Experiment 6: Magnetic Force on Current-Carrying Wires

OBJECTIVES

1. To predict and verify the nature of the magnetic force acting on a current-carrying wire when the wire is placed in a magnetic field.
2. To make magnetic field measurements of the field due to a permanent magnet.
3. To make magnetic field measurements of the field near a multiloop current-carrying coil.

INTRODUCTION

The force on a segment $d\vec{s}$ of a wire carrying current $I$ in a magnetic field $\vec{B}_{\text{ext}}$ is given by

$$d\vec{F} = I d\vec{s} \times \vec{B}_{\text{ext}}$$

(6.1)

where $\vec{B}_{\text{ext}}$ is the magnetic field produced by an external source somewhere else (not the magnetic field caused by the wire segment itself). By performing the necessary integral, which will be a different integral for different situations, you can in principle find the magnetic force on any extended current-carrying wire sitting in any external magnetic field $\vec{B}_{\text{ext}}$. For a more detailed discussion of the forces on current-carrying wires of different configurations, see the 8.02 Course Notes, Section 8.3.

The first parts of this experiment involve the magnetic field due to a permanent magnet. The field lines from this magnet are similar to those you found in the previous experiment, where the field lines due a bar magnet were mapped. For the purposes of making Predictions 1-5 below, you may assume that the field lines of the rare-earth magnet are similar to those shown for a tightly-wound solenoid, as presented in the 8.02 Course Notes, Section 9.4, and Figure 9.4.1, reproduced here:

![Magnetic Field lines due to a tightly-wound coil.](image)

Figure 1 Magnetic Field lines due to a tightly-wound coil.
The next part of the experiment measures the magnetic field due to a single multiloop current-carrying coil. The field due to this coil will have properties similar to that of a permanent magnet or multiloop coil.

For a single coil of radius \( R \) with \( N \) turns carrying current \( I \), the magnetic field due to the coil at a distance \( x \) along the axis passing through the center of the coil and perpendicular to its plane can be calculated using the Biot-Savart Law (see the 8.02 Course Notes, Example 9.2 for a derivation). The result (plotted in Figure 2) is

\[
\mathbf{B} = \frac{N \mu_0 I R^2}{2} \frac{1}{(x^2 + R^2)^{3/2}} \mathbf{\hat{x}}.
\]  

\( \text{(6.2)} \)

**Figure 2** Magnetic field of a single coil of wire along its axis.

**PREDICTIONS**

For this experiment, you are asked to make several predictions regarding the direction of the force on a current-carrying wire and the direction of the magnetic field near a current-carrying loop. Then, you will be asked to confirm your predictions.

*(Please reproduce your predictions, either words or figures, on the tear-sheet at the end of these instructions.)*

**A. Magnetic Force on a Straight Wire**

**Prediction 1 (answer on your tear-sheet at the end):** Suppose the rare-earth magnet in your experimental setup has its North magnetic pole on top. If a wire is located above the magnet as shown in the figure, with the current in the wire moving from left to right, predict the direction of the force on the wire, and draw it on Figure 3 and on the tear-sheet.
Prediction 2 (answer on your tear-sheet at the end): Suppose you now place the wire in front of the magnet in its midplane, as shown in the figure below, with the current in the wire again running from left to right. Now predict the direction of the force on the wire, and draw it on Figure 4 and on the tear-sheet.

![Figure 4](image)

Figure 4 A wire in front of the magnet.

Prediction 3 (answer on your tear-sheet at the end): Suppose you place the wire behind the magnet in its mid-plane, with the current in the wire again running from left to right. Now what is the direction of the force on the wire? Is it into the page or out of the page?

B. Magnetic Force on a Coil of Wire

Prediction 4 (answer on your tear-sheet at the end): Suppose you now place a circular coil carrying current above the magnet and coaxial with it, see Figure 5(a), with the current in the coil running so that current moves counterclockwise as seen from above. Will the coil of wire be attracted to or repelled by the permanent magnet, or will it feel no force at all; that is, will the force on the coil be upwards, downwards, or zero? (Remember, the North pole of the magnet is assumed to be on the top.)

