MOTORS AND GENERATORS

Mind map

CHAPTER 5

The motor effect

Motors use the effect of forces on current-carrying conductors in magnetic fields

Introduction

As the module title 'Motors and generators' suggests, this module consists of two main physics topics—electric motors and electric generators. Motors are electric devices that convert electrical energy into mechanical rotations. They have extensive applications in all industries and are also the functional component for many household devices such as fans and drills. On the other hand, electric generators work in the opposite way, converting mechanical rotations into electricity. They form the heart of many power stations.

This chapter analyses in detail the physics principles behind the functioning of an electric motor.

5.1 Some facts about charges and charged particles

- A stationary charge produces an electric field.
- A moving charge with constant velocity produces an electric field as well as a magnetic field.
- A moving charge that is accelerating produces electromagnetic radiation.
- A stationary charge will experience a force in an external electric field. This is because the field produced by the stationary charge interacts with the external field and results in a force.
- Similarly, a moving charge with constant velocity will experience a force in both an electric field and an external magnetic field.

5.2 The motor effect

- ***Identify that the motor effect is due to the force acting on a current-carrying conductor in a magnetic field***
- ***Discuss the effect on the magnitude of the force on a current-carrying conductor of variations in:***
  - ***the strength of the magnetic field in which it is located***
  - ***the magnitude of the current in the conductor***
  - ***the length of the conductor in the external magnetic field***
  - ***the angle between the direction of the external magnetic field and the direction of the length of the conductor***

■ *Solve problems and analyse information about the force on current-carrying conductors in magnetic fields using $F = BIl\sin\theta$*

SR

Worked example 16

Definition

The phenomenon that a current-carrying conductor experiences a force in a magnetic field is known as the **motor effect**.

This of course comes as no surprise since we know that current is created by a stream of moving electrons. Since electrons are moving charges, and we know that moving charges experience a force in a magnetic field, it follows that a current-carrying wire will experience a force in a magnetic field.

A quantitative description of the motor effect

It can be shown through experiments (such as using a current balance) that the force on a current-carrying wire, when it is placed in a magnetic field, will depend on the following factors:

1. As the strength of the magnetic field increases, the force increases.
2. As the current in the wire increases, the force increases.
3. If the length of the wire inside the magnetic field increases, the force increases.
4. The size of the force is a maximum when the wire is placed perpendicular to the field lines. It reduces in magnitude and eventually becomes zero when the wire is rotated to a position where it is parallel to the magnetic field.

Mathematically, the force is related to the above factors by the equation:

$$F = BIl\sin\theta$$

Where:

F = force due to motor effect, measured in N

B = magnetic field, measured in Tesla (T)

I = current, measured in amperes (A)

l = length of the wire, measured in m

θ = angle made between the magnetic field lines and current-carrying wire. This is shown in Figure 5.1.

When the wire is perpendicular to the magnetic field, the force is a maximum: $\theta = 90°$, hence $F = BIl$ (Figure 5.1(a))

When the wire is parallel to the magnetic field, $\theta = 0°$. The force is zero. (Figure 5.1(b))

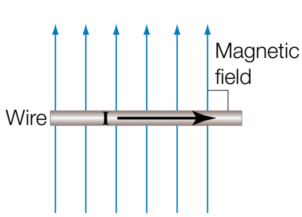


Figure 5.1 (a) Forces on a wire that is perpendicular to a magnetic field

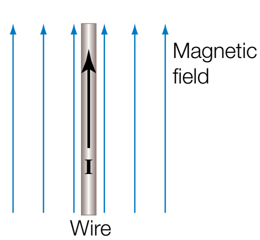


Figure 5.1 (b) Forces on a wire that is parallel to a magnetic field

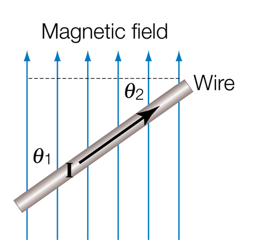
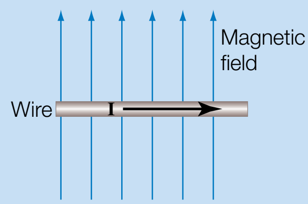


Figure 5.1 (c) Forces on a wire on an angle within a magnetic field

In Figure 5.1(c) the angle θ is measured *between* the magnetic field lines and the wire carrying the current.

NOTE: It is easy to make mistakes when choosing which angle to use for the equation $F = BIl\sin\theta$. In the situation shown in Figure 5.1 (c), it is the angle labelled θ_1, NOT the angle labelled θ_2. The use of $\sin\theta_1$ resolves the wire to obtain the component of the length that is perpendicular to the magnetic field. The parallel component does not contribute to the force, so it can be disregarded.



Wires and magnetic field perpendicular

Example 1

A 20 cm long current-carrying wire is placed inside a magnetic field, as shown in the diagram on the left. The magnetic field has strength of 1.0 T, and the current in the wire is 1.5 A. Calculate the magnitude of force on the wire when:

(a) It is at the position shown in the diagram above.
(b) It makes an angle of 30° to the magnetic field.
(c) It is parallel to the magnetic field.

Solution

(a) $\boldsymbol{F} = \boldsymbol{BIl}\sin\theta$

$\boldsymbol{B}$ = 1.0 T

$\boldsymbol{I}$ = 1.5 A

l = 20 cm = 0.20 m

θ = 90°

$\boldsymbol{F} = 1.0 \times 1.5 \times 0.20 \sin 90°$

$\boldsymbol{F}$ = 0.30 N

(b) $\boldsymbol{F} = \boldsymbol{BIl}\sin\theta$

$\boldsymbol{B}$ = 1.0 T

$\boldsymbol{I}$ = 1.5 A

l = 20 cm = 0.20 m

θ = 30°

$\boldsymbol{F} = 1.0 \times 1.5 \times 0.20 \sin 30°$

$\boldsymbol{F}$ = 0.15 N

(c) $\boldsymbol{F} = \boldsymbol{BIl}\sin\theta$

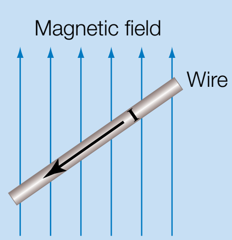
θ = 0°

$\boldsymbol{F} = (1.0) \times (1.5) \times (0.20) \sin 0°$

$\boldsymbol{F}$ = 0 N

Example 2

The current-carrying wire shown in the diagram below experiences a force of 0.5 N. If the strength of the magnetic field is halved and the current quadrupled, what is the new force acting on the wire?



Wires and magnetic field at an angle

Solution

The original force $\boldsymbol{F} = \boldsymbol{BIl}\sin\theta$

Now for the new force $\boldsymbol{F}'$

$\boldsymbol{B}' = \tfrac{1}{2}\boldsymbol{B}$

$\boldsymbol{I}' = 4\boldsymbol{I}$

$\boldsymbol{F}' = \tfrac{1}{2}\boldsymbol{B} \times 4\boldsymbol{I} \times \boldsymbol{l}\sin\theta$

$\boldsymbol{F}' = 2\,(\boldsymbol{BIl}\sin\theta)$

$\boldsymbol{F}' = 2\boldsymbol{F}$

$= 2 \times 0.5 = 1$ N

Therefore, the new force is 1 N.

The direction of the force

Force is a vector quantity, which means that *it must have both magnitude (size) and direction.* In order to determine the direction of the force acting on a current-carrying wire, a rule called the 'right-hand palm rule' can be adopted.

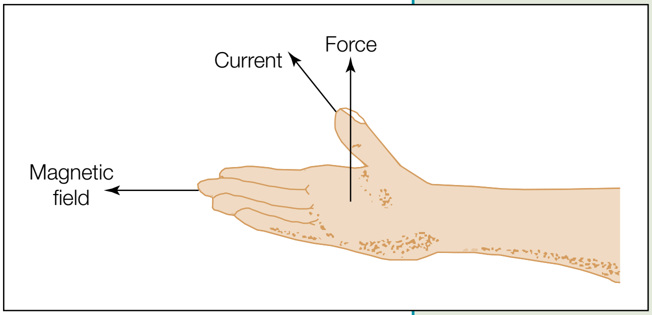


Figure 5.2 The right-hand palm rule

The right-hand palm rule

Using the right hand, when the fingers point to the direction of the magnetic field, and the thumb points to the direction of the conventional current, then the palm points to the direction of the force.

Example 1

Determine the direction of the force acting on the wire in examples 1 and 2 on page 90:

Solution

From Example 1 on page 90

(a) Fingers point up, thumb points to the right and the palm (hence the force) points out of the page.

(b) Fingers point up, thumbs points to the right and the palm (hence the force) points out of the page.

(c) Zero force, hence no direction is applicable.

From Example 2 on page 90

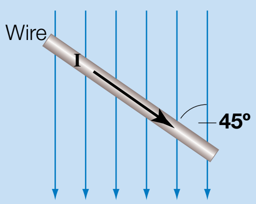
Fingers point up, thumb points to the left and the palm (hence the force) points into the page.

NOTE: Vector quantities are not complete without directions. When you are asked to calculate vectors, find the magnitude and never leave out the direction!

