**Chapter #13 Electromagnetism**

**History:**

As early as 600 B.C. the Greeks knew that a certain form of iron ore, now known as magnetite or lodestone,had the property of attracting small pieces of iron.Later,during the Middle Ages,crude navigational compasses were made by attaching Pieces of lodestone to wooden splints.These splints always come to rest pointing in a N—S direction, and were the forerunners of the modern aircraft and ship compasses.

The word ‘lodestone’ is derived from an old English word meaning way, and refers to the directional property of the stone mentioned above.Chemically,it consists of iron oxide having the formula Fe3O4.The word magnetism is derived from Magnesia,the place where magnetic iron ore was first discovered.

In 1820,a Danish Physicist Hans Christian Orsted made one of the most important discovery of all times.He determined that when a current carrying wire is held near a compass needle,the needle is defelected.This discovery leads to the entire field of electromagnetism.

**Definition:**

***“The branch of Physics which deals with the study of magnetic effects of electric current is called electromagnetism.”***

**Explanation:**

The electric and magnetic fields are different aspects of electromagnetism but intrinsically related.Thus,a changing electric field generates a magnetic field and conversely a changing magnetic field generates an electric field.The latter effect is called electromagnetic induction and is the basic operation for electric generators,induction motors and transformers and is studied in electromagnetism(we will cover it in next chapter).

**Magnetic Field:**

***“The space around a magnet or current carrying conductor,where a test magnet can feel a force of attraction or repusion is called magnetic field.”***

**Forces of magnets:**

Magnets exert forces on each other.These forces are either attraction or repulsion.The effects may be summarised in the law of magnets:

***“Like poles repel and unlike poles attract.”***

**Magnetic field lines:**

***“Magnetic field lines are the curves drawn so that the tangent to a given curve at a point gives the direction of magnetic field at that point.”***

**Properties of Field Lines:**

Magnetic field are not visible but they can be represented by lines of magnetic force extending in three dimensions.The properties of magnetic lines of force are given as:

(i)The magnetic field lines start at a north pole and end at a south pole.

(ii)These lines are smooth curves,they never cross or touch.(Can you state why?)

(iii)The strength of the field is indicated by the distance between the lines\_closer lines mean a stronger field and vice versa.

(iv)Magnetic field lines always form closed curves.

**Magnetic Field of an Electric current:**

As it is known that all electruc currents produce magnetic fields.The size and shape of magnetic field depends on the size of the current and the shape(configuration) of the conductor through which the current is travelling.

**Magnetic field of a Straight Current Carrying Wire:**

The magnetic field due to a straight wire may be plotted using the apparatus shown in the figure below.Iron fillings are sprinkled on a horizontal board and current is passed through the wire as a result of which a magnetic field will be produced.Iron fillings will be in the indicated pattern showing the magnetic field around a straight current carrying wire will be in the form of concentric circles.

The seperation of lines increases with the distance from the wire,indicating the field is decreasing in strength as we move away from the wire.The field also increases as the current is increased in the wire.The direction of field can be found by placing magnetic compasses or using right hand rule which states that:

***“Imagine hold the conductor in the right hand with the thumb pointing in the direction of the current,the curled fingers will point in the direction of field.”***

**Force on a current carrying conductor:**

The interaction of magnetic fields produced by two magnets causes force of attraction or repulsion between the two.If a conductor is placed between the poles and a current is passed through the conductor,the magnetic fields of the current-carrying conductor and the magnet may interact,causing forces between them.In order to explain,we will demonstrate it by the following experiment:

Place a straight wire between the poles of a magnet.When a current flows in the wire,a force is exerted on the wire.In first demonstration,the current flows inward direction(into the page),the wire experiences a downward push.This force is neither parallel to magnetic field nor parallel to the wire.Instead this force is directed at right angle to the magnetic field and wire.Now,if the current is reversed(out of the page),the direction of push will also be reversed i.e. upward.It is found that the direction of force is always perpendicular to the wire and also perpendicular to the direction of field.

These demonstrations lead us to define a rule for the direction of force,i.e.

***“Outstrech the fingers of your right hand in the direction of current,then bend the fingers in the direction of magnetic field,the extened thumb will indicate the direction of the force in the current carrying wire.”***

**Magnitude of Force:**

It is found experimentally that the magnitude of the force is directly propotional to :

* Current in the wire
* Length of the wire inside the magnetic field
* Strength of the field

i.e.

F ILB ………………

**Secondly,it was also found that** :

* When the wire was perpendicular to the field,the force was maximum
* When the wire as parallel to to the field,there was no force at all
* At any angle,it varies with the sine of the angle between and .

