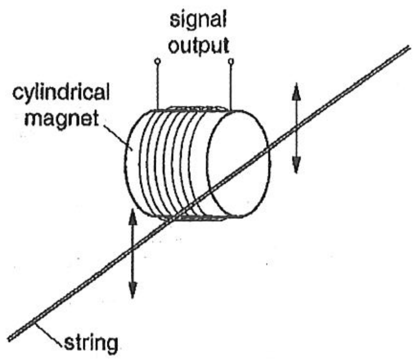
(e)
Rotating the loop about the vertical diameter by pulling the left side toward the reader and pushing the right side away from the reader in a magnetic field that points from right to left in the plane of the page



(d)
A copper ring moves through space and and passes through a rectangular region where a uniform magnetic field is directed downward.

D2 Faraday's Law (N2001/P2/Q6)

The pick-up on an electric guitar produces an electrical signal from the vibrations of the guitar strings. The pick-up consists of a small coil of insulated wire wound round a small cylindrical bar magnet as illustrated in the figure.



The strings of the guitar are made of steel. When a string vibrates, an electrical signal is generated between the terminals of the coil.

(a) (i) State Faraday's law of electromagnetic induction.

(ii) Use Faraday's law to explain why an electrical signal is generated. [4]

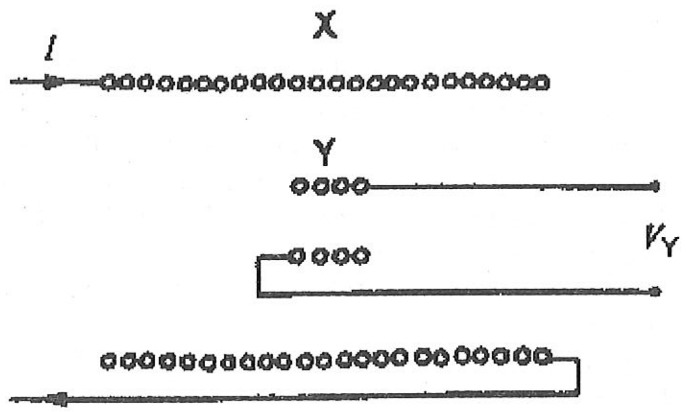
(b) Suggest why

(i) the electrical signal must be amplified before connection to a loudspeaker,

(ii) the design of the pick-up would be inappropriate for use on a guitar with nylon strings. [3]

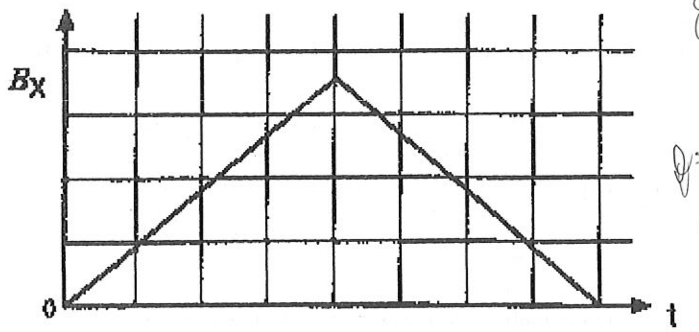
D3 Induced EMF

A small coil Y is placed inside a long solenoid X. The coils are coaxial, as shown in the figure below.



I varies ⇒ B changing
ϕ changing
⇒ induced emf

By changing the current, I, the magnetic flux density B_X within the solenoid X is varied with time t as shown below. This produces an induced e.m.f. V_Y in the coil Y.



$\mathcal{E} = -\frac{dN\phi}{dt}$

$= -\frac{dN(BA\cos\theta)}{dt}$

$\theta = 0^\circ$

$= -NA\frac{dB}{dt}$

(a) Sketch the variation of V_Y with t.

(b) During the change in magnetic flux density in solenoid X, the maximum induced e.m.f. in coil Y is 5.0 V. The maximum magnetic flux through each turn of coil Y is 0.75 Wb. Coil Y has 20 turns. Calculate the time required for the magnetic flux density in solenoid X to increase from zero to its maximum value.