Example 2

Find the size and the direction of the force acting on the current-carrying wire in each scenario:

(a)



Magnetic field strength: 2 T
Current size: 1.0 A
Length of wire: 1.2 m

Wires and magnetic field at angle of 45°

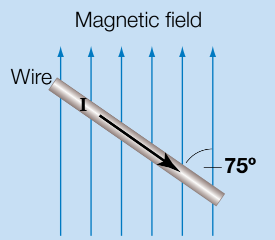
Solution (a)

$F = BIl\sin\theta$

$F = 2.0 \times 1.0 \times 1.2 \times \sin 45°$

$F \approx 1.7$ N into the page

(b)



Magnetic field strength: 3.0 T
Current size: 0.20 A
Length of wire: 35 cm

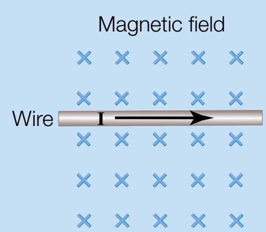
Solution (b)

$F = BIl\sin\theta$

$F = 3.0 \times 0.20 \times 0.35 \times \sin 75°$

$F \approx 0.20$ N into the page

(c)



Magnetic field strength: 5.0 T
Current size: 10 A
Length of wire: 0.20 m

Solution (c)

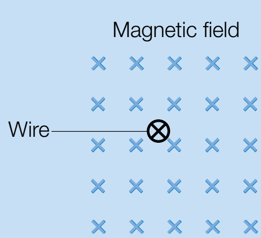
$F = BIl\sin\theta$

Since the wire is to the right, and the magnetic field is into the page, the angle between them is 90°.

$F = 5.0 \times 10 \times 0.20 \times \sin 90°$

$F = 10$ N up the page

(d)



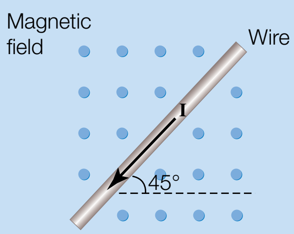
Magnetic field strength: 0.30 T
Current size: 2.0 mA
Length of wire: 35 m

Solution (d)

$F = BIl\sin\theta$

Since the wire is parallel to the magnetic field, the force the wire experiences will be zero.

(e)



Magnetic field strength: 0.50 T
Current size: 3.0 A
Length of wire: 0.47 m

Solution (e)

$F = BIl\sin\theta$

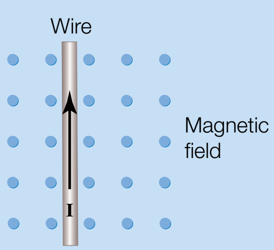
NOTE: It is important to realise that the angle between the wire and the magnetic field is still 90°, despite the wire being inclined at 45° as shown.

$F = 0.50 \times 3.0 \times 0.47 \times \sin 90°$

$F = 0.71$ N

Direction: Fingers point out of the page, thumb points 45° left-down, hence the palm (force) points 45° left-up, (or NW).

(f)



Magnetic field strength: 2.5 T
Current size: 4.0 A
Length of wire: 300 mm

Solution (f)

$F = BIl\sin\theta$

$F = 2.5 \times 4.0 \times 0.30 \times \sin 90°$

$F = 3.0$ N to the right

Forces on electrons

Electrons, as they move through a magnetic field, will also experience a force; this is also true for all moving charges. The direction of the force can also be determined by the right-hand palm rule, however with modifications:

Using the right hand: when the thumb points *opposite* to the direction in which the electron or negative charge is moving, and the fingers point to the direction of the magnetic field, the palm points to the direction of the force.

NOTE: Negative charges moving in one direction are equivalent to positive charges moving in the opposite direction.

The magnitude of the force acting on charged particles will be covered in Chapter 10.

5.3 Force between two parallel current-carrying wires

- ***Describe qualitatively and quantitatively the force between long parallel current-carrying conductors:***

$$\frac{F}{\ell} = k\frac{I_1 I_2}{d}$$

Magnetic field around a current-carrying wire

A current-carrying wire produces a magnetic field around it. The nature of the field is that it forms planar (two-dimensional) concentric rings around the wire. See Figure 5.3.

The *direction* of the magnetic field can be determined by using 'the right-hand grip rule'.

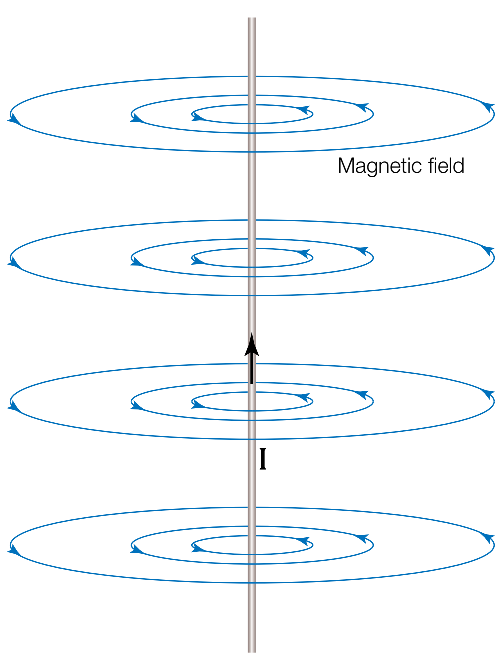


Figure 5.3 (a) Magnetic field around a current-carrying wire

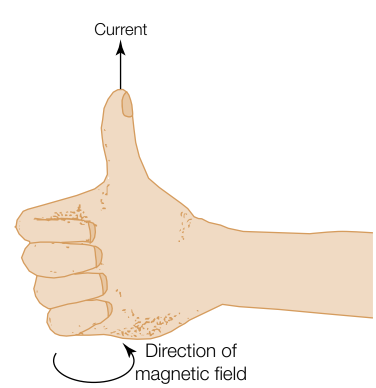


Figure 5.3 (b) The right-hand grip rule

The right-hand grip rule

When the thumb points in the direction of the conventional current, the fingers curl in the direction of the magnetic field.

The *intensity* of the magnetic field is proportional to the size of the current and inversely proportional to the distance from the wire. Mathematically:

$$\boldsymbol{B} = \boldsymbol{k}\frac{\boldsymbol{I}}{\boldsymbol{d}},$$

where $\boldsymbol{B}$ is the magnetic field strength, k is a constant which has a value of 2×10^{-7}; $\boldsymbol{I}$ is the current; and d is the distance from the wire. (*This equation is not required by the syllabus.*)

NOTE: The intensity of the magnetic field around a straight current-carrying wire does not follow the inverse square law, as the intensity of the magnetic field is only inversely proportional to the distance, not its squared value.

A quantitative description of the force between two parallel current-carrying wires

It follows that if two straight current-carrying wires are placed parallel to each other, one wire produces a magnetic field and the other wire experiences a force due to this magnetic field. Hence there must be a force between two current-carrying wires.

Magnitude of the force

Consider two equal-length wires separated by a distance of d. Wire 1 carries a current $\boldsymbol{I}_1$ and wire 2 carries a current $\boldsymbol{I}_2$. Wire 1 produces a magnetic field, and its strength at distance d is given by:

$$\boldsymbol{B} = \boldsymbol{k}\frac{\boldsymbol{I}_1}{\boldsymbol{d}} \qquad (1)$$

Wire 2 experiences a force given by $\boldsymbol{F} = \boldsymbol{BI}_2\boldsymbol{l}\sin\theta$

Since the two wires are parallel, one must be perpendicular to the magnetic field produced by the other wire (recall, the magnetic field is planar concentric rings that are perpendicular to the wire, see Fig. 5.3a). Therefore, θ is 90°, $\sin\theta = 1$.

Hence:

$$\boldsymbol{F} = \boldsymbol{BI}_2\boldsymbol{l} \qquad (2)$$

Substituting equation 1 into equation 2, we can obtain the equation that quantitatively describes the force between two parallel current-carrying wires:

$$\boldsymbol{F} = \left(k\frac{\boldsymbol{I}_1}{\boldsymbol{d}}\right) \times \boldsymbol{I}_2 \times \ell$$

$$\boldsymbol{F} = k\frac{\boldsymbol{I}_1\boldsymbol{I}_2\ell}{\boldsymbol{d}}$$

or

$$\frac{\boldsymbol{F}}{\ell} = k\frac{\boldsymbol{I}_1\boldsymbol{I}_2}{\boldsymbol{d}}$$

$$\frac{F}{\ell} = k\frac{I_1 I_2}{d}$$

Where:

F = the magnitude of the force between the two current-carrying wires, measured in N

B = the strength of magnetic field, measured in T

I_1 and I_2 = the currents in the respective wires, measured in A

d = the distance of separation between the wires, measured in m

ℓ = the length of the wires that are parallel to each other, measured in m

NOTE: take care when you apply the above equation:

- Remember that unlike the gravitational attraction equation, this equation involves d not d^2.
- The value for ℓ has to be the common length.

Direction of the force

As we have discussed earlier, force is a vector, so calculations of a force are never complete without stating the direction.

Consider two wires carrying currents in the same direction; their end view is shown in Figure 5.4 (a).

Using the right-hand grip rule, wire 1 produces a magnetic field that is anti-clockwise. At the position of wire 2, the magnetic field produced by wire 1 has an upward component.