So,

F sin ………………………………………

Comibing relations (i) and (ii)

F ILBsin

Here constant of propotionality is 1,so

**F = ILBsin**

**Generalized Form:**

The magnitude as well as the direction of the magnetic force on a current carrying wire can be described in vector notations by the following cross product:

= I

= ILBsin

Where,

is a vector whose magnitude is the length of the wire and whose direction is along the wire(assumed straight) in the direction of current.The unit vector is along the direction of and is perpendicular to , and plane determined by .

**Fleming’s Left-Hand Rule:**

The rule we discussed earlier is known to us already if we have a knowledge of cross product (extending fingers in the direction of first vector in the cross product and curl them towards other vector,thumb will indicate the direction of the resultant of this cross product i.e the direction of .An alternate rule for the direction of force is the Fleming’s left hand rule which states that :

“If the forefinger,central finger and thumb of left hand are held mutually perpendicular with the **F**orefinger pointing in the direction of **F**ield,**C**entral finger in the direction of **C**urrent,the thu**M**b would indicate the **M**otion of conductor(the direction of force on conductor).”

**Defintion of :**

being a vector has magnitude as well as direction.

**Direction of :**

The direction of at any point of the magnetic field is the direction in which the force acting on a straight current carrying wire,placed at that point,is zero, i.e. .

As we know that when the wire is in the direction of field,it experiences no force,so we move wire so that the point comes when it experiences no force,we say that the direction of the wire at that point will be the direction of field.

**Magnitude of :**

The magnitude of is defined when angle between and is 90 and force is maximum,so,

B =

So,***“It is the maxiumum force acting on a conductor of unit length when one ampere current passes through it.”***

**Unit of Magnetic Field:**

The SI unit of magnetic field is telsa (T) and :

1 T = 1 N A-1 m-1

**One tesla:**

***“Magnetic field at any point is said to be one tesla if it exerts a force of 1 N on one metre length of the conductor palced at right angles to the field when a current of 1 A passes through it.”***

**Other units:**

An older name of tesla is weber per metre squared i.e. Wb/m2.Another commonly used unit ois gauss (G).

And,

**1 G =10-4 T**

Magnetic field of earth is half a gauss:

**½ G = 0.5 10 -4** T

**Magnetic Flux:**

***“The number of magnetic field lines passing through a surface is known as magnetic flux.”***

OR

***“The dot product of magnetic induction and vector area element is known as magnetic flux.”***

**Symbol:**

Its symbol is ΦB

**Mathematical Form:**

If is the magnetic induction and is the area vector (a vector having magnitude equal to the area of surface and direction normal to the area element ),then the flux would be :

ΦB = BAcos

where is the smaller angle between and .

**Explanation:**

As magnetic flux for magnetic induction and element of area is given by:

ΦB = BAcos

We know that area vector is normal to the plane of area.If the area is not a flat surface i.e. the angle between area vector and magnetic induction is different at different points,thus we divide area into smaller ‘n’ elements.So,the total magnetic flux through the whole area placed in a field of magnetic induction is the sum of the contributions from the individual area elements is given by:

ΦT =

ΦT =

In a uniform field ,

**ΦT = B**

**Maximum Flux:**

If the surface area is held normal to the field lines such that area vector is parallel to the field,then the maximum lines of force will pass and flux will be maxiumum i.e.

ΦB = BAcos 0

ΦB = BA

**Minimum Flux:**

If the surface area is placed such that it is parallel to the lines of force,so that area vector is normal to the field,no lines will pass, will be 90 degrees,flux will be zero.

ΦB = BAcos

ΦB = 0

**Unit:**

Unit of magnetic flux is T m2 called as weber(Wb).

**Magnetic flux density:**

Using eqn :

B =

So magnetic induction B can also be defined as:

***“Magnetic flux per unit area.”***Hence it is also called magnetic flux density.

It has unit Wb/m2 (T).

**Ampere’s Circuital Law:**

**Background:**

We know that a current carrying wire has a magnetic field around it.The direction of the field can be determined by right hand rule.The magnitude of the field can be determined by a relation called Ampere’s circuital law.

**Statement:**

***“The sum of the dot products ‘B’ and ‘L’ around a closed path in the magnetic field of a current is equal to μo times the current enclosed by the path.”***

**Mathematically:**

= μoI

Where I is the current enclosed.

**Explanation:**

Let us first consider a special case of the magnetic field of a long straight-current carrying wire as shown:

From experiments as well as from the cylindrical symmetry of the wire,it is obvious that the magnitude of magnetic induction is constant on a circle of radius ‘r’ centred on wire.It is further observed that ‘B’ around a long straight current-carrying wire is directly propotional to the current ‘I’ and inversely propotional to the distance ‘r’ from the wire i.e.

