Magnetic Forces

Introduction

As you read in the last lab, less than a year after Ørsted discovered that currents create magnetic fields, Ampère found that a current-carrying wire experienced a force in a magnetic field. In this lab you will explore the force and some of its applications.

1. Force on a current-carrying wire

Introduction

In this first experiment you will explore the force on a current-carrying wire when it is immersed in a magnetic field. The magnetic field will be produced by a pair of thin, flat, extremely strong permanent magnets. (They have been glued to wood blocks acting as spacers, but if the glue breaks or a piece of steel is brought near them they can painfully pinch your finger.)

By the end of this first section you should be able to answer the following questions:

- How does the force on a current-carrying wire in a magnetic field depend on the current?
- How does the force on a current-carrying wire in a magnetic field depend on the angle between the current and the magnetic field, and on the length of the wire?
- How can the magnitude of the force be used to determine the strength of the magnetic field?

a. Visualizing the magnetic field

Introduction

Before experimenting, carry out this activity to visualize the magnetic field that will be used.

Questions

- The magnets used in this experiment are thin, flat rectangles. Two edge-on views of a single such magnet are shown below. As the figure illustrates, the magnets have been manufactured so that the poles are on the two large rectangular faces. Based on what you already know about the field around a bar magnet, sketch the magnetic field lines for the field produced by a single magnet of this type on the two drawings below.
In the experiment two of these magnets will be facing each other. Sketch the magnetic field lines for the field produced by the pair of magnets on the two drawings below.

Would you expect the magnetic field between the two magnets to be fairly uniform over the whole region between the magnets, a portion of the region, or none of the region? Support your conclusion by explaining how your field sketches show uniform or non-uniform fields.

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b. Measuring the force on a current-carrying wire

Introduction
In this activity you will measure the force on a current-carrying wire and determine how the force depends on current.

Procedure
• The electronic balance should be placed on the plastic platform. On top of the balance place the foam base, the protractor and the magnets. Center the magnet assembly on the compass with its long axis aligned with the ±90° markings.

• While sighting down the copper wire, adjust the location of the balance so that the 1-cm long horizontal segment of copper wire is centered between the two magnets and runs parallel to the magnets. If necessary, bend the copper wire to adjust the height. Figure 1 shows the proper alignment.

• Turn on the electronic balance. After a brief warm-up the balance should read 0.00 g.

• The power supply should be connected to the copper wire as shown in Figure 2. Make the following adjustments to configure the supply as a current source.
  • Set the digital display to read Amps using the black switch to the right of the display.
• Turn all four control knobs fully *counterclockwise* and then turn on the supply. It should read 0.00 A.

• Turn the fine voltage control knob all the way clockwise. The current should still read 0.00 A.

• Adjust both the coarse and fine current control knobs, as needed, until the current reads 3.00 A.

• With the power supply delivering 3A of current the electronic balance should show a small force on it, well less than 1 g. It may be positive or negative.

• Now that you have learned how to use the equipment, make a series of measurements of the weight displayed on the balance for a variety of current values. Use both positive and negative currents. To change the direction of the current, first turn off the power supply, then reverse the two leads to the power supply. Record your results in the table below.

(Recall that though a balance measures force, it displays the results in grams, a unit of mass. To convert to Newtons multiply the value in grams by \( g = 9.8 \times 10^{-3} \text{ N/g} \). Use this conversion to calculate the forces and write them in the right-hand column.)

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Balance display (g)</th>
<th>Force on balance (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-3.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 1: Force vs. Current*

As a general rule, turn off the scale and power supply when not in use. However, to be properly zeroed, the scale must be turned back on before the power supply.

• Analyze your results by plotting the force as a function of current. Is the force proportional to the current? That is, is the slope a straight line? Does the force double when the current doubles? Does the force reverse direction when the current reverses direction? Explain how your graph supports your conclusions.
c. Direction of current, force and magnetic field

Introduction

The force on a current-carrying wire is given by the cross product $\vec{F} = i \vec{l} \times \vec{B}$, and so its direction is given by applying the right-hand-rule. In the experiment just conducted you know the directions of the current and force, so you can use the right-hand rule to find the direction of the magnetic field.

Procedure

- You know that conventional current goes out of the red (positive) terminal of the power supply and into the black (negative) terminal. Consistent with your experiment, in each diagram circle whether the scale reads positive or negative for the direction of current shown.
- Use Newton’s third law to relate the force on the balance exerted by the wire and the force on the wire exerted by the balance. That is, when the balance displays a positive (negative) number, is the force on the wire up or down? In each diagram circle the correct answer.
- Now, using the right-hand-rule, determine the direction of the magnetic field in each case. Add magnetic field lines between the bar magnets to each figure with arrowheads pointing in the correct direction.
- Consistent with your answers, label the poles of the magnets, as in the diagrams on page 2. (That’s 4 poles to label for each case.)