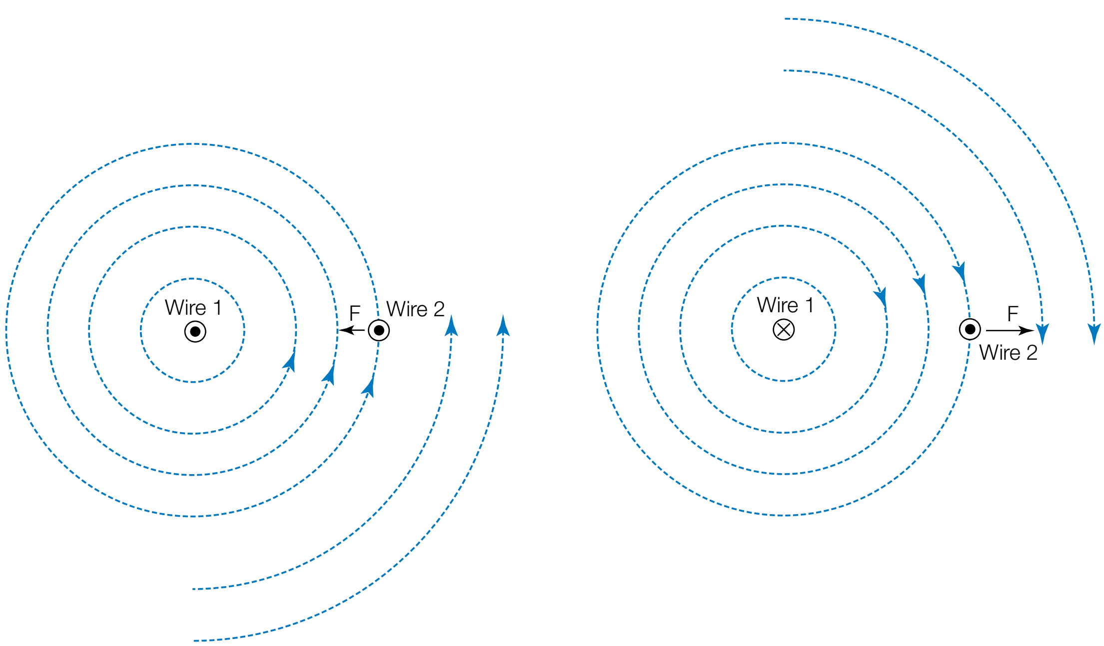


Figure 5.4 (a) Two wires carrying currents in the same direction (out of the page)

Figure 5.4 (b) Two wires carrying currents in the opposite direction, wire 1 into the page, wire 2 out of the page

Then apply the right-hand palm rule on wire 2, the force acting on it is to the left. By the same argument, the field produced by wire 2 at the position of wire 1 is downwards, so that the force acting on wire 1 is towards the right.

Therefore the force is attraction.

Now consider two wires carrying currents in the opposite direction, their end view is shown in Figure 5.4 (b).

According to the right-hand grip rule, wire 1 produces a magnetic field that is clockwise. At the position of wire 2, the field has a downward direction. Applying the right-hand palm rule, the force acting on wire 2 is to the right. By the same argument, the force acting on wire 1 is to the left.

Therefore, the force is repulsion.

To conclude:

Two parallel wires that carry currents in the same direction attract each other, whereas if they carry currents running in opposite directions, they will repel each other.

NOTE: To remember this, just think that it is opposite to magnets, since two of the same magnetic poles repel and two of the opposite magnetic poles attract.

■ *Solve problems using:* $\frac{F}{\ell} = k\frac{I_1 I_2}{d}$

H14.1A
H14.2A
H14.3A, D

SR

Worked examples 14, 15

Example 1

Two wires that carry electricity into a factory (same direction) are separated by a distance of 0.20 m: if each carries a current of 6.0×10^3 A, state the force acting per unit length of the wires. Explain why these wires have to be held firmly to the ground.

Solution

The force per unit length $\frac{F}{\ell} = k\frac{I_1 I_2}{d}$

$$= \frac{2 \times 10^{-7} \times 6.0 \times 10^3 \times 6.0 \times 10^3}{0.20}$$

$$= 36 \text{ N m}^{-1} \text{ attraction}$$

There will be 36 N of force acting per metre of the wires. This force will bring the wires together and may short-circuit the wires—they need to be held firmly to avoid this.

Example 2

In the laboratory, a student set up some apparatus 1.0 to determine the size of the currents passing through two parallel wires, each 1 m long. The student measured the force between the two wires to be 2.0×10^{-3} N when they were separated by 1.0 cm in air. If both wires carried the same current, determine its size.

Solution

$$F = k\frac{I_1 I_2 \ell}{d}$$

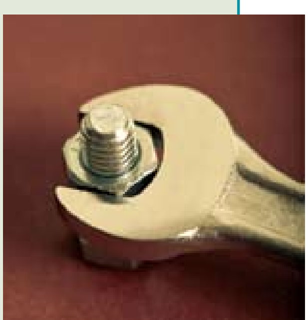
$$2.0 \times 10^{-3} = \frac{2 \times 10^{-7} \times I^2 \times 1.0}{0.010}$$

$$I^2 = 100$$

$$I = 10 \text{ A}$$

NOTE: It is easy to see that the force between two current-carrying wires is an extension of the motor effect.

5.4 Torque: the turning effect of a force



Torque is demonstrated in everyday activities such as turning a nut on a bolt with a spanner

■ *Define torque as the turning moment of a force using: $\tau = Fd$*

Think about when you want to shut a door with just one push. If you push on the door near the hinges, it is probably not enough to shut the door. However, if you push at the edge of the door with the same amount of force, then you will probably slam the door. Thus in order to describe the turning effect of a force, we need to introduce the term **torque**.

Definition

Torque is the turning effect of a force. Quantitatively, it is the product of the distance from the pivot of turning to where the force is applied and the size of the force perpendicular to the distance.

Mathematically, torque is equal to:

$$\tau = F_p \times d$$

Where:

F_p = the perpendicular force, measured in N

d = the distance from the pivot, measured in m

τ = the torque, measured in N m

See Figure 5.5 (a) and (b) for how to apply the equation

If the force F is perpendicular to the axis of rotation, then $F_p = F$

If F is not perpendicular to the axis of rotation, then we can resolve the vector, and only take the perpendicular component. Hence $F_p = F \times \cos\theta$ (or $F \times \sin\phi$)

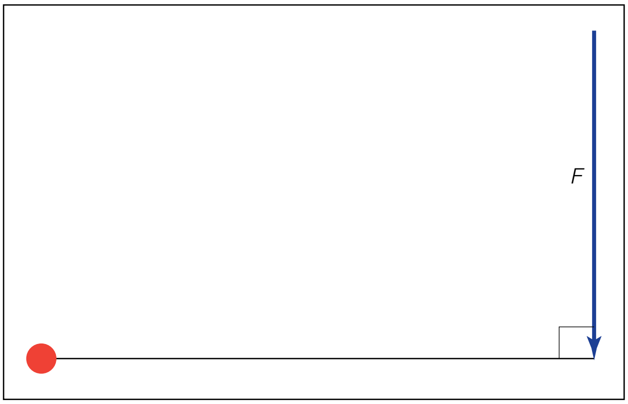


Figure 5.5 (a) Force ***F*** is perpendicular to the axis of rotation

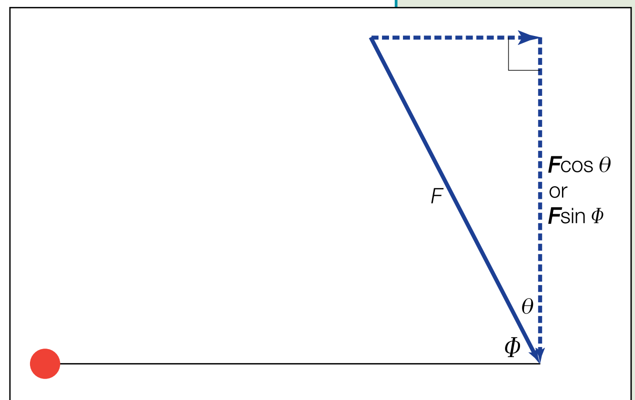
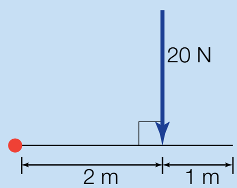


Figure 5.5 (b) Force ***F*** is not perpendicular to the axis of rotation

Example

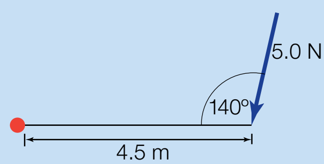
Calculate the torque for the following situations. The force is shown by the arrow, and the dot represents the pivot point:

(a)



Calculating torque

(b)



Solution (a)

$\boldsymbol{\tau} = \boldsymbol{F_p} \times \boldsymbol{d}$

Since the force is perpendicular to the distance, $\boldsymbol{F_p} = \boldsymbol{F} = 20$ N

Distance is measured from the pivot, which is 2 m, not 3 m.

$\boldsymbol{\tau} = 20 \times 2$

$= 40$ N m, object will turn clockwise.

Solution (b)

$\boldsymbol{\tau} = \boldsymbol{F_p} \times \boldsymbol{d}$

Since the force is not perpendicular to the distance, we need to resolve the vector to obtain the perpendicular component, $\boldsymbol{F_p} = \boldsymbol{F} \times \sin(180 - 140) = 5\sin 40° = 3.21$ N

Distance is 4.5 m.

