Magnetic Induction of a Current Carrying Long Straight Wire

OBJECTIVES

- ❑ Use a compass to determine the direction of the **B** field surrounding a current carrying long straight wire to confirm that it is consistent with the right-hand rule.
- ❑ Determine the induced voltage in a small inductor coil placed near the long straight wire as a relative measurement of the **B** field.
- ❑ Demonstrate that the magnitude of the **B** field surrounding a long straight wire decreases as $1/r$ where r is the perpendicular distance from the wire.

EQUIPMENT LIST

- Direct current power supply (low voltage, 2 A), direct current ammeter (2A)
- Sine wave generator (variable frequency up to 100 kHz, 5 V peak to peak)
- Alternating current digital voltmeter (frequencies up to 100 kHz)
- 100-mH inductor coil (length $\approx$ 1 cm and inside diameter $\approx$ 1 cm)
- Small compass, long straight wire apparatus (Consists of a frame on which a continuous strand of wire is wrapped for 10 loops. The 10 strands are taped together over a length of approximately 40 cm to approximate a wire with a current having 10 times the current as in a single strand of the wire. The apparatus can be placed with the long straight section parallel to the laboratory table or perpendicular to the table.)

THEORY

When a current I exists in an infinitely long straight wire, the lines of **magnetic induction B** are concentric circles surrounding the wire. At a perpendicular distance r from the wire, the **B** field is tangent to the circle as shown in Figure 35-1. The direction of the current I is perpendicular to the plane of the page and directed out of the page. The direction of the current is by definition the direction that positive charge would flow. The magnitude of the **B** field as a function of I and r is given by

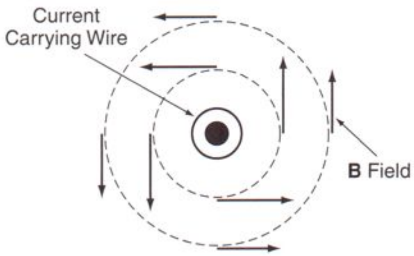

Figure 35-1 *B* field near a wire carrying current out of the page.

$$B = \frac{\mu_o I}{2\pi r} \qquad \text{(Eq. 1)}$$

where $\mu_o = 4\pi \times 10^{-7}$ weber/amp-m, I is in amperes, and r is in meters. The units of **B** are weber/m^2, which has been given the name Tesla.

The direction of the **B** field relative to the current direction is given by the following right-hand rule. If the thumb of the right hand points in the direction of the current, the four fingers of the right hand curl in the direction of the **B** field. This rule assumes that the **B** field forms circles, and the rule determines only in which direction to take the tangent to the circles as shown in Figure 35-1. In Figure 35-1 the lengths of the **B** vectors are shorter for the larger circles, which shows that the **B** field decreases with distance from the wire as predicted by Equation 1.

In a strict sense, the above statements apply only to an infinitely long straight wire. In this laboratory, the straight portion of the wire is of some finite length L. For measurements made at the center of the wire length within a perpendicular distance of $L/4$ from the wire, the finite wire will approximate an infinite wire. If the current in the long straight wire is constant in time, the **B** field created by that current will be constant in time. The direction of the **B** field will be determined by observing the effect of the **B** field on a small compass placed in the vicinity of the long straight wire.

If the current in the long straight wire is an alternating current produced by a sine wave generator, the **B** field surrounding the wire will also vary with time. If a small coil of self-inductance 100 mH is placed next to the wire, an alternating voltage will be induced in the coil, according to Faraday's law of induction. The **induced voltage** in the coil is proportional to the rate of change of the magnetic flux through the coil, and hence to the magnitude of the time-varying **B** field. The quantity actually measured is an alternating electric voltage, but its magnitude is proportional to the **B** field and will be taken to be a *relative* measurement of the **B** field at different distances from the wire.