Figure 3: Field direction

Figure 4: Wire length

d. Determining the strength of the magnetic field

Introduction

With the data you have collected you can determine the strength of the magnetic field between the bar magnets, in which the current-carrying wire is immersed. As you arrive at a result, for comparison, recall that the surface magnetic field of Earth is on the order of $10^{-5} \text{T}$ and the field near the poles of weaker bar magnets used in the previous lab was on the order of $10^{-4} \text{T}$.

Procedure

The force on a current-carrying wire is given by $F = ilB \sin \theta$, where $i$ is the current in amps, $l$ the length of the wire that is inside the magnetic field in meters, $B$ the field in Teslas, and $F$ the force in Newtons. The angle $\theta$ is the angle between the current and magnetic field.

- Based on this equation, symbolically state what the slope of a graph of force versus current is, for the special case where $\theta = 90^\circ$.
  
  \[ \text{slope} = \frac{F}{i} = \frac{\text{force}}{\text{current}} \]

- Carefully measure the length, $l$, of the wire in the field to the nearest millimeter and report the length in meters.
  
  $l = \underline{\text{___________}} \text{ m}$
• Finally, use the slope of the best fit line to your data in Table 1 to calculate the magnetic field in the region between the two magnets. Show your work.

\[ B = \text{___________} \text{T} \]

e. Uniformity of the field between the magnets

Introduction
You might have concluded from your sketches in section 1a that the magnetic field is fairly uniform between the bar magnets. In this activity you will experimentally examine its uniformity.

Procedure
• If the field is uniform, then the force should not change if you move the loop to different locations between the two magnets. With current set at 3.0 A, try moving the loop first closer to one magnet and then to the other. Try lifting it slightly or gently pushing it down.
• Because the force is proportional to the field, a 10% increase in force means a 10% increase in field. Report your results. How uniform is the field? Where is it stronger? Weaker?

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f. Dependence of force on angle

Introduction
Theory says the force is proportional to the sine of the angle between current and field, \( F(\theta) = ilB \sin \theta \). So far, force measurements have been made with current perpendicular to the magnetic field, \( F(90^\circ) = ilB \). In this activity you will test the angle dependence, which can be stated succinctly in terms of earlier results as \( F(\theta) = F(90^\circ) \sin \theta \).

Procedure
• With the current at a constant 3.0 A, rotate the stand on which the magnets are mounted to change the angle the current makes with the field. Use the compass to set the angle as shown in Figure 5. (Precise alignment will improve your results.)
• Record the force for the angles listed in the table below. (You can skip a conversion to Newtons because you will be taking a ratio of forces.)
• Calculate \( F(\theta)/F(90^\circ) \) and compare the result with \( \sin \theta \).
### Table 2: Angle dependence

<table>
<thead>
<tr>
<th>θ</th>
<th>Sin θ (calc.)</th>
<th>F(θ) (meas.)</th>
<th>F(θ)/F(90°) (calc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>−30°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>−60°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>−90°</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Is the force proportional to \( \sin \theta \)? Use your data to support your conclusion.

- If the ratio \( F(\theta)/F(90°) \) is not equal to \( \sin \theta \), could the disagreement be explained by your results for the uniformity of the magnetic field?

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### f. Dependence of force on length of wire

**Introduction**

In this activity you will explore how the magnetic force depends on the length of wire immersed in the magnetic field.

**Procedure**

- Measure the length of the longer (2 cm) loop, again to the nearest millimeter and report the length in meters.
  
  \( l = \) _________ m.

- Replace the short loop with the longer loop. Carefully center the loop in the magnetic field. Measure the force, again with 3A current, when the wire is perpendicular to the magnetic field.

- \( F(1\text{-cm wire}) = \) ___________ \( F(2\text{-cm wire}) = \) ___________

- The force is supposed to be proportional to the length of the wire in the magnetic field. Is the ratio of the two forces equal to the ratio of the two lengths?

- Return the magnet to its protective case when you are finished and turn off the scale.
2. **Application: an electric motor**

**Introduction**

In this section you will observe an important application of the physics explored in the last section, an electric motor. Your goal is to understand how a motor works. The toy motor you will observe is dubbed “the world’s simplest motor”. Its few parts and open framework should allow you to make a direct connection with the physics studied in the last section, the force exerted on a current-carrying wire when immersed in a magnetic field.

**Exploration**

- Examine the toy motor, pictured in Figure 6, consisting of a small coil of wire, a D-cell to create a current in the wire, and a small magnet.
- Closely examine the coil. The wire is coated with thin enamel insulation. The insulation has been removed from the two leads, but only on one side of the wire, as shown in Figure 7.
- Place the coil on the supports and spin it. It should continue spinning. If it doesn’t, try spinning it in the opposite direction.
- Finally, remove the magnet from its holder and try holding the magnet in other locations, but always near the coil. In particular, try above the coil and to each side of it. In which location does the coil spin fastest?

**Explanation**

Why does the coil turn? The poles are the faces of the ceramic disk magnet, so the magnetic field lines go out of (or into) the faces. The field is strong near the face and gets rapidly weaker as you go away from the magnet.