$\boldsymbol{\tau} = 3.21 \times 4.5$

≈ 14.5 N m, object will turn clockwise.

NOTE: Understanding the concept of torque is essential for understanding the functional principle of electric motors.

Simulation: beam balance

Simulation: torque puzzle

5.5 Motor effect and electric motors

■ *Describe the forces experienced by a current-carrying loop in a magnetic field and describe the net result of the forces*


A simple DC motor

As we have seen earlier, a current-carrying wire will experience a force inside a magnetic field. Not surprisingly, with the correct design, we can utilise this property to do useful work for us. The device is an **electric motor** and is employed in a range of useful applications.

Definition

An **electric motor** is a device which converts electrical energy to useful mechanical energy (usually rotation).

Electric motors can be classified into:

- direct current (DC) motors
- alternating current (AC) motors

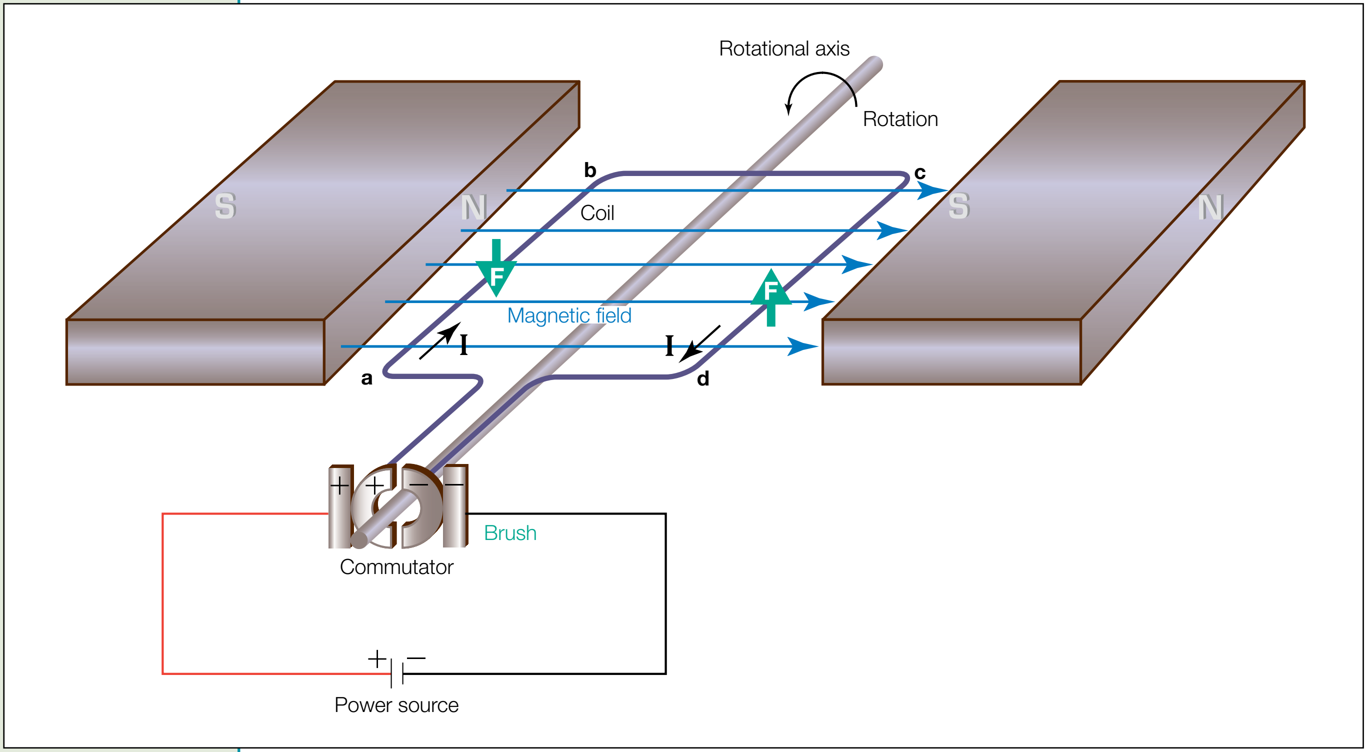
depending on the current that they use to run. They share some common functional principles; however, there are subtle differences in their structures. In this chapter, all explanations will be based on DC motors. AC motors and induction motors will be discussed in Chapter 9.

Functional principle of a simple DC motor

To begin our study of DC motors, let us first look at a very simple DC motor that you can easily construct at home. Figure 5.6 is a schematic drawing.

A loop of wire is placed between the poles of two magnets. The coil is mounted on a central axis that allows it to rotate freely. The ends of the coil are connected to

Figure 5.6
A simple DC motor



an external power source. When the power source is switched on, the current will run in a clockwise direction, that is, from a to b to c then to d.

NOTE: Conventional current always leaves the positive terminal of a power source and enters the negative terminal.

Now let us examine the force acting on each of the four sides of the coil:

- *On side ab*: The current is running into the page; therefore, if we apply the right-hand palm rule, we can see that the force is acting down. Hence there is a **torque** acting on the side ab which causes it to rotate anti-clockwise about the central axis.
- *On side cd*: The current is running out of the page, thus the force is up. There is also a torque on the side cd which causes it to rotate in the anti-clockwise direction as well.

Consequently, the two torques act as a couple—a pair of torques on each side of a pivot that both cause the same rotation—on the coil, and the coil spins in an anti-clockwise direction. So now we have a functional motor.

NOTE: It can also be seen here that sides ab and cd will always be perpendicular to the magnetic field regardless of the position of the coil as it spins.

Side bc is initially parallel to the magnetic field, so it does not experience any force. However, as the coil starts to turn, the current will start to have an upward component, by applying the right-hand palm rule, the force acting on side bc is into the page.

Side ad will be in a similar situation to side bd, except as the coil spins, its current will have a downward component. Hence the force is out of the page. There is no contribution to the torque.

Consequently, the forces acting on sides bc and ad stretch the coil. However, since the coil is usually rigid, the stretching effect is usually not seen. Hence their contribution to the function of motors is usually neglected in the descriptions in this chapter. Only the two sides which are (always) perpendicular to the magnetic field (ab and cd) are considered to be the functioning part of a motor, as they are responsible for creating the motor's torque and rotation.

A quantitative description of the torque of a DC motor

The torque acting on a coil (loop) of current-carrying wire inside a magnetic field is caused by the forces acting on the sides which are always perpendicular to the magnetic field, such as sides 'ab' and 'cd' in Figure 5.6. It can be quantitatively determined by the equation:

$$\tau = nBIA\cos\theta$$

Where:

τ = the torque, measured in Nm

n = the number of turns of the coil

B = the magnetic field strength, measured in T

I = the current in the coil, measured in A

A = the area of the coil, measured in metres squared (m^2)

θ = the angle between the plane of the coil and the magnetic field, measured in degrees. See Figure 5.7 (a) to (c).

NOTE: This equation can easily be derived from combining the equations $\tau = F_p \times d$ and $F = BIl\sin\theta$. This is not required by the syllabus, but you should try!

Consider the following side views of a DC motor, illustrating the size of the torque where the coil is at different angles to the magnetic field. Note that the current runs out of the page at A and into the page at B.

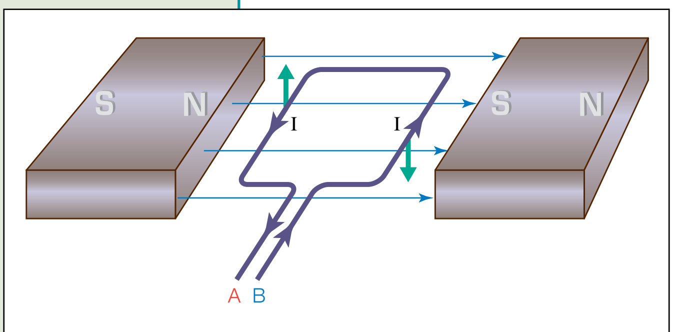


Figure 5.7 (a) The plane of the coil is parallel to the magnetic field, hence θ is 0° and cos θ is 1; the torque is a maximum

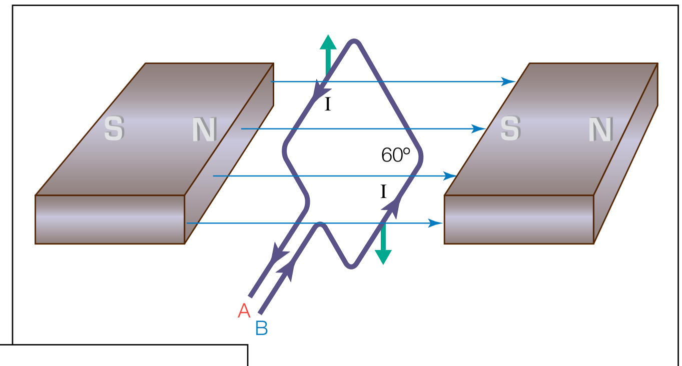


Figure 5.7 (b) The coil is at 60° to the magnetic field, and cos 60° is ½, hence the torque on the coil is half the maximum

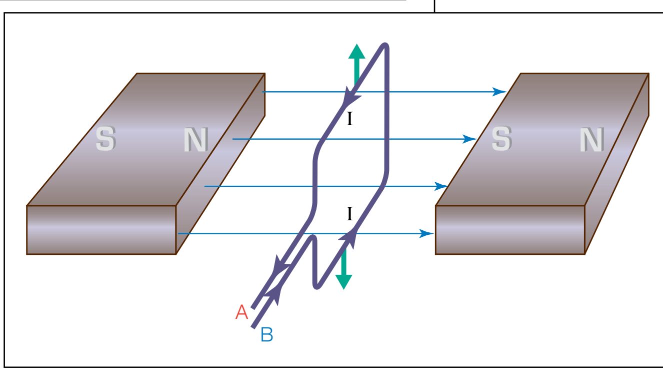


Figure 5.7 (c) The coil is now perpendicular to the magnetic field, so θ is 90°, and cos 90° is 0, hence no torque is acting on the coil; this comes as no surprise, as the force is now stretching the coil rather than turning the coil

H14.1A, D, G
H14.2A, B
H14.3C, D

■ *Solve problems and analyse information about simple motors using: $\tau = nBIA\cos\theta$*

Example

In a DC motor, a circular loop of coil with a radius of 50 cm is placed between the poles of two magnets which provide a uniform magnetic field of 0.3 T. The coil is situated at 55° to the magnetic field.