B I ……………..

B ………………….

B

B = …………………..

Where,

is constant of propotionality and its value is 4π10-7 Wb A-1 m-1 and is called its permeability of free space.

Equation shows radial dependency of B.This radial dependence is used to derive expression for Ampere’s law.

**Derivation:**

Let us consider a circle of radius ‘r’ around current carrying wire as shown below:

To find . ,where L is the circumference of circle.For this path,we divide into small segments ,,…………………...Then:

. = ……………………………

As it is clear from the figure that is parallel to the at each point,therefore:

=

As B is constant ,so we pull it out of summation:

= B

As,

= 2πr (for circle) and B = r (for circle) and B =

= 2πr

= μoI……………….

where,

‘I’ is the current closed.From equation ,it is clear that is independent of the shape or size of the closed path.It can be applied to closed path of any shape.

Note:

***(i)Ampere’s law can be applied to any assembly of currents.The closed path in the magnetic field is called amperian loop.***

***(ii)If there is no current enclosed within the amperian path,the amperian summation of is zero.***

**Magnetic Field due to a Current Carying Solenoid:**

**Solenoid:**

***“If a straight wire is wrapped in the form of several closely spaced loops,the resulting device is called solenoid.”***

**Magnetic Force on a Moving Charge:**

We know that force acting on a conductor of length ‘L’ having current ‘I’ placed at right angles to the magnetic field ‘B’ is given by:

Fmax = ILB…………………….

It is also our well-established knowledge that the conductor contains charges and current in a conductor is due to drift of the charges.Therefore,we conclude that the force on the conductor is due to the force on the charges in motion in the conductor.

If the charge on a particle is ‘+q’ and there are ‘n’ charges per unit length of the wire moving with velocity ‘V’ ,then:

Distance moved by charges in one second will be:

S= V(1) = V m

The charges contained in ‘V’ metres will pass through the section PP’ in one second which makes the current ‘I’.

The charge contained in V m will be nqV,so current will be:

I = nqV

Put value of I in eqn

Fmax = nqLVB

The number of charges in unit length will be: n

And in length L,they will be :nL

So,force on ‘nL’ charges is:

Fmax = nqLVB

The force on each charge will be:

Fmax =

Fmax = qVB

This was the special case when the conductor was placed perpendicular to the field,in our case, ‘’ is perpendicular to ‘’,but if there is an angle θ between ‘’ and ‘’ ,then:

F = qVBsinθ……..

The equation gives the magnitude of the magnetic force on a particle of charge ‘q’ moving with velocity ‘V’ in a magnetic field of strength ‘B’ and θ is the angle between ‘’ and ‘’.

**Maximum Force:**

When θ=90,sin 90=1,so,

Fmax = qVB

This means that the force is maximum when the charge particle moves perpendicular to the magnetic field.

**Minimum Force:**

When θ=0,sin 0=0

i.e.

F =qVBsin0=0

F=0

This means that when the particle moves parallel to the field direction,the force will be minimum i.e zero.

**Direction:**

We know that force is a vector quantity,so it must have a specific direction.Equation can be written in vector form as:

= q ()

= qVBsinθ

The direction of the force is perpendicular to velocity and magnetic field and the plane formed by them and can be determined by right hand rule of cross product.Interestingly,you can extend fleming’s left hand rule to determine the direction of this force,***“Hold your forefinger,middle finger and thumb of your left hand mutually perpendicular such that forefinger points in the direction of field,middle finger in the direction of velocity of a charged particle,then the thumb would indicate the direction of force on that moving charge.”***

**Note:**

(i)If the force on ‘+q’ is upward,then force on ‘-q’ will be downward in the same field.

= -qVBsinθ

= qVBsinθ (-

This means that the force on negative charge is opposite to that of positive charge.

(ii)As the force is perpendicular to the direction of motion,therefore it can only change the direction of motion of the charged particle.It can neither speeds up or slowd down the particle.

**Applications:**

The deflection of charged particles by magnetic field is used in T.V tubes,electron microscopes,spectrographs and charged particles accelerators like Cyclotron and Betatron.

**Circular Trajectory of a Charged Particle in a Magnetic Field:**

Let us consider a particle of charge ‘+q’ thrown perpendicular to a uniform magnetic field of magnetic flux density ‘B’ with velocity ‘v’ as shown:

The magnetic force in the above case:

Fm = qvB…….

As this force is all the time perpendicular to the direction of velocity and magnetic field,thereforce it compels the charge to move in circular path.So,magnetic force is the necessary centripetal force i.e.