$\phi_Y = 0.75(20)$
$= 15$ Wb
$E = \frac{\Delta\phi}{t}$
$t = \frac{(15-0)}{5}$
$= 3$ s

5 Laws of Electromagnetic Induction

- **Faraday's Law** [Michael Faraday: 1791-1867]

Faraday's Law states that the magnitude of the induced emf E in a circuit is directly proportional to the rate of change of flux-linkage or to the rate of cutting of magnetic flux.

ΔB, ΔA, Δθ
cut magnetic lines

- **Lenz's Law** [Heinrich Friedrich Lenz : 1804-1865]

solid object → cut flux to induce emf

Lenz's Law states that the direction of any induced current is such as to oppose the change in flux that causes it.

loop → Δ of flux

Mathematically, the two laws can be summed up in a mathematical equation:

$$\boxed{E = -\frac{d(N\phi)}{dt}}$$

where E is the induced emf in volts and

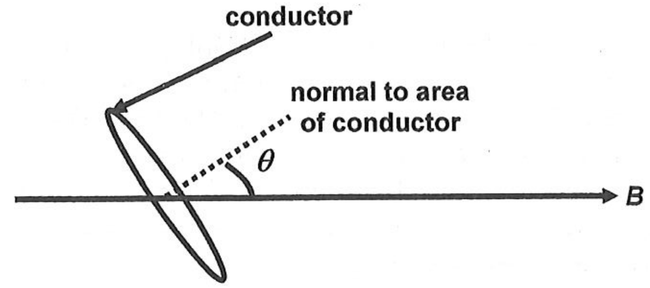
$\frac{d(N\Phi)}{dt}$ is the rate of change of flux-linkage in webers per second.

Note: The minus sign expresses Lenz's Law. It is used to determine the direction of the induced current. However, we sometimes *omit the minus sign* in our workings. But we must always remember to account for the direction of the emf and/or current.

It is more fundamental to deal with the e.m.f. than the current as current depends on both e.m.f. and resistance.

Calculation of induced e.m.f.:

$$E = -\frac{d}{dt}(N\phi) = -\frac{d}{dt}(NBA\cos\theta)$$

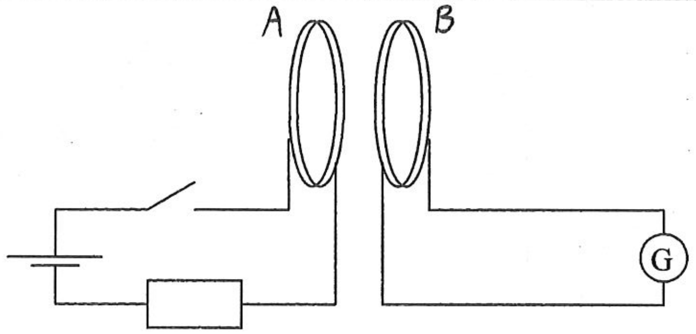


(a) Magnet is at rest: There is no change in magnetic flux through the coil, hence no e.m.f is induced.
(b) Magnet is approaching the coil: magnetic flux through the coil increases and induced e.m.f. detected.
(c) Magnet is moving away from the coil: magnetic flux through the coil decreases and induced e.m.f. in the opposite direction detected.

Alternatively, induced e.m.f. can be produced if the coil is moved towards or away from the stationary magnet.

QUESTION What can you deduce from this experimental observation?
When there is relative motion between the coil and magnet, magnetic flux through the coil changes, and hence e.m.f is induced.

(ii)



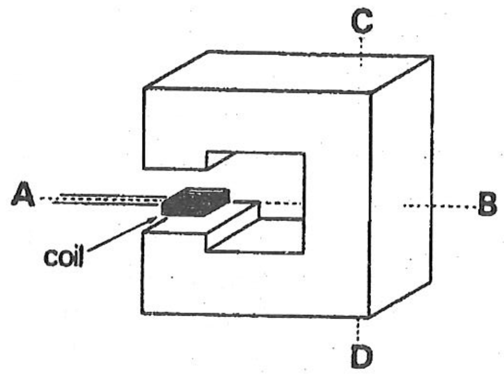
Electromagnetic induction can also occur without any motion at all. This can be demonstrated by switching on and off the current to coil A as shown above.

QUESTION The deflection of the galvanometer is only observed at the instant when the circuit is on or off; the induced emf is zero when a steady current is passing through the coil. Why?