(a) Calculate the size of the torque acting on the wire when a current of 2.3A passes through the coil.

(b) If the number of turns is increased to 150 turns, what is the new torque?

Solutions

(a) $\boldsymbol{\tau} = \boldsymbol{nBIA}\cos\theta$

$n = 1$

$\boldsymbol{B} = 0.30$ T

$\boldsymbol{I} = 2.3$A

$\boldsymbol{A} = \pi r^2 = \pi \times 0.50^2$

$\theta = 55°$

$\boldsymbol{\tau} = 1 \times 0.30 \times 2.3 \times \pi \times 0.50^2 \cos 55°$

≈ 0.31 N m

(b) Similarly, when $n = 150$

$\boldsymbol{\tau} = \boldsymbol{nBIA}\cos\theta$

$\boldsymbol{\tau} = 150 \times 0.30 \times 2.3 \times \pi \times 0.50^2 \cos 55°$

≈ 46.6 N m

Problem! The coil in a motor will rotate correctly when it is parallel or inclined to the magnetic field. However, when the coil is at the vertical position, the torque acting on it is zero, hence there is no turning affect. As pointed out before, at the vertical position, the forces acting on the coil try to stretch the coil rather than turn the coil. It follows that in order to make a DC motor spin continuously, a split ring commutator is needed.

5.6 The need for a split ring commutator in DC motors

What happens to the coil of a DC motor without a split ring commutator?

As we have seen in the previous section, the torque on the coil is a maximum when the plane of the coil is parallel to the magnetic field, and becomes smaller as it rotates. The torque becomes zero when the coil is at the vertical position, or perpendicular to the magnetic field. At this point, despite the absence of torque, the coil will still rotate through the vertical position due its momentum or inertia. However, the force acting on sides A and B will still be up and down respectively. Hence, as soon as the coil passes through the vertical position, it will be pushed back to the vertical line and carried over to the initial side, as shown in Figure 5.8. When the coil reaches the initial side, it is pushed past the vertical line once again and the process repeats. However, each time, the coil loses some of its momentum and inertia due to friction, so each time it will move less distance past the vertical line as it's carried over by its momentum. The subsequent motion of the coil is that it oscillates about the vertical plane and eventually comes to rest.

Thus, in order to ensure that DC motors spin continuously and smoothly, a device called a **'split ring' commutator** must be employed.

In a simple DC motor, a split ring consists of two halves of a metal (usually copper) cylindrical ring electrically insulated from each other (see Fig. 5.9).

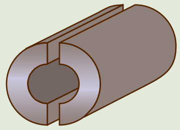


Figure 5.9 (a) A DC split ring commutator

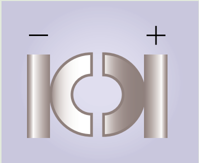


Figure 5.9 (b) End view of a split ring commutator; it is in firm contact with carbon brushes that are held in position by springs

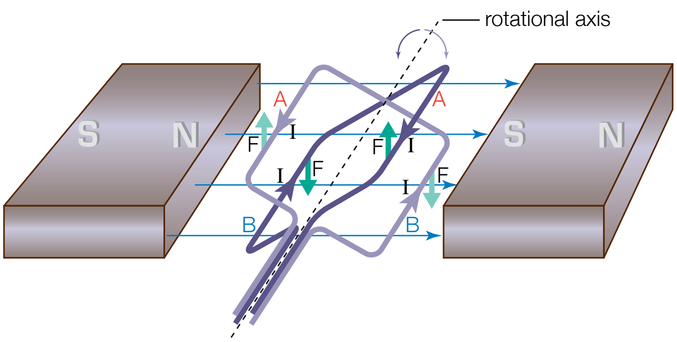


Figure 5.8 A DC motor without a split ring commutator

A split ring commutator

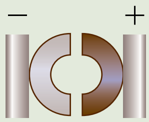


Figure 5.10 (a) End view of a split ring commutator position (a)

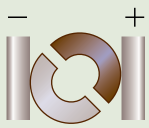


Figure 5.10 (b) End view of a split ring commutator position (b)

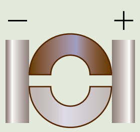


Figure 5.10 (c) End view of a split ring commutator position (c)

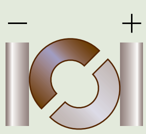


Figure 5.10 (d) End view of a split ring commutator position (d)

How does a split ring commutator work?

When the coil is parallel to the direction of the magnetic field, the commutator is horizontal as shown in Figure 5.10 (a). As the coil rotates, say anti-clockwise, the commutator also rotates between the brushes; however, each half of the commutator is still in contact with the brush of the same polarity (Fig. 5.10b). When the coil reaches the vertical position, the halves of the commutator are not in contact with the brushes, and the current flowing through the coil drops to zero (see Fig. 5.10c). This however has no net effect, as the current in the coil when the coil is at the vertical position only stretches the coil anyway. The critical part is when the coil swings past the vertical position. Each half of the commutator changes the brush it is contacting to the one of opposite polarity (see Fig. 5.10d). This effectively reverses the current direction in the coil. Consequently, the direction of the force acting on the two sides of the coil will also be reversed, allowing the coil to continue to turn in the same direction rather than pushing it back (shown in Fig. 5.11). When the coil reaches the vertical position again after another half cycle, the halves of the commutator will change their contacts again, reversing the current direction and consequently reversing the direction of the force and maintaining the rotation in the one direction. The repetition of this process via the action of a split ring commutator allows a DC motor to rotate continuously in one direction.

In summary

A split ring commutator helps a DC motor to spin in a constant direction by reversing the direction of current at vertical positions every half cycle by changing the contact of each half of the split ring commutator with the carbon brushes. This allows the force and hence the torque acting on the two sides of the coil which are perpendicular to the magnetic field to change direction every half revolution at the vertical positions, consequently allowing the coil of the DC motor to spin continuously.

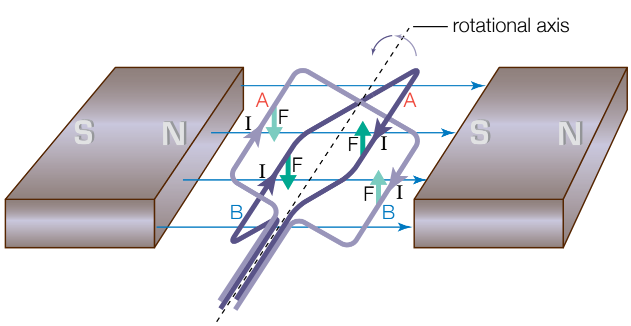


Figure 5.11 The reversal of the current direction, hence the force direction due to the action of a split ring commutator

5.7 Features of DC motors

- ***Describe the main features of a DC electric motor and the role of each feature***
- ***Identify that the required magnetic fields in DC motors can be produced either by current-carrying coils or permanent magnets***

The main features of a DC motor are those that are essential for the function of the motor. They are:

- a magnetic field
- an armature
- a commutator
- carbon brushes

Magnetic field

Magnets

As the motor effect states, a current-carrying wire in a magnetic field will experience a force. So for a functional motor, a magnetic field is essential.

Recall that a magnetic field can be represented by magnetic field lines. The direction of the field lines shows the flow of the magnetic field and the density of the lines shows the strength of the magnetic field. Where the field lines are closer together, the magnetic field has greater strength, and where field lines are spread out, the field strength is smaller.

Magnetic fields can be provided by either *permanent magnets* or *electromagnets*.

Furthermore, as we have seen in this chapter, the structure which provides the magnetic field usually remains stationary, and is called the **stator**, whereas the coil usually rotates inside the field, and is called the **rotor**. However, many industrial motors work with the coil held stationary and the magnets rotating.

Permanent magnets

Permanent magnets are ferromagnetic metals which retain their magnetic property at all times.

