8.3 Magnetic Force on a Current-Carrying Conductor

Other than the musicians, probably the most important parts of a concert are the speakers. You might have seen the large boxes that transmit sound to both the performers and the audience (**Figure 1**). Speakers are so common that we rarely think about the impact this invention has had on our culture. People use speakers at music concerts, in cars, and in portable devices. Telephones, computers, and televisions all rely on speakers to transmit sound. Intercom systems in buildings, megaphones used by firefighters and police officers, and even electronic readers for sight-impaired people are all possible because of the speaker.

Figure 1 Musicians rely on the magnetic force in speakers to transmit sound during a performance.

How does a speaker work? Inside a speaker is an electromagnet as well as a permanent magnet. The magnetic field of the permanent magnet exerts a force on the current in the coil of the electromagnet. The speaker uses this force to produce sound waves. Simply put, a speaker works because a current-carrying conductor experiences a force in a magnetic field.

Magnetic Force and Current

An electric current consists of a collection of moving charges. We can therefore use the formula for the magnetic force on a single moving charge to determine the magnetic force on a current-carrying wire. This force is important in many applications, including electric motors. Consider a current-carrying wire placed in an external magnetic field as shown in **Figure 2**. The magnetic field $\vec{B}$ is uniform and perpendicular to the wire. An external force, not the current in the wire, produces this field. We can calculate the magnetic force on the wire due to this external field by adding the magnetic forces on all the moving charges in the wire.

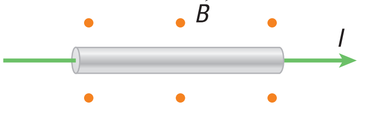

Figure 2 This current-carrying wire is in an external magnetic field. The magnetic field is perpendicular to the wire and is directed out of the page as indicated by the dots.

A segment of the wire of length L is shown in **Figure 3**. The current, I, in this segment is

$$I = \frac{q}{\Delta t}$$

where q is the electric charge that passes by one end of the wire segment in a time interval Δt.

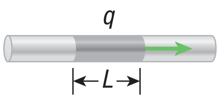

Figure 3 In our analysis to determine the magnetic force on a current-carrying wire, we examine a section of the wire and call it length L.

This equation is the relationship between charge and current you have studied before. The magnetic force on this moving charge is given by

$$F_M = qvB \sin\theta$$

The speed of the charge is just

$$v = \frac{L}{\Delta t}$$

Substituting the speed, v, in the magnetic force equation gives

$$\begin{aligned} F_M &= qvB \sin\theta \\ &= q\frac{L}{\Delta t}B \sin\theta \\ F_M &= \frac{q}{\Delta t}LB \sin\theta \end{aligned}$$

Using the relationship between current and charge, $I = \frac{q}{\Delta t}$, we get

$$F_M = ILB \sin\theta$$

The magnetic force on the moving charge is really a force on the wire. We can rewrite the equation to express this relationship explicitly:

$$F_{\text{on wire}} = ILB \sin\theta$$

where θ represents the angle between I and $\vec{B}$.

Figure 4 shows how to use the right-hand rule to determine the direction of $\vec{F}_{\text{on wire}}$. Begin with the fingers of your right hand in the direction of the magnetic field and point your thumb in the direction of the current. Your palm then points in the direction of the force on the wire. The external magnetic field pulls this wire downward as long as the current is directed to the right. The magnetic force on a current is due to the force on a moving charge, so the right-hand rule used here is similar to other right-hand rules you have used before. The direction of the current replaces the direction of $\vec{v}$ for a moving charge.

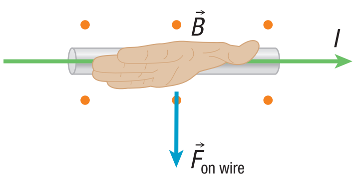

Figure 4 You can use the right-hand rule to determine the direction of the magnetic force on the wire.

In the following Tutorial, you will calculate the magnetic force on a current-carrying wire in a magnetic field.