![Figure 5](image)

Figure 5 A circular coil placed above the magnet with current running (a) counterclockwise, and (b) clockwise, as seen from the top.

Prediction 5 (answer on your tear-sheet at the end): Suppose that the current in the coil runs so that current moves clockwise as seen from the top, see Figure 5(b). Will the coil of wire be attracted or repelled by the permanent magnet, or will it feel no force at all?
C. Fields near a Multiloop Coil

**Prediction 6 (answer on your tear-sheet at the end):**

From our expression in Equation (6.2), we have \( \mathbf{B}_{\text{center}} = (N \mu_0 I / 2R) \hat{x} \) as the the field at the center of the coil, where \( \mu_0 = 4\pi \times 10^{-7} \text{T} \cdot \text{m/A} \). A typical coil in our experiment has 22 turns and an average radius of \( R = 2.5 \text{ cm} \). If we run 0.25 amps through the coil, what is the magnetic field at the center of the coil in tesla? In gauss?

\( 1 \text{ gauss} = 1 \text{ G} = 10^{-4} \text{ tesla} = 10^{-4} \text{T} \)

Figure 2 shows the magnitude of the field along the axis of the coil. What about the shapes of the field lines off-axis? The shapes of the magnetic field lines for a single coil of wire are shown in Figure 6. The field directions shown are appropriate for current in the coil running counterclockwise when viewed from above. Another way to describe this is if you put the thumb of your right hand vertical (in the \( +\hat{x} \) direction in the figure), then your fingers will curl in the direction of the current flow.

![Figure 6](image)

**Figure 6** The magnetic field lines of a single coil of wire.

**Prediction 7 (answer on your tear-sheet at the end):** Suppose you move from left to right along the horizontal path indicated in Figure 6 above. Predict the behavior of the \( x \)-component (i.e. the vertical component) of the magnetic field as you move along that path, and draw it in the panel of Figure 7 and on your tear-sheet at the end.

![Figure 7](image)

**Figure 7** Your prediction of the behavior of the \( x \)-component (the vertical component) of the magnetic field as you move along the path shown in Figure 6.
**Prediction 8 (answer on your tear-sheet at the end):** Suppose you move from left to right along the horizontal path indicated in Figure 6. Predict the behavior of the \( z \)-component (i.e. the horizontal component) of the magnetic field as you move along that path, and draw it in the panel on Figure 8.

![Figure 8](image-url) Your prediction of the behavior of the \( z \)-component (the horizontal component) of the magnetic field as you move along that path shown in Figure 6.

**PROCEDURE**

The source of the external field \( \vec{B}_{\text{ext}} \) will be a strong “Rare-Earth” magnet and the current in the wires will be provided by two 1.5-volt batteries.

**THE RARE EARTH MAGNET IS EXTREMELY STRONG, STRONG ENOUGH TO WIPE YOUR CREDIT CARDS, STOP YOUR WATCH, OR DO SERIOUS DAMAGE TO YOUR COMPUTER, IF IT COMES CLOSE ENOUGH TO ANY OF THESE.**

**DO NOT REMOVE THE MAGNET FROM ITS PROTECTIVE PLASTIC CASE!**

You will use the AC/DC Electronics Board to mount two 1.5-volt batteries, which will provide the current for the wires. You will use a piece of wire about 60 cm (2 ft) in length and a coil of wire with 22 turns (different coils might have a different number of turns). You will compare your above predictions, first by finding the directions of the forces you find acting on the wires (**Predictions 1-5**), and then using the Magnetic Field Sensor to investigate the nature of the magnetic field of the multiloop coil (**Predictions 7 & 8**).