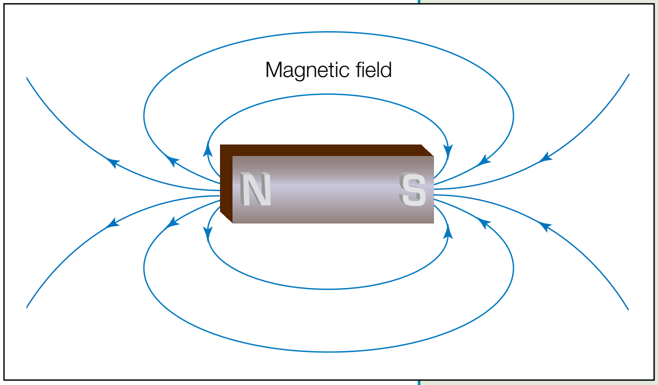


Figure 5.12
Magnetic field around a bar magnet

They can be made with different shapes, the most common ones being horseshoe magnets and bar magnets like those shown in Figure 5.12. Permanent magnets, like all magnets, have two poles, a north and a south pole.

Using a bar magnet as an example, the magnetic field lines come out from the north pole and return into the south pole. The magnetic field strength is much stronger at the poles than on the sides.

Electromagnets

An electromagnet consists of a coil of current-carrying wire called a **solenoid** wound around a soft iron **core**. The electromagnet, as its name suggests, only possesses magnetic properties when a current is made to pass through the coil.

Electromagnets are usually able to provide stronger magnetic fields than permanent magnets and have major advantages over permanent magnets in that their strengths are adjustable and can be switched on and off when desired.

The magnetic field around an electromagnet is similar to that around a bar magnet, as shown in Figure 5.13 (a). In order to determine the poles of the electromagnet, we can use another 'right-hand grip' rule as shown in Figure 5.13 (b).

Radial magnetic field

As we have discussed, the torque acting on the coil varies as it rotates to different positions with respect to the magnetic field lines. The variation in the torque results in a varying speed of rotation of a motor: faster at the point when the coil is parallel to the magnetic field and slower when it is perpendicular. Fortunately, motors usually spin at speeds as high as 3000 revolutions per minute (rpm), hence the variation in

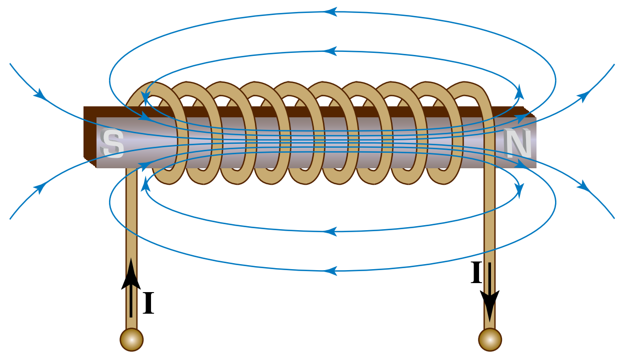


Figure 5.13 (a) Magnetic field around an electromagnet

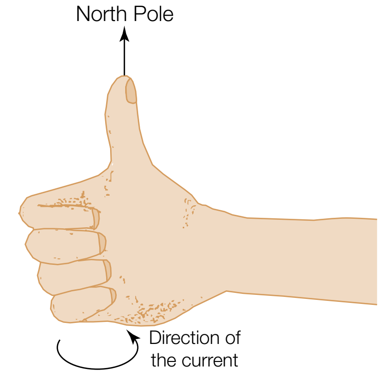
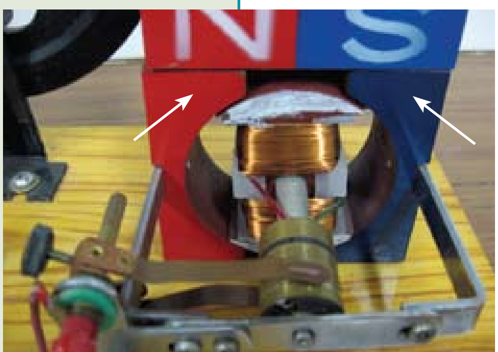


Figure 5.13 (b) Right-hand grip rule: do *not* confuse this with the other right-hand grip rule mentioned earlier in this chapter



Radial magnets (arrows)

the rotational speed is undetectable by sight, and usually has negligible impact.

Nevertheless, when DC motors are used in applications that require a constant rotation speed, a **radial magnetic field** must be introduced in order to solve this technical difficulty.

A radial magnetic field can be created by shaping the pole pieces of magnets into curves, hence the word 'radial'. The radial magnetic field ensures that the plane of the coil is parallel to the magnetic field at a greater range of positions, so that the angle between the magnetic field and the coil remains zero for longer. Consequently, the torque acting on the coil is kept at the maximum for longer. (Since $\cos\theta$ is always 1, $\boldsymbol{\tau} = n\boldsymbol{B}IA$.) This is shown in Figure 5.14.

With the torque maintained at the maximum for longer, the motor is more efficient.

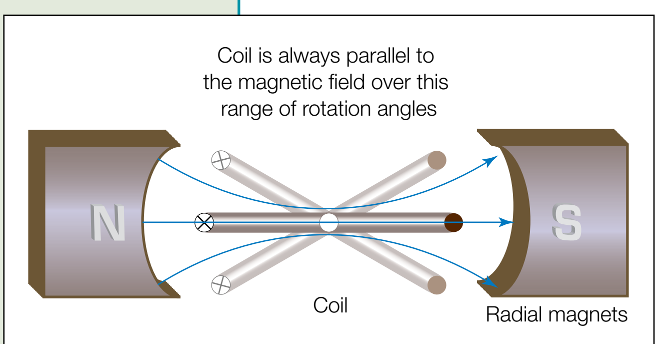


Figure 5.14 The coil is between the poles of a set of radial magnets: note that the coil is always parallel to the magnetic field lines

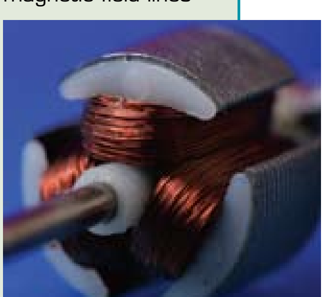
Armature

Armature' refers to the coil of wire that is placed inside the magnetic field.

The coil is almost always wound around a soft iron core in order to maximise the performance of the motor. A justification is given in Chapter 6.

In this chapter, all armatures are represented as if they only have a single loop. In real DC motors, armatures have numerous loops to maximise the torque that is acting on them, since the torque $\boldsymbol{\tau}$ is directly proportional to the number of turns of the coil, n. Also, in real DC motors, three coils are usually used instead of a single coil, with the coils aligned at 120° to each other. This maximises the torque that can act on the coils, thus making the motor run more efficiently.

Finally, as we discussed in the magnetic field section, the coils can either be the **rotor** or the **stator**, depending on the design of the DC motor.



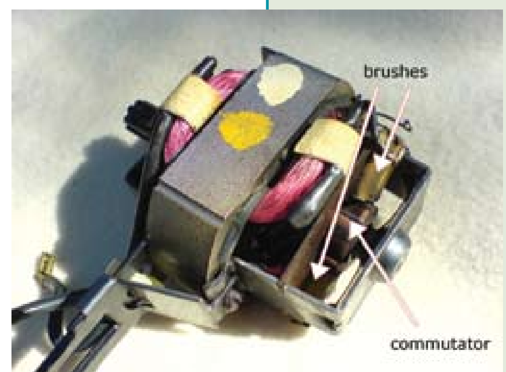
An armature with a soft iron core. Note also the three sets of coil used

Split ring commutator

The features and the significance of a split ring commutator have already been discussed in detail in this chapter pages 103–104. Although all parts of a DC motor are important to its function, the split ring commutator is the most subtle part of the DC motor's design.

Carbon brushes

Working with the commutators are the carbon brushes. They are responsible for conducting current into and out of the coil. They are also responsible for contacting different parts of the commutator every half cycle in order to reverse the current to ensure the continuous spin of the motor.



Carbon brushes of a DC motor

Carbon brushes are usually made of graphite (a type of carbon), and are pressed firmly onto the split ring commutator by a spring system.

Carbon brushes are preferred to wires and soldering for obvious reasons. If wires were soldered to the armature, not surprisingly, as the armature rotates, the wires would eventually tangle up and break. Brushes can serve the same role as the wires in terms of conducting electricity but they do not rotate along with the moving armature.

Also, carbon or graphite is used to make brushes because:

1. The graphite is a lubricant; it can reduce the friction between the brushes and the commutator. Reduced friction enables the motor to run more efficiently, and minimises wear and tear.
2. Graphite is a very good conductor of electricity.
3. Graphite is able to withstand the very high temperatures generated by the friction between brushes and commutators.

Over time, carbon brushes gradually wear out. Motors are designed so that these can be replaced very easily.

SR

For simulation 20.3 Electrical motor

Applications of the motor effect

SECONDARY SOURCE INVESTIGATION

PHYSICS SKILLS

H13.1A, B, C, E
H14.1G, H
H14.3D

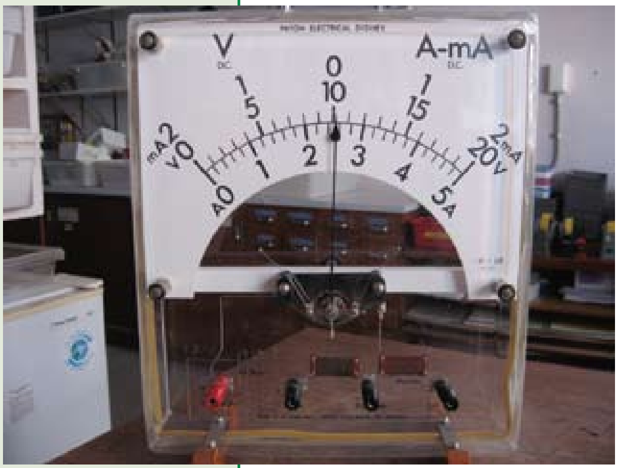
- ***Identify data sources, gather and process information to qualitatively describe the application of the motor effect in:***
  - ***the galvanometer***
  - ***the loudspeaker***

Galvanometer

Definition

A **galvanometer** is a very sensitive device that can measure small amounts of current. It is the basic form of an ammeter or a voltmeter.