Tutorial 1 Calculating the Magnetic Force on a Wire

Sample Problem 1: Calculating the Magnitude of the Magnetic Force on a Wire in a Uniform Magnetic Field

A piece of wire 45.2 cm long has a current of 12 A (**Figure 5**). The wire moves through a uniform magnetic field with a strength of 0.30 T. Calculate the magnitude of the magnetic force on the wire when the angle between the magnetic field and the wire is (a) 0°, (b) 45°, and (c) 90°.

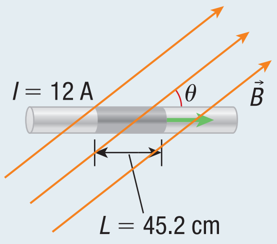

Figure 5

Given: $I = 12$ A; $L = 45.2$ cm $= 0.452$ m; $B = 0.30$ T

Required: $F_{\text{on wire}}$

Analysis: Use the equation for the magnitude of the magnetic force on a current-carrying wire: $F_{\text{on wire}} = ILB\sin\theta$. Note that 1 A = 1 C/s.

Solution:

$$\begin{aligned} F_{\text{on wire}} &= ILB\sin\theta \\ &= \left(12\ \frac{\cancel{\text{C}}}{\text{s}}\right)(0.452\ \text{m})\left(0.30\ \frac{\text{kg}}{\cancel{\text{C}}\cdot\text{s}}\right)\sin\theta \\ &= (1.627\ \text{kg}\cdot\text{m/s}^2)\sin\theta \\ F_{\text{on wire}} &= (1.627\ \text{N})\sin\theta \text{ (two extra digits carried)} \end{aligned}$$

(a) When $\theta = 0°$, then $\sin\theta = 0$, so

$$\begin{aligned} F_{\text{on wire}} &= (1.627\ \text{N})(0) \\ F_{\text{on wire}} &= 0\ \text{N} \end{aligned}$$

(b) When $\theta = 45°$, then $\sin\theta = 0.707$, so

$$\begin{aligned} F_{\text{on wire}} &= (1.627\ \text{N})(0.707) \\ F_{\text{on wire}} &= 1.2\ \text{N} \end{aligned}$$

(c) When $\theta = 90°$, then $\sin\theta = 1$, so

$$\begin{aligned} F_{\text{on wire}} &= (1.627\ \text{N})(1) \\ F_{\text{on wire}} &= 1.6\ \text{N} \end{aligned}$$

Statement: The magnitude of the force on the wire is 0 N when $\theta = 0°$, 1.2 N when $\theta = 45°$, and 1.6 N when $\theta = 90°$.

Sample Problem 2: Determining Magnetic Force on a Segment of a Current-Carrying Wire in Earth's Magnetic Field

Two electrical poles support a current-carrying wire. The mass of a 2.5 m segment of the wire is 0.44 kg. A 15 A current travels through the wire. The conventional current is oriented due east, horizontal to Earth's surface. The strength of Earth's magnetic field at the location is 57 μT and is oriented due north, horizontal to Earth's surface (**Figure 6**).

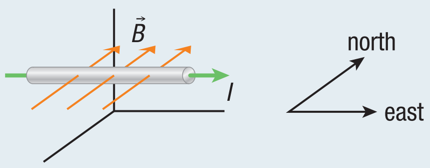

Figure 6

(a) Determine the magnitude and the direction of the magnetic force on the 2.5 m segment of wire.

(b) Calculate the gravitational force on the 2.5 m segment of wire.

Solution

(a) **Given:** $B = 57\ \mu\text{T} = 5.7 \times 10^{-5}$ T; $I = 15$ A; $L = 2.5$ m; $\theta = 90°$

Required: $F_{\text{on wire}}$

Analysis: Use the equation $F_{\text{on wire}} = ILB\sin\theta$ to determine the magnitude of the magnetic force; then use the right-hand rule for a current-carrying wire in a magnetic field to determine the direction.