Fm = Fc

As,

Fc = mv2/r

So,putting values we get

= qVB

r =

This equation gives the radius of the circular path in which a charge ‘q’ of mass ‘m’ and velocity ‘V’ will move in a magnetic field when projected perpendicularly.

Also,

v= rω

Put in eqn

r =

ω =

This is the angular frequency of the circulating body.

As,

ω = 2πf

f =

f = ………….

And ,

f = 1/T

so,

T = ………………

From the equation,it is clear that the time period of the particle is independent of the radius of the path followed by the charge.Smaller the radius,less will be the velocity and larger radius will increase the velocity as a result time period for a given charge will remain same.

The frequency found in eqn is called ‘cyclotron frequency’(cyclotron is a device used for accelerating charged particles) of the circulating particle.

Helical Trajectory of a charged particle:

If the direction of velocity is not perpendicular to the magnetic field,then instead of circular trajectory,charged particle adopts a helical path as shown:

Actually,velocity has two components,the vertical component and horizontal component is affected by magnetic force describing circular path and horizontal moves it straight.As a result,it follows a spiral path.

**Determination of e/m for electron:**

**Principle:**

Circular trajectory of charged particle in magnetic field.

**Mathematical Derivation:**

A narrow beam of electrons moving with constant velocity ‘v’ is projected at right angles to a uniform magnetic field ‘B’ as shown:

The magnetic force provides the necessary centripetal force,So,

= evB

= …………………..

Knowing v,B and r,value of e/m can be calculated.

**Determination of radius:**

The radius is measured by making the electrons trajectory visible.This done by filling a glass tube with a gas such as hydrogen at low pressure.The tube is placed in a region occupied by a uniform magnetic field of known value.As the elctrons are shot into this tube,they begin to move along a cirle under the action of magnetic force.As the electrons move,they collide with the atoms due to which they emit light and their path becomes visible as a circular ring.The diameter of this ring can be easily determined.

**Determination of Velocity:**

We know that the kinetic energy gained by electrons is due to the electric potential.

Gain in Kinetic energy=1/2mv2=eV

So,

v =……………….

Squaring:

v2 =

Squaring eqn

= ……………………

Putting value of v2 in equation

=

=

Using potential which is known and substituting all values ‘e/m’ can be calculated.The accurately known value of ‘e/m’ for electron is 1.77588×1011 C/kg.

**Charge in Combined Electric and Magnetic Field:**

**Electric Force:**

We know that force on a charge ‘q’ placed in an electric field of intensity ‘E’ is given by:

F = qE……….

Also,from Newton’s 2nd law:

F=ma…………..

If charges are free to move,then acceleration will be:

ma = qE

a = ………………

If the electric field is uniform,the force is constant.The acceleration produced will be uniform.Therefore,the position and velocity of the particle at any instant of time can be determined by using the equations for uniformly accelerated motion.The figure shows how a beam of electrons is deflected by the uniform electric field.

**Note:**We can prove that electrons would follow a parabolic path.

**Magnetic Force:**

The force on a charge ‘q’ moving with velocity ‘v’ in a region of magnetic field ‘B’ is:

= q ( ×)………………..

As this force is always perpendicular to the motion of charged particle.So it will move the particle in circular path as shown:

**Combined Electric and Magnetic Field:**

If a charge particle ‘q’ is projected in a region with velocity ‘v’ where there is magnetic field ‘B’ and electric field ‘E’,then force on the particle will be:

= q + q ( ×)……………….

This force is called Lorentz force.

**Note:**

The electric field can:

* ***Deflect the charge particle***
* ***Speed up or slow down the particle or impart energy to it***

Whereas magnetic field can:

* ***Deflect the charge particle***
* ***Not speed up or slow down the particle means can not change kinetic energy of the moving charge.This is because magnetic force is perpendicular to v.***

**Velocity Selector:**

***“When the electric field is perpendicular to the magnetic field such that a charge particle with a particular velocity passes undeflected,the arrangement is called velocity selector.”***

**Construction:**

A velocity selector consists of a tube in which electric field ‘E’ is oriented perpendicular to the magnetic field ‘B’ as shown:

The field strengths ‘E’ and ‘B’ are so oriented that the electric force and the magnetic force act in opposite direction.A charged particle that enters the tube in a direction perpendicuar to both ‘E’ and ‘B’ with speed V= E/B will pass undeflected.

**Derivation:**

As discussed above,the electric and magnetic forces are equal and opposite for velocity selector,so,

FE = Fm

qE = qVB

V =

So charge particles with this velocity will pass undeflected and those with velocities other than this will be deflected either upwards or downwards.