A galvanometer works on the principle of the **motor effect**. A simple galvanometer consists of a fine coil with many turns wound around a soft iron core; the coil is placed inside a radial magnetic field produced by permanent magnets with shaped pole pieces. It also has a



A galvanometer

torsional spring attached to the axis of rotation of the coil. A pointer is attached to the coil and a scale is developed. All these are shown in Figure 5.15.

When the galvanometer is used to measure a small current, the current is passed through the coil. The coil experiences a force inside the radial magnetic field (motor effect) and starts to rotate, similarly to the rotation of DC motors as described earlier. (In the case of the galvanometer shown in Fig. 5.15, the coil rotates clockwise.) However, as the coil rotates, it stretches the spring, which will then exert a torque that counteracts the initial torque created by the motor effect. As the coil rotates, the spring is stretched more and the opposing torque exerted by the spring increases. Eventually, when the opposing torque is equivalent to the forward torque, the coil stops rotating. The degree of movement of the coil is indicated by the pointer on the scale (in this case, to the right of the zero); the bigger the forward torque, the more the coil will move. Since the magnetic field strength and the area of the coil are both kept constant, the forward torque will only depend on and in fact will be directly proportional to the size of the current. ($\tau = nBIA$, since a radial magnetic field is used.) Hence, the appropriately developed scale gives a reading of the measured current.

The role of the radial magnetic field is again significant to the function of the galvanometer. As discussed before, it is used to produce a constant maximum torque. This also ensures that the size of the forward torque is *only* dependent on the current and is independent of the position of the coil. Thus, the conversion from the angle of rotation, which is a direct measure of the size of the forward torque, to current is made possible.

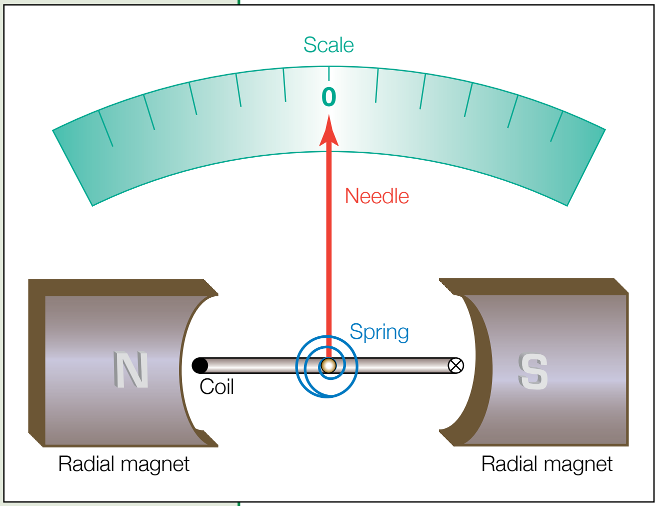


Figure 5.15
A moving coil galvanometer

Loudspeaker

A loudspeaker also works on the basis of the motor effect: it converts electrical energy to sound energy.

A simple loudspeaker consists of a coil of wire between the pole pieces of the magnets which form the core. A paper diaphragm is then attached to this coil–magnet unit.

Electrical signal inputs to the loudspeaker are in the form of alternating currents in which the waves vary in frequency and amplitude. When signals are fed into the coil inside the loudspeaker, the coil experiences a force as a consequence of the motor effect. As we can see in Figure 5.16, when the current flows from A to B and we apply the right-hand palm rule, we can see that the force acting on the wire pushes the wire out. However, when the current flows from B to A, the force will pull the coil in. Since we know that the AC signals vary in direction very rapidly, the coil should move in and out very rapidly as well. However, because the coil is very tightly wound on the magnetic pole piece, they cannot move freely but they can vibrate. The vibration of the coil–magnet unit causes the paper diaphragm to vibrate with it. The vibration of the paper diaphragm causes air to vibrate which produces sound waves.

A loudspeaker

The nature of the sound waves will depend purely on the characteristics of the AC signal inputs. The pitch of the sound is dictated by the frequency of the sound waves, which is directly related to how fast the coil vibrates, which in turn is dependent on the frequency of the AC signals. The loudness of the sound is the amplitude of the sound waves, this in turn depends on the degree or the strength of the vibration, which is dependent on the amplitude of the input AC signals.

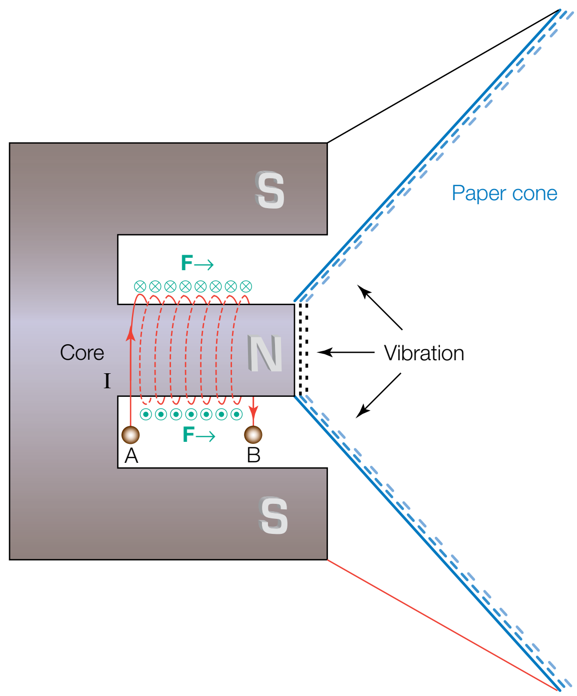


Figure 5.16
A loudspeaker

Demonstrating the motor effect

■ *Perform a first-hand investigation to demonstrate the motor effect*

FIRST-HAND INVESTIGATION

PFAs

H1, H2

PHYSICS SKILLS

H11.1E
H11.2E
H11.3A, B
H12.1D, D
H12.2B
H14.1D, G, H

The syllabus requires you to perform a first-hand investigation to demonstrate the motor effect. The first-hand investigation could include both demonstrating the factors that affect the size of the motor effect, that is the formula $F = BIl\sin\theta$, and the application of the right-hand palm rule.

To demonstrate the formula $F = BIl\sin\theta$, experiments can be set up to show that the size of the motor effect is directly related to the magnetic field (B), the strength of the current (I), the length of the wire (l), or the sine of the angle between the magnetic field and the current-carrying wire. It is important to realise that as there are four variables that can change the size of the force, it is important to test only one at a time. For example, if you wish to demonstrate the effect of the current on the size of the motor effect, then it is important to change only the current and keep the other three factors constant as the controls. An example of that—a **current balance**—is shown in the exercise questions.

To demonstrate the right-hand palm rule, you can choose to change either the direction of the current or the direction of the magnetic field, and see the resultant movement of the conductor, which indicates the direction of the force. Again, since there are two variables that can affect the direction of the force, it is important to only change one at a time and keep the other one constant as the control.

TR

Risk assessment matrix

A current balance from a school laboratory

If the school does not have access to a current balance, there are a number of simpler ways to demonstrate the motor effect, such as the method outlined here.

1. Link approximately 2 m of connecting wires together, and plug the ends into the DC output of a power pack.
2. With the connecting wires lying loosely on a desk, place either a strong horseshoe magnet or opposing poles of a pair of strong bar magnets so that the wire passes through the magnetic field.
3. With the power pack set to 6 V, turn the current on and off again quickly (to prevent the power pack from overheating).
4. If the wire does not jump up, repeat the experiment with the poles of the magnet reversed. (The movement of the wire while the current is flowing is due to the motor effect.)

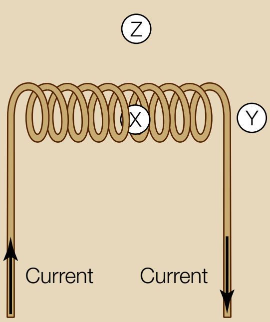
CHAPTER REVISION QUESTIONS

1. Draw the magnetic field pattern for the following bar magnets:

(a)

(b)

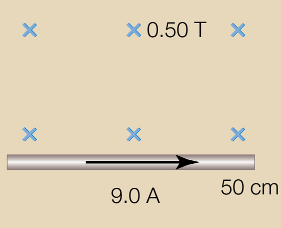
2. The diagram shown below is a solenoid.



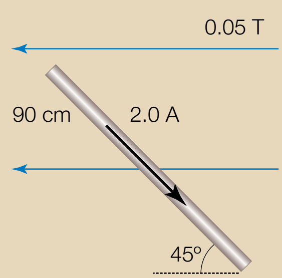
(a) State the direction of the magnetic field at points X, Y, Z respectively.
(b) At which point is the magnetic field strongest?
(c) List two factors that will affect the strength of the magnetic field produced by this solenoid.