Solution:

$$\begin{aligned} F_{\text{on wire}} &= ILB\sin\theta \\ &= \left(15\ \frac{\cancel{\text{C}}}{\text{s}}\right)(2.5\ \text{m})\left(5.7 \times 10^{-5}\ \frac{\text{kg}}{\cancel{\text{C}}\cdot\text{s}}\right)(\sin 90°) \\ &= 2.1 \times 10^{-3}\ \text{kg}\cdot\text{m/s}^2 \\ F_{\text{on wire}} &= 2.1 \times 10^{-3}\ \text{N} \end{aligned}$$

Using the right-hand rule, point the fingers of your right hand in the direction of the current, east. Next, curl your fingers in the direction of the magnetic field, north. Your thumb points in the direction of the resulting magnetic force, upward.

Statement: The magnitude of the magnetic force on the 2.5 m segment of wire is 2.1×10^{-3} N. The force is directed upward.

(b) **Given:** $m = 0.44$ kg

Required: F_g

Analysis: $F_g = mg$

Solution:

$$\begin{aligned} F_g &= mg \\ &= (0.44\ \text{kg})(9.8\ \text{m/s}^2) \\ F_g &= 4.3\ \text{N} \end{aligned}$$

Statement: The gravitational force on the 2.5 m segment of wire is 4.3 N.

Practice

1. A 155 mm part of a wire has a mass of 0.27 kg and carries an electric current of 3.2 A. The conventional current passes through a uniform magnetic field of 1.8 T. The direction of the wire and the magnetic field are shown in **Figure 7**. T/I
   (a) What is the magnitude of the magnetic force on the wire? [ans: 0.89 N]
   (b) Use the right-hand rule to determine the direction of the magnetic force. [ans: in the direction of the *x*-axis]
2. The magnitude of the force exerted on a length of wire in an electric motor is 0.75 N. The 15 A current in the wire passes at a 90° angle to a uniform magnetic field of 0.20 T. Calculate the length of the wire, in centimetres. T/I [ans: 25 cm]
3. Earth's magnetic field exerts a force of 1.4×10^{-5} N on a 0.045 m segment of wire in a truck motor. The motor wire is positioned at an 18° angle to Earth's magnetic field, which has a magnitude of 5.3×10^{-5} T at the truck's location. Calculate the current in the wire. T/I A [ans: 19 A]
4. An electrical cord in a lamp carries a 1.5 A current. A 5.7 cm segment of the cord is tilted at a right angle to Earth's magnetic field. This segment experiences a 5.7×10^{-6} N magnetic force due to Earth's magnetic field. Calculate the magnitude of Earth's magnetic field around the lamp. T/I [ans: 6.7×10^{-5} T]

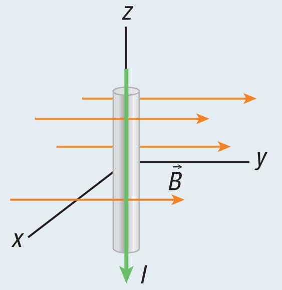

Figure 7

Loudspeakers

Figure 8 shows how a loudspeaker uses a magnetic force on a current to produce sound. The wire coil inside the speaker is part of an electromagnet. Electrical signals corresponding to sounds produce a changing current in the coil. The changing current produces a changing magnetic field around the coil. The permanent magnet also has a magnetic field. This field exerts a force on the current-carrying wire. Variations in the current produce variations in the force on the wires in the coil. The coil moves back and forth in response. The vibrating coil causes the cone to vibrate, pushing sound waves through the air and into your ears.

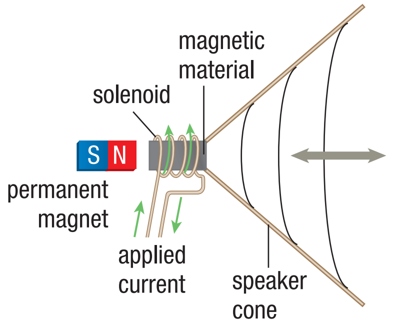

Figure 8 A loudspeaker changes electrical signals to sound using a permanent magnet and an electromagnet.