- On the drawing in Figure 8 use the right-hand rule to determine the force on the wire. Illustrate the direction of the force on the diagram.
- It should now be clear why the coil begins to rotate. But why was insulation removed from only part of the wires? Suppose insulation was removed from the entire wire. After the coil had rotated through 180° (half a revolution), what was the top of the coil would now be near the magnet. Would the forces on the coil be in the same direction as you drew above? Explain.
• With insulation removed from only part of the wire, after the coil has made half a revolution the insulated part of the wire would be touching the support and current through the coil would stop. Why does the coil keep rotating?

• Not all coils had the insulation scraped off the wire in the same way, so in some cases there is current through the coil when the coil is vertical, in some when it is horizontal, in some when it is at a different angle. Given that, explain why placing the magnet at the top or side of the coil may have made your motor turn faster.

• Later in this lab you’ll have the opportunity to use a more complicated and useful motor.
• Remove the rotating coil from the motor to avoid draining the battery.

3. **Faraday’s Law**

**Introduction**

You have seen that moving charges (currents) produce magnetic fields, and that a current-carrying wire in a magnetic field experiences a force that can move the wire. Is the reverse true? Can a magnetic field produce a current in a wire? In the 1820s questions of this sort drove the English physicist Michael Faraday to spend almost ten years doing experiments until he finally discovered the key to answering the question.

**Goals**

By the end of this activity you should be able to answer the following questions.

• What is needed for a magnetic field to induce a potential difference across a wire or current through it?

• On what does the induced potential difference (EMF) depend?

**Preparation**

As shown in the photo, the solenoid should be placed on a wood block with the Slinky® going through it. A function generator will be used to create a changing magnetic field in the Slinky®. Connect the cable from the output of the function generator to the ends of the Slinky®.

The magnetic field will be measured by the magnetic field probe that should be placed in the center of the Slinky® very close to one side of the solenoid. The probe is connected to Input 1 of the LabPro.

A potential difference will be induced across the large solenoid. Black and red leads go from the solenoid to the instrumentation amplifier, which should be connected to Input 2 of the LabPro.

*Figure 9: Slinky, solenoid and field probe*
All these connections are shown in Figure 10 below.

![Figure 10: Connections](image)

Open the MagneticInteractions folder and double click on Faraday. Faraday will allow you to display the magnetic field and the potential difference simultaneously. (If questioned about the sensor setup, click Connect.)

While the function generator is off, zero both sensors by clicking the zero button on the toolbar.

On the function generator push the 1-Hz button and turn the dial to 1.0. Select a sine wave and turn the amplitude control to the full clockwise position. Set the gain switch on the Instrumentation Amplifier to ±20 mV.

Turn the function generator on. Click the Collect button when you are ready to acquire data.

**Exploration**

- How does the induced EMF depend on the field? Is it largest when the field is largest? Smallest? Changing fastest?

- Decrease the winding density of the Slinky® by stretching it. How does this affect the induced EMF? (When finished, return to the original higher winding density.)

- Reduce the amplitude of the signal from the function generator. This will reduce the current in the solenoid. How does this affect the induced EMF?

- Increase the frequency by turning the dial to 2 Hz, then 4 Hz. How does this affect the induced EMF?

**Analysis**

Faraday’s law states that the EMF induced in each turn of the large solenoid is

$$EMF = -\frac{d}{dt}\Phi_B$$
where $\Phi_0$ is the magnetic flux through each turn in the solenoid. As you have seen, the magnetic field is uniform inside a large solenoid and is given by

$$B = \mu_0 ni$$

where $n$ is the number of turns per meter and $i$ is the current. The flux is equal to the magnetic field inside the solenoid multiplied by the cross sectional area of the solenoid,

$$\Phi_B = \mu_0 ni \pi r^2$$

where $r$ is the radius of the Slinky®. Finally, because the current is produced by the function generator set to deliver a sine wave,

$$\Phi_B = \mu_0 ni \pi r^2 I_0 \sin(2\pi ft)$$

where $f$ is the frequency of the sine wave. Therefore the EMF produced across the solenoid with $N$ turns is given by

$$EMF = -(2\pi^2 \mu_0 r^2 N nf I_0) \cos(2\pi ft)$$

This is a pretty messy equation! Notice three things about it:

1) The EMF varies with time as $\cos(2\pi ft)$. The magnetic field varied as $\sin(2\pi ft)$. Thus, the field and the EMF are out of phase.

2) The quantity $(2\pi^2 \mu_0 r^2 N nf I_0)$ is the amplitude of the oscillation. In this amplitude the quantities $2$, $\pi^2$, $\mu_0$, $r^2$, and $N$, the number of turns in the solenoid, cannot be changed.

3) You have changed $n$ by stretching the solenoid and thus reducing the number of turns per unit length, $I_0$ by changing its amplitude, and $f$ by increasing the frequency of the sine wave.

Explain how your data support the claims that the EMF should be proportional to

$n$ __________________________________________

$I_0$ __________________________________________

$f$ __________________________________________

What would be the induced EMF if you had a constant (DC) current through the Slinky®? Explain.

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