3. Determine the force acting on the following current carrying wires:

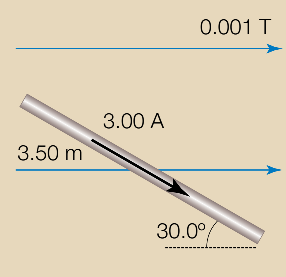
(a)

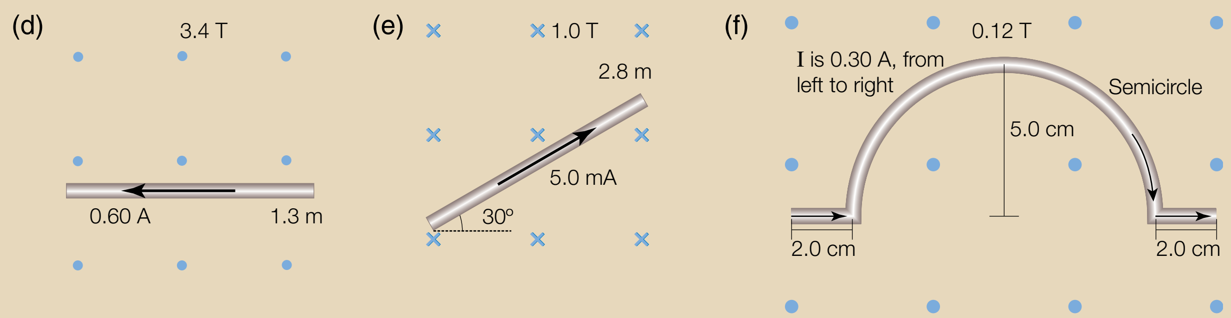


(b)



(c)



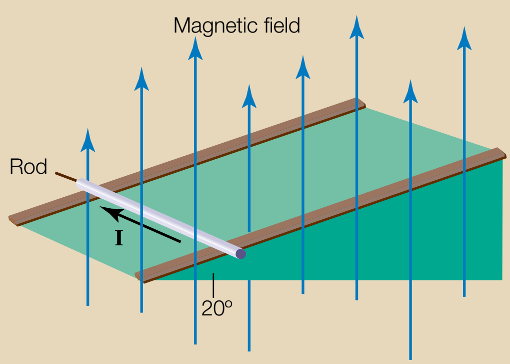


4. When a current-carrying wire is placed inside an external magnetic field, it will experience a force.

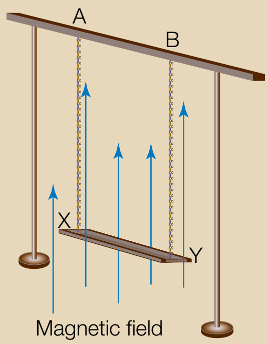
   (a) Use appropriate axes to plot the relationship between the angle inscribed by the wire and magnetic field and the force experienced by the wire, such that a straight line can be obtained.

   (b) Suppose the gradient of this straight line is 1, the length of the wire is 20 cm and the current flowing through it is 0.45 A, determine the strength of the external magnetic field.

5. A slope is set up with one conducting rail on each side, a power source is connected to the rails. A rod is placed on the slope perpendicular to both rails so that a current is running through it. If the rod has a mass of 30 g and is 25 cm long inside a magnetic field which is 0.6 T in strength, and the current size is 1.3 A, determine the acceleration of the rod.



6. A child is sitting on a swing in a modern fun park that is operated electronically. As shown in the figure below, the swing seat hangs off the support at points A and B, and is immersed in a uniform magnetic field of 0.50 T directed up the page. To start the swing moving, a current is passed into the swing in the direction of AXYB.



(a) Which part(s) is/are responsible for the swing moving—AX, XY, or BY—justify your answer.

(b) In which direction will the swing move initially?

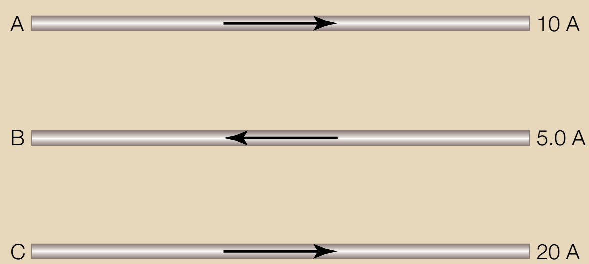
(c) Calculate the magnetic force that is developed to move the swing, if side (the seat) XY is 4.0 m long and the current passing through it is 50 A.

Extension

(d) If sides AX and BY have a negligible mass, and side XY plus the child weighs 45 kg altogether, calculate the angle the swing will move through initially. The magnetic field is then turned off to allow the swing to pursue a simple pendulum motion.

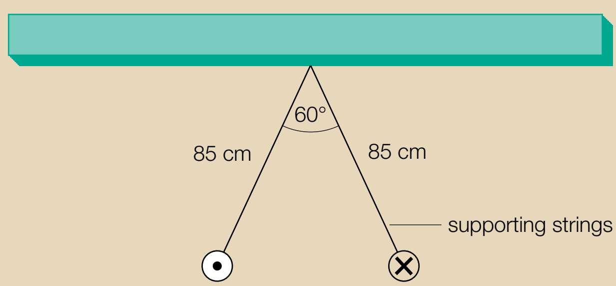
(e) If the sides AX and BY are 3 m long, how many cycles will the swing make in a 1 minute interval? (Assume there is no friction.)

7. Wires A, B, C are three parallel current-carrying wires as shown in the diagram below; the wires are all 3.3 m long and 1.0 m apart from each other.



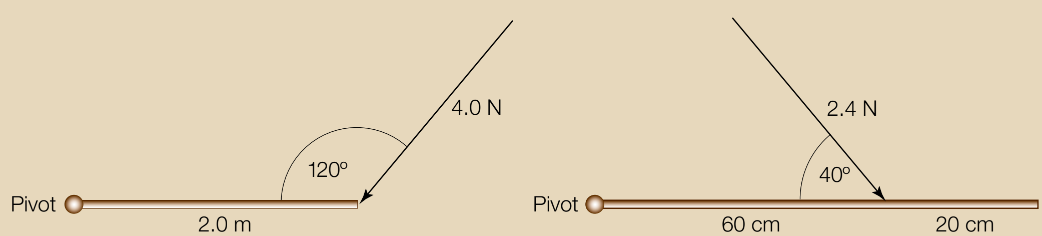
Determine the resultant force acting on wire B.

8. Two massless parallel current carrying wires are supported by strings as shown in the diagram. If each of the wires is 1 m long and carries a current of 50 mA, and the supporting strings are 85 cm long, calculate the force acting on each of the wires when the angle between the strings is 60°.



End view

9. Determine the size of the torque acting on the following rods:

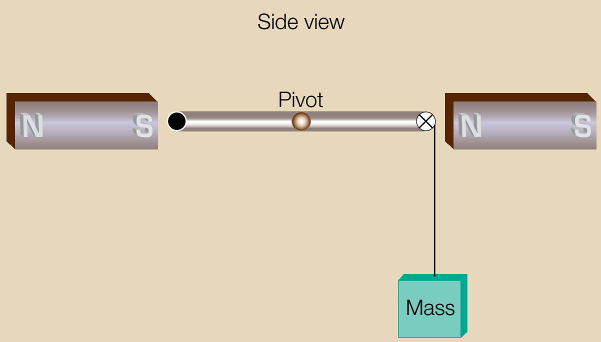


10. The armature of a DC motor consists of 40 turns of circular coil with a diameter of 20 cm. A voltage of 6.0 V is supplied to the coil. If the coil has a total resistance of 0.50 Ω, and the magnetic field has a strength of 0.20 T:

(a) Determine the size of the torque when the coil is in the horizontal position (its starting position).
(b) How would this torque affect the motion of the coil?
(c) Determine the size of the torque when the coil has moved through an angle of 30°.
(d) Determine the size of the torque when the coil has reached the vertical position.
(e) Comment on the magnitude of the net torque once the motor has reached a constant speed.

11. The coil of a DC motor inclining at 30° to a magnetic field is experiencing a torque of 3.2 N m. If the coil has now turned so that it is inclining at 45° to the magnetic field and the current through the coil is suddenly tripled, determine the new torque acting on this coil.

12. A motor system is designed to lift a mass, as shown in the diagram.



If the maximum magnetic field is 2.0 T, the maximum current size is 40 A and the coil is square with sides measured by 2.4 m, what is the maximum mass the system is able to lift?

13. Assess the role of split ring commutator in allowing DC motors to spin continuously in one direction.

14. Simple motors used at domestic levels use copper for their commutators. State two advantages and two disadvantages of copper commutators compared with graphite commutators.

15. The spring inside a galvanometer is essential for its function.
(a) What is the role of this spring?
(b) The radial magnetic field of this galvanometer is 0.2 T: what is the siginificance of using the radial magnetic field?
(c) If the galvanometer contains 30 turns of a square coil, with sides each measuring 2.0 cm, calculate the torque exerted by the spring when the needle is pointing at 0.20 A.

16. Evaluate the importance of the motor effect to the functioning of a loudspeaker.

17. Design a first-hand investigation to assess the relationship between the current in a straight wire (conductor) and the force it experiences when it is placed inside a magnetic field.

SR

Answers to chapter revision questions