EXPERIMENTAL PROCEDURE

Direction of the B Field

1. Connect the circuit shown in Figure 35-2 using the direct current power supply and the direct current ammeter. Arrange the long wire apparatus so that the outside long wire is in a horizontal plane along a north-south axis. Ask your instructor the direction of north in the laboratory room. Arrange the wire so that the direction of the current is from north to south. Determine the direction of the current by tracing the wires from the (+) terminal of the power supply. Have the circuit approved by your instructor to ensure that the current is in the proper direction.
2. Turn on the power supply and turn up the voltage until a current of 2.00 A is read on the ammeter. Do not exceed a current of 2.00 A.
3. Place the compass in the middle of the long wire section directly above the wire as close to the wire as possible. State the direction (north, south, east, northeast, etc.) that the compass needle points. Record your answer in Data Table 1.

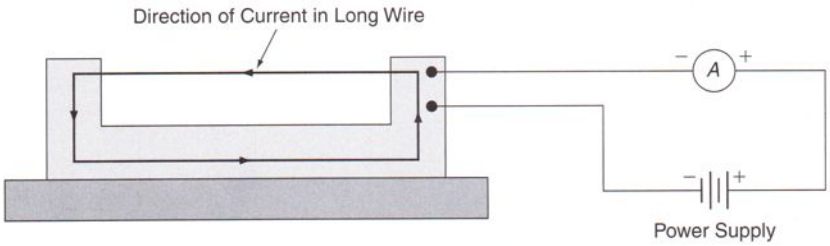

Figure 35-2 Long wire apparatus connected to direct current supply.

4. Repeat Step 3 with the compass immediately below the long wire section.
5. Stand the long wire apparatus on its end so that the current in the outside long wire is vertically downward. Place the compass next to the wire at the four positions indicated by the open circles in Figure 35-6 in the Laboratory Report section. The ⊗ represents the downward current viewed from above. In the open circles that represent the four compass positions, draw an arrow showing the direction that the compass needle points.

B Field as a Function of Distance

1. Connect the circuit shown in Figure 35-3 using the long wire apparatus and the sine wave generator. Turn the generator to maximum amplitude. Stand the long wire apparatus on its end so that the outside long wire is vertical. Place in the apparatus the platform that serves to hold the inductor coil.
2. Connect the inductor coil to the digital voltmeter. Twist the leads about 10 to 15 times before connecting them between the inductor coil and the voltmeter. This is extremely important because it will minimize the voltage that is induced in the leads themselves, and will ensure that the voltage induced is in the inductor coil. Place the inductor coil on the platform as shown in Figure 35-4. The axis of the inductor coil should be perpendicular to an imaginary line that is perpendicular to the

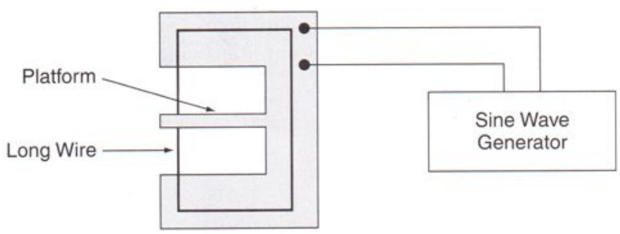

Figure 35-3 Long wire apparatus connected to the sine wave generator.

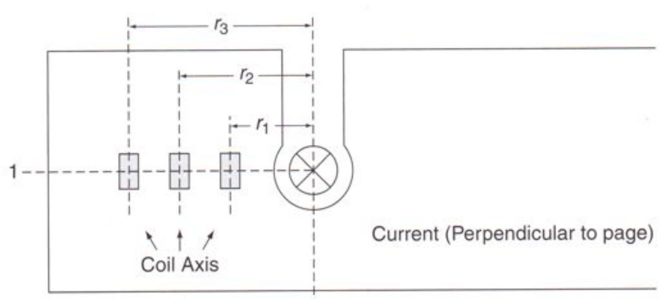

Figure 35-4 View looking down from above. Current alternates in and out of the page.