- At the instant when the circuit is on, the current in A grows to its steady value. This rate of growth of current causes an increasing magnetic field to set up in coil A. (Recall the magnetic effect of a current flowing in a conductor in Electromagnetism)
- The magnetic field in A is linked to B due to its close proximity, hence coil B experiences a change in magnetic flux resulting in an induced e.m.f in it.
- When the circuit is opened, the sudden cut off of the current also causes a decrease in the magnetic flux and thus an induced emf in coil B. The deflection would be in one direction when the circuit is made and in the opposite direction when it is broken.

D4 N89/P3/Q12 (part)

(a) Distinguish between *magnetic flux density* and *magnetic flux*. [2]
(b) (i) State Faraday's laws of electromagnetic induction. [2]
(ii) State Lenz's law and explain why it is an example of the law of conservation of energy. [4]
(c) A small square coil has its plane set at right angles to the uniform magnetic field between the pole pieces of a horseshoe magnet as shown in figure shown.

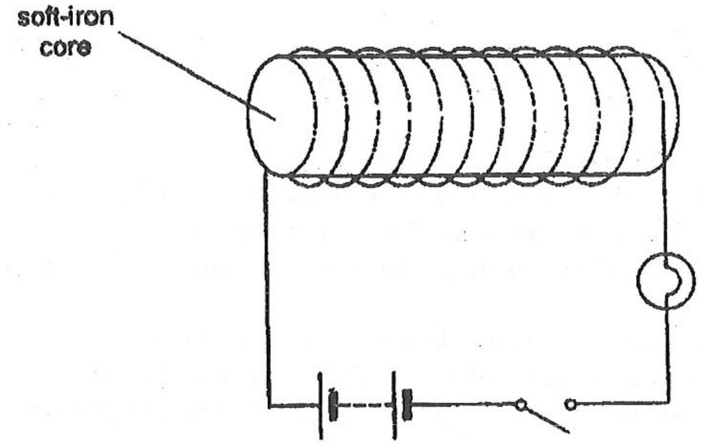


The magnet is now rotated at constant angular velocity about the axis **AB**. Draw sketch graphs, on the same time axis, to show the variation of
(i) the magnetic flux through the coil; and
(ii) the e.m.f. induced in the coil. [3]

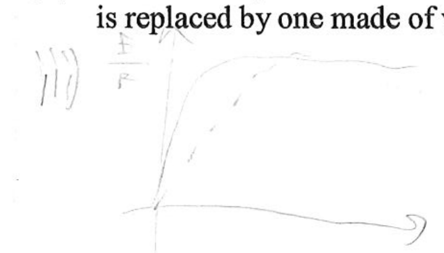
Draw a second set of graphs for the case where the magnet rotates at constant angular velocity about the axis **CD**. (You may assume that the magnetic flux density in the region outside the pole pieces is zero.) [7]

D5 J95/P2/Q4 (part)

A coil, consisting of many turns of insulated metal wire wrapped around a soft-iron core, is connected in series with a battery, a switch and a lamp, as shown in the figure below.



(i) State what happens to the magnitude of the magnetic flux in the coil as the current increases from zero when the switch is closed. Increases
(ii) Hence explain why an e.m.f. is induced in the coil as the current increases.
(iii) Explain, also, why there is a noticeable delay before the lamp lights up after the switch is closed.
(iv) State and explain what will happen to the length of the delay if the soft-iron core is replaced by one made of wood. [6]



D6 N89/P3/Q12 (part)
A helical spring is clamped vertically. The free end of the spring is attached to a sheet of aluminium and a mass, as illustrated in **Fig. 6.1**.
An electromagnet is placed near to the centre of the aluminium sheet. The mass is displaced vertically and, with the electromagnet switched off, the mass is released. The variation with time t of the displacement x of the mass is shown in **Fig. 6.2**.