**EXPERIMENT**

**Part 1: Direction of the Forces**

Use the Magnetic Field Sensor to determine which pole, North or South, is the upper pole on your magnet. Attach the magnet probe cable to the 750 Interface as was done in the previous experiment. Download the DataStudio Activity **exp06.ds** and save it on your desktop (the Coil Current graph display will be used later). Decide whether it’s best to use the sensor on **AXIAL** or **RADIAL**. First try the probe on 1X; use 10X only if your data trace is too small to see. If the results of your investigation suggest that the North pole of your magnet is upward, then all of your predictions above should be correct; if the South pole is upward, your predictions should all reverse sign.
Perform the five experiments needed to verify **Predictions 1-5** above, using the only batteries, your length of wire, and coil of wire (no resistors in this first part) to see if reality agrees with your predictions. Use leads to and from the “switch” on the AC/DC board, indicated by the red button. This will allow you to make the connections without having the current run until you’re ready to find the force direction. Since we are directly shorting out the batteries to get a high current, it is important that you do this so our batteries don’t run down rapidly.

In looking for the force on a small piece of wire, bend your long wire into a long U shape so that there is plenty of length of wire to allow movement of the wire due to the magnetic force. You should be able to hold the leads (the alligator clips) to the wires on the board with the magnet, in such a way that a portion of the wire is near but not touching the plastic casing. This way, you’ll be able to see the wire deflect and so determine the direction of the force.

For the multiloop coil, the direction of the force is much easier to determine. In fact, with the proper direction of the current and position of the wire, you might even be able to get the coil to almost levitate (stable levitation is known to be impossible when only magnetic forces and gravity are acting).

**Question 1 (answer on your tear-sheet at the end):** If any of your Predictions 1-5 were incorrect, briefly explain why.

**Part 2: Coil Field Configuration**

Put the permanent magnet aside without annoying your neighbors. Put the 10-ohm resistor in series with the batteries and the switch. Put the Current Sensor in series with your circuit, and attach the Current Sensor cable to Analog Channel A on your 750 Interface if this is not already done.

Use the RADIAL setting of your Hall (Magnetic) Probe Sensor to measure the vertical component of magnetic field as you sweep across the path above the single coil (passing through the axis of the coil) shown in Figure 7. Which way should the white dot on your sensor be facing for an upward magnetic field to show up as positive in your measurement?

**Question 2 (answer on your tear-sheet at the end):** Does this graph look like the your predicted curve in Figure 7?

Use the RADIAL setting of your Hall (Magnetic) Probe Sensor to measure the horizontal component of magnetic field as you sweep across the path above the single top coil (passing through the axis of the coil). Again, which way should the white dot be facing?

**Question 3 (answer on the tear-sheet at the end):** Does this graph look like your predicted curve in Figure 8?
Experiment Summary 6: Magnetic Force on Current-Carrying Wires

Group and Section __________________________ (e.g. 10A, L02: Please Fill Out)

Names ____________________________

________________________________________________________________________

A. Magnetic Force on a Straight Wire

Prediction 1: With the current in the wire moving from left to right, predict the direction of the force on the wire, and draw it on Figure 3 __________________________

Figure 3 A wire placed above a magnet

Prediction 2: Now place the wire in front of the magnet in its midplane, with the current in the wire again running from left to right. Now predict the direction of the force on the wire, and draw it on Figure 4 __________________________

Figure 4 A wire placed in front of a magnet

Prediction 3: Suppose you place the wire behind the magnet in its mid-plane, with the current in the wire again running from left to right. Now what is the direction of the force on the wire, that is, is it into or out of the page? __________________________

B. Magnetic Force on a Coil of Wire

Prediction 4: You now place a coil above the magnet, with the current in the coil running counterclockwise as seen from above. Will the coil be attracted to or repelled by the permanent magnet, or will it feel no force at all? __________________________
Prediction 5: The current in the ring now runs *clockwise* as seen from the top. Will the coil of wire be attracted or repelled by the permanent magnet, or will it feel no force?

Question 1: Now do the actual measurements. If any of your predictions were incorrect, briefly explain why.

Prediction 6: What is the magnetic field at the center of the coil in tesla? In gauss?

Prediction 7: Predict the behavior of the *x-component* (i.e. the vertical component) of the magnetic field as you move along that path.

![Graph of Bx vs Z](image)

Prediction 8: Predict the behavior of the *z-component* (i.e. the horizontal component) of the magnetic field as you move along that path.

![Graph of Bz vs Z](image)

Questions 2 & 3: Do these graphs look like the your predicted curves above and in Figure 8?