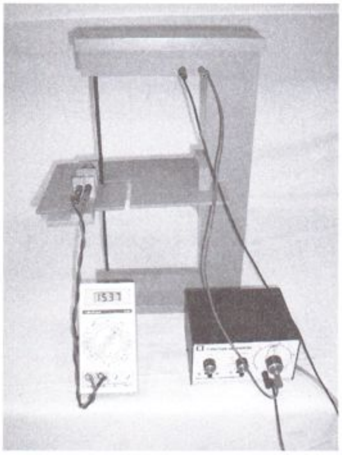

Figure 35-5 Homemade long wire apparatus with inductor coil in position.

current-carrying wire (shown as the dotted line labeled 1 in the figure). The inductor coil is shown at three different distances r_1, r_2, and r_3 from the wire. At each position of the inductor coil shown, the **B** field will alternate in opposite directions along the axis of the coil. The coil is chosen to be short ($\approx$ 1 cm) and of small cross-section (diameter $\approx$ 1 cm) because for that choice, the **B** field direction is approximately along the coil axis and is approximately uniform over the cross-section of the coil.

3. The amplitude of the induced voltage on the digital voltmeter will depend upon the frequency of the generator. With the inductor about 3 cm from the wire, with its axis positioned as shown in Figure 35-5, vary the generator frequency until the maximum voltage is read on the digital voltmeter. Make all measurements at this frequency.
4. Measure the voltage induced in the inductor coil as a function of r, the distance from the center of the coil to the center of the wire. Take data from $r = 3.0$ cm to $r = 9.0$ cm in increments of 1 cm. Data are not taken for r less than 3 cm because at distances close to the wire, the **B** field is extremely non-uniform over the coil cross-section. Record the values of the voltage as trial one in Data and Calculations Table 2 under the column labeled B_1. If this was actually the **B** field, the units would be Tesla. The measured quantity is a voltage that is proportional to **B**, so no units are stated.
5. Repeat Step 4 two more times measuring the induced voltage at each r. Record the values of trials two and three in Data and Calculations Table 2 under B_2 and B_3.

CALCULATIONS

1. Calculate the mean and standard error for the three trials of B and record them as $\overline{B}$ and α_B in Data and Calculations Table 2.
2. Calculate the percent standard error at each point by calculating $\alpha_B/\overline{B}$ and expressing it as a percentage. Record the values in Data and Calculations Table 2.
3. Calculate the value of $1/r$ for each of the values of r and record them in Data and Calculations Table 2.
4. Perform a linear least squares fit to the data of $\overline{B}$ versus $1/r$ with $\overline{B}$ as the vertical axis and $1/r$ as the horizontal axis. Record the value of the slope, the intercept, and the correlation coefficient.

GRAPHS

1. Make a graph of the data with $\overline{B}$ as the vertical axis and $1/r$ as the horizontal axis. Also show on the graph the straight line obtained from the least squares fit.

Name Section Date

35 LABORATORY 35 *Magnetic Induction of a Current Carrying Long Straight Wire*

PRE-LABORATORY ASSIGNMENT

1. State the right-hand rule that relates the direction of the **B** field near a long straight wire to the direction of the current in the wire.

2. The direction of current is defined to be the direction in which ____________ charges would flow.

3. State the equation that relates the magnitude of the **B** field near a long straight wire to the current I in the wire and the distance r from the wire.

   $B =$ ____________

4. There is a current of 10.0 A in a long straight wire. What is the magnitude of the **B** field 5.00 cm from the wire? Show your work.

5. When a current that is constant in time passes through a wire, the **B** field that is produced around the wire is (a) time varying (b) constant in time (c) negative (d) zero.

6. Why are measurements using the inductor coil not taken close to the wire? In other words, why do the measurements start 3.00 cm away from the wire?

7. If an inductor coil is placed near a long wire carrying a current that is constant in time, the voltage induced in the coil is (a) positive (b) negative (c) zero (d) nonzero.