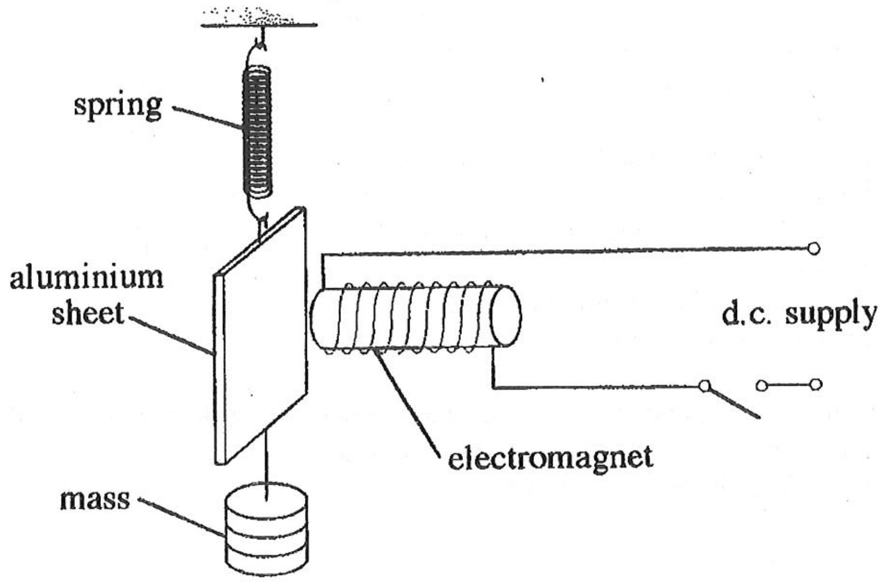


Fig. 6.1

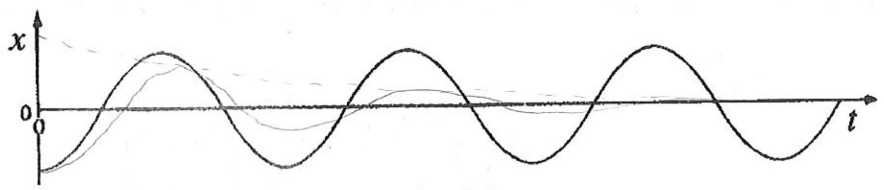


Fig. 6.2

(a) The electromagnet is switched on and the experiment is repeated with the same initial displacement. Damped oscillations are observed.

(i) On **Fig. 6.2**, sketch the new variation with time t of the displacement x of the mass. [2]

(ii) **1.** State Faraday's law of electromagnetic induction.
2. Explain why the oscillations of the mass are damped. [6]

(b) Suggest how critical damping could be demonstrated using the apparatus of **Fig. 6.1**. [2]

Numerical answers to selected questions			
S1 −0.100 V		**S2**	0.13 V
S3 **(a)** 1.20×10^{-3} Wb;		**S4**	9.5×10^{-2} V
(b) 0.00 Wb;		**S5**	First and third
(c) 1.04×10^{-3} Wb			
D3 3.0 s			

3 Magnetic Flux Linkage

If a coil has N turns and that the flux linking each turn is Φ, the total flux through the coil is called flux-linkage $N\Phi$, hence