Electromagnetic Pumps

An understanding of the magnetic force on a current enabled medical researchers to devise electromagnetic pumps to move fluids in kidneys and artificial hearts. Traditional mechanical pumps can cause damage to blood cells. The use of magnetic fields eliminates this problem. Scientists are able to keep the blood flowing to the heart during kidney dialysis, for example, by creating a magnetic field over tubes of blood containing an electric current. A magnetic force acting on the charged particles keeps the blood in motion. WEB LINK

UNIT TASK **BOOKMARK**

You can apply what you have learned about magnetic force and current to the Unit Task on page 422.

8.3 Review

Summary

- The magnetic force on a current-carrying wire is equivalent to the sum of the magnetic forces on all of the moving charges in the wire.
- A straight, current-carrying conductor in a uniform external magnetic field $\vec{B}$ experiences a magnetic force due to the field. The magnitude of the force is $F_{\text{on wire}} = ILB \sin \theta$, where I is the current in the conductor, L is the length of the conductor, and θ is the angle between the direction of the current and the direction of the magnetic field.
- A magnetic field does not exert a force on a current moving parallel to the direction of the magnetic field. The magnetic force on the current is greatest when the current moves perpendicular to the direction of the magnetic field.
- You can use the right-hand rule for a moving charge in a magnetic field to determine the direction of the magnetic force on the conductor. Point the fingers of your right hand in the direction of the magnetic field. Your right thumb points in the direction of the conventional current in the conductor. The palm of your right hand points in the direction the wire will be forced.
- Many technologies exist that use magnetic forces acting on wires.

Questions

1. A current is carried by a straight conductor in a magnetic field of 1.4 T. The conductor is perpendicular to the magnetic field. The conductor is 2.3 m long, and the magnetic field exerts a 1.8 N force on it. T/I
   (a) Calculate the current in the conductor.
   (b) What is the angle between the conductor and the magnetic field when the magnetic force is at a maximum? Explain your reasoning.
2. A 120 mm segment of wire has a mass of 0.026 kg. The segment of wire is oriented at a 45° angle to a uniform magnetic field. The strength of the magnetic field is 0.40 T, and the current in the wire segment is 2.3 A. T/I
   (a) Calculate the magnitude of the magnetic force on the wire segment.
   (b) What is the direction of the magnetic force if the direction of the conventional current is due south and both the wire and the magnetic field are horizontal?
3. A 2.6 m wire carries a current of 2.5 A. The direction of the conventional current is due west. The strength of Earth's magnetic field at the location of the wire is 5.0×10^{-5} T and the orientation of the field is north. Both the wire and Earth's magnetic field are horizontal. T/I
   (a) What are the magnitude and direction of Earth's magnetic force on the wire?
   (b) What will the force on the wire be if the wire is rotated to an angle of 72° with the magnetic field?
4. A long, straight wire of length 1.4 m carries a current of $I = 3.5$ A. A magnetic field of magnitude $B = 1.5$ T is directed perpendicular to the wire. Calculate the magnitude of the force on the wire. T/I
5. The current loop in **Figure 9** forms a right-angled triangle. The loop carries a current I. A uniform magnetic field is directed perpendicular to one edge of the loop. The angle θ in Figure 9 is 39°, L has a length of 1.2 m, and the magnetic field strength has a magnitude of 1.6 T. T/I

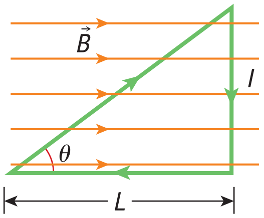

Figure 9

   (a) What is the force on the part of the loop parallel to the magnetic field?
   (b) What is the sum of the forces on the remaining two segments of the loop? (Hint: Write the length of each segment in terms of θ and L, and then use trigonometry.)
   (c) What can you conclude about the magnetic force on a closed loop in a uniform magnetic field?