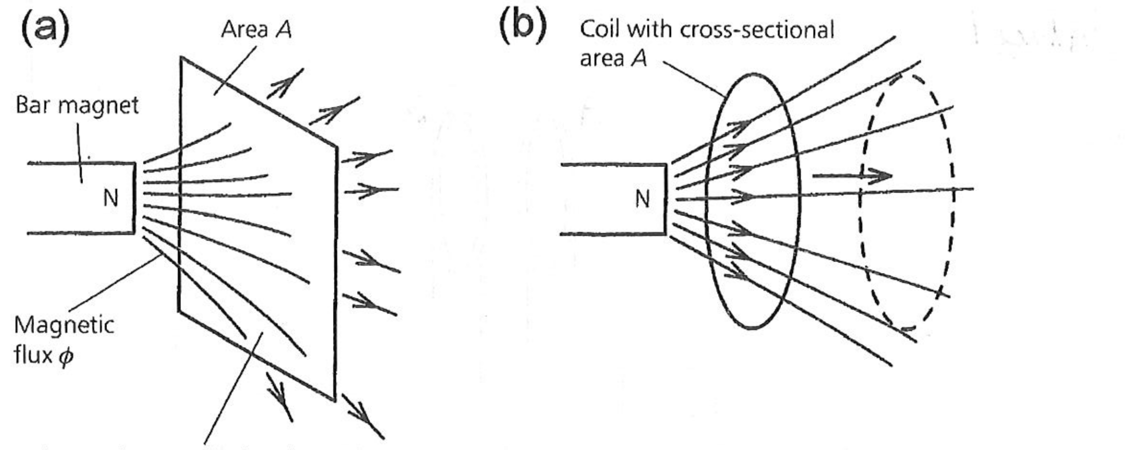
scalar

mag flux lines is vector

ϕ

$$\boxed{N\phi = NBA\cos\theta}$$

Magnetic flux linkage through a coil is the **total** magnetic flux through the individual turns of the coil.

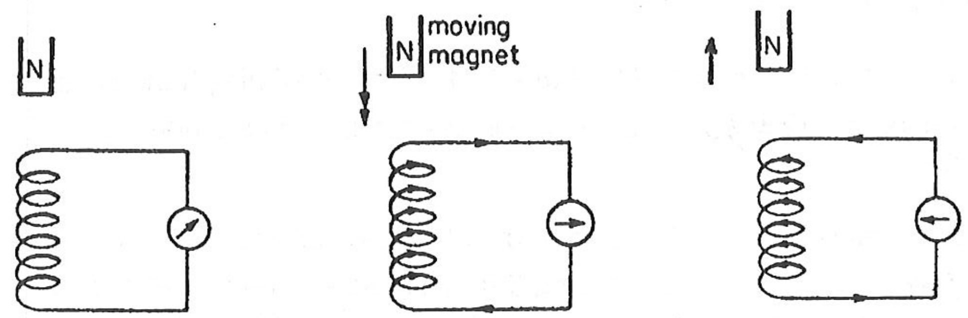


The total magnetic flux through the area A is ϕ, so the flux density at this point is ϕ/A.

If the coil of wire is moved relative to a bar magnet, there is a change in the magnetic flux passing through the coil.

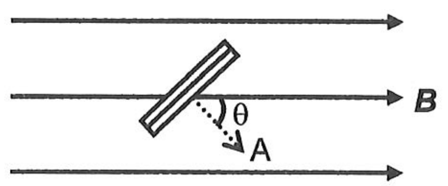
4 Experiments on Electromagenetic Induction

If the magnetic flux through a coil is altered, then an e.m.f. will be generated in the coil. There are **two ways** to alter the magnetic flux through the coil:
(i)



(a) **(b)** **(c)**

1 Magnetic Flux

1. It is a measure of the number of magnetic field lines passing through the region.
2. Consider a magnetic field of flux density B making an angle θ with the normal of a plane surface of area A.
3. 

Only vertical component of B considered ∴ cos θ

4. Definition:

The magnetic flux Φ is defined as the product of the area and the magnetic flux density that is perpendicular to it.

SI unit: weber (Wb)

5. $\boxed{\phi = BA\cos\theta}$

where θ is the angle between the direction of B and the normal to A

6. If the normal to the area A is parallel to B, then $\Phi = BA$
(since $\theta = 0°$ so that $\cos\theta = 1$)
7. If the normal to the area A is perpendicular to B, then $\Phi = 0$
(since $\theta = 90°$ so that $\cos\theta = 0$)

Example 1
A single turn coil of cross-sectional area 5.0 cm^2 is oriented with its normal at an angle of 30° to magnetic field lines of flux density 20 x 10^{-2} T. Calculate the magnetic flux through the coil.

Magnetic flux through coil, Φ $= BA\cos\theta$
$= 20\times10^{-2}\times5.0\times10^{-4}\times\cos 30°$
$= 8.7\times10^{-5}$ Wb

2 The Weber

The **weber** is defined as the magnetic flux which induces in a one-turn coil coil an e.m.f. of one volt when the flux through the coil is reduced to zero in one second.

- Note: 1 Wb = 1 Vs

Assignment Problems

A1 N94/P3/Q4 (part)

(a) A straight wire **AB** is moved across magnetic field, as shown in **Fig. A2.1.**

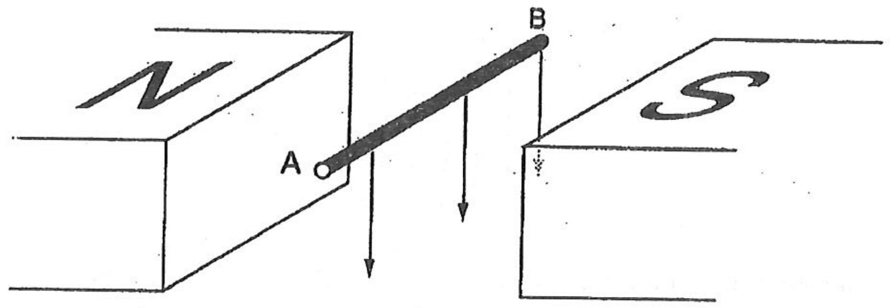


Fig. A1.1

State three factors which determine the value of the induced e.m.f. measured between **A** and **B**. [3]

(b) The wire **AB** is then replaced by a single loop of wire which is rotated with constant angular velocity in the magnetic field, as shown in **Fig. A1.2.**

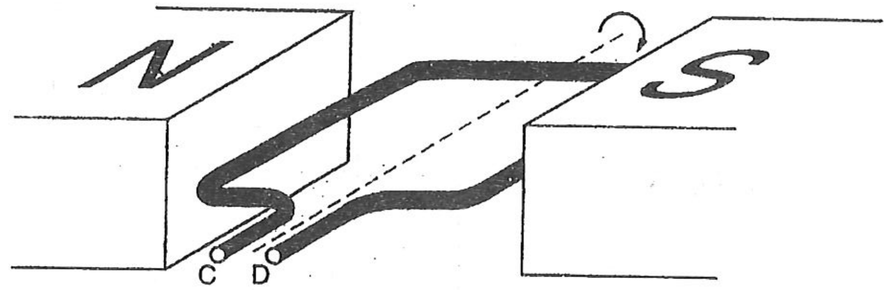
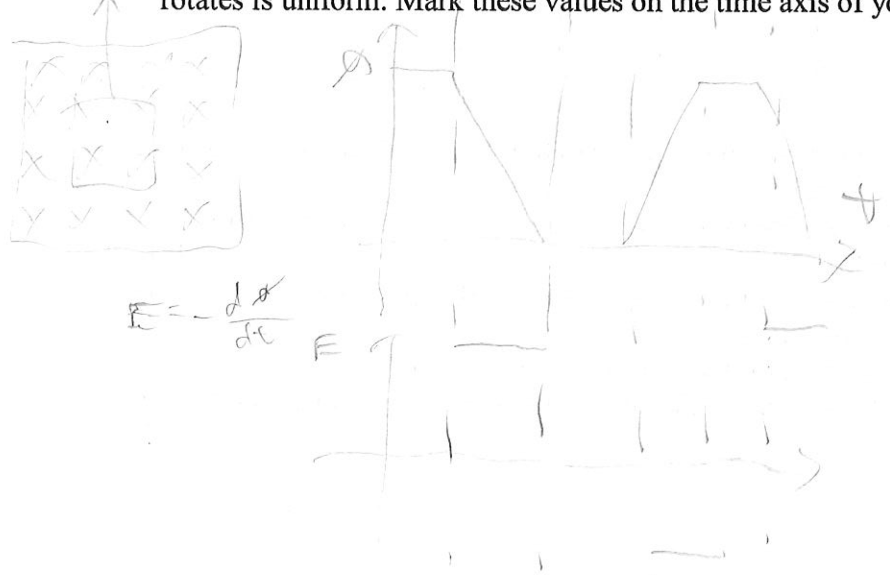


Fig. A1.2

Sketch a graph of the e.m.f. induced across **CD**, the two ends of the loop, against time t. You should assume that $t = 0$ for the coil in the position shown, that $t = T$, after one complete revolution and that the magnetic field within which the coil rotates is uniform. Mark these values on the time axis of your graph. [3]



A2 J93/P2/Q4 (part)

(a) A current-carrying solenoid is placed near to a search coil as shown in **Fig. A2.1**.

$F = BIL$

$B = \frac{F}{IL}$

$B \propto \frac{1}{I}$

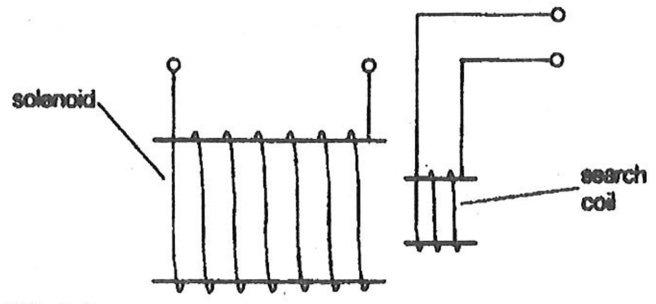


Fig. A2.1

The variation with time t of the current I in the solenoid is shown in **Fig. A2.2**.

$F = BIL \sin\theta$

$B = \frac{F}{IL}$

$E \propto \frac{1}{I}$

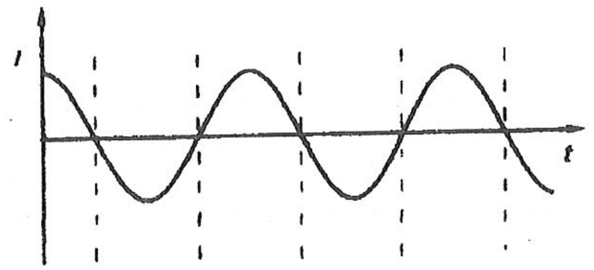


Fig. A2.2

$E = -\frac{d\phi}{dt}$

$= -\frac{d}{dt}(NBA)$

$\propto -\frac{d}{dt}\left(\frac{1}{I}\right)$

$BIL \sin\theta$

$F = \frac{d(Nq)}{dt}$

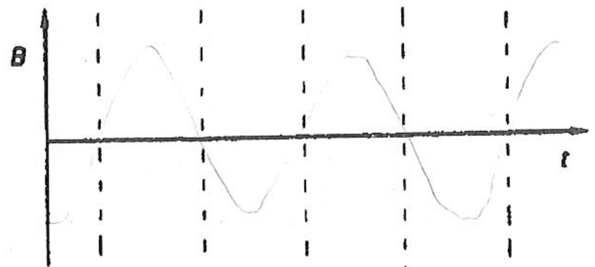


Fig. A2.3

$E \propto -\frac{d}{dt}(B)$

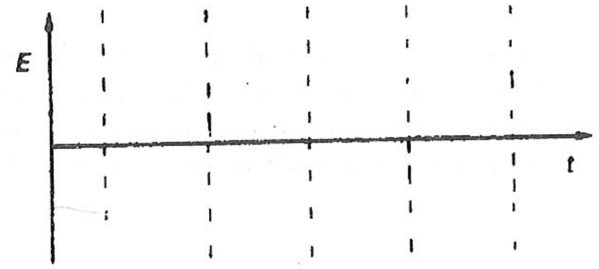


Fig. A2.4

(i) Copy **Fig. A2.3** and sketch on it the variation with t of the magnetic flux density B in the solenoid.

(ii) Copy **Fig. A2.4** and sketch on it the variation with t of the e.m.f. E induced in the in search coil. [3]

(b) For the experiment outlined in **(a)**, briefly describe and explain the effect on the amplitude and frequency of E if, separately,

(i) a ferrous core is slowly introduced into the solenoid; and

(ii) the frequency of the current in the solenoid is increased, whilst maintaining the same amplitude. [6]

Electromagnetic Induction

Content

1 **Magnetic Flux**
2 **The Weber**
3 **Magnetic Flux Linkage**
4 **Laws of Electromagnetic Induction**

Assessment Objectives

After this module, students should be able to:

(a) Define magnetic flux and the weber;

(b) Recall and use $\phi = BA$;

(c) Define magnetic flux linkage;

(d) Infer from appropriate experiments on electromagnetic induction:

(i) that a changing magnetic flux can induce an emf in a circuit,

(ii) that the direction of the induced emf opposes the change producing it and

(iii) the factors affecting the magnitude of the induced emf.

(e) Recall and use Faraday's laws of electromagnetic induction to determine the magnitude and Lenz's law to determine the direction of induced e.m.f's; and

(f) Describe and explain simple applications of electromagnetic induction.

Mind-Map