

Lab 9: Faraday's and Ampere's Laws

Introduction

In this experiment we will explore the magnetic field produced by a current in a cylindrical coil of wire, that is, a solenoid. In the previous experiment you studied the direction of the field by placing a small compass needle at various points in and around the coil and noting the direction in which the needle pointed. You can measure the magnitude of a static magnetic field (produced by a steady DC current) by a number of methods. The most common is to measure the Hall effect voltage generated across a current-carrying conductor in a magnetic field.

You can measure the field produced by a sinusoidally varying current by taking advantage of Faraday's law of induction. As you saw, an *EMF* can be induced in a conductor placed in a changing magnetic field. The amplitude of the *EMF* depends on the rate of change of the magnetic flux intercepted by the conductor.

Experimentally, we will measure the *EMF* induced across a small coil, called a search coil. The magnetic field will be generated by a fixed frequency AC current. Thus the amplitude of the *EMF* across the coil will be proportional to the amplitude of the time-rate-of-change of the magnetic flux. If you measure the *EMF* induced across the search coil you can tell the relative strength of the component of the magnetic field parallel to the axis of the coil. In this experiment, the current through the solenoid will be produced by a function generator. The voltage induced in the search coil will be measured with an oscilloscope.

Experiment

1. Preliminary Observations

Connect the solenoid to the function generator as shown below. Place graph paper on the platform surrounding the solenoid.

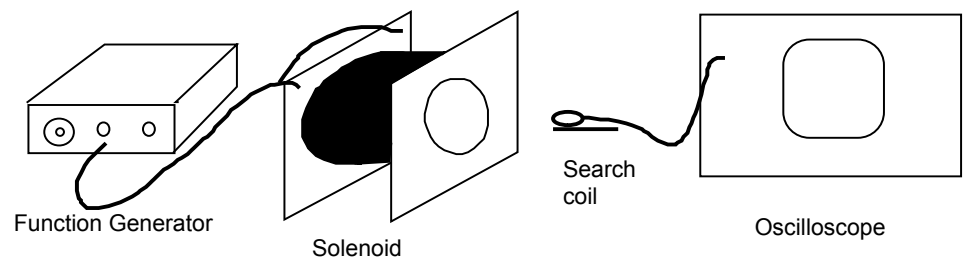


Figure 1. Apparatus for field measurements

Procedure

- Turn the function generator to maximum output voltage with zero attenuation at 1000-Hz frequency, sine wave shape.
- Turn on the oscilloscope. Connect the search coil to the vertical input cable and set the trigger on AUTO INTERNAL.
- Hold the search coil inside the solenoid and observe the sine wave. Find the location that gives the largest *EMF*. This should be the center of the solenoid.
- Move the search coil to one end of the solenoid. Watching the voltage, rotate it so its axis is first parallel and then perpendicular to the solenoid.
- Find the direction of the axis of the search coil that produces the largest voltage.

2. Calibration of the Search Coil

Introduction

The method of measuring the field with a search coil will give only relative field strengths. We must first calibrate the system to convert the *EMF* measured by the oscilloscope into magnetic field strength. To do the calibration a known field will be measured with the search coil. The known field will be provided by the field at the center of a current carrying wire loop. If the loop has N turns of wire, radius a , and current i flowing through it, then B is given by

$$B = (N \mu_0 i) / (2a) \tag{1}$$

where $\mu_0 = 4\pi \times 10^{-7} \text{ T m/A}$.

Procedure

- Connect the twenty-turn loop in place of the solenoid. Put the AC ammeter in series with the loop to measure the current through it. The uncertainty in a digital meter is ± 1 digit.
- Place the search coil at the center of the loop where the *EMF* is largest and record the voltage from the oscilloscope screen. Be sure to estimate the uncertainty in your result.
- Measure the diameter of the loop ($2a$) and use equation (1) to calculate B at the center of the loop. Express the magnetic field in teslas (T).
- The ratio of the calculated B -field to the voltage read on the oscilloscope gives a calibration constant, c , that can be used to convert all your *EMF* measurements into values of the field in T.
- Calculate this ratio (calibration constant) and record on the data sheet.

3. Variation of Field Strength Along the Axis of a Solenoid

Procedure

- Remove the 20 turn loop and ammeter and reconnect the solenoid to the function generator.
- Place the search coil at the center of the solenoid (where the EMF is largest). Holding the search coil parallel to the solenoid axis, record the EMF out to 20 cm from the center. Take the data every 0.5 cm from 0 cm to 10 cm; at 1 cm intervals thereafter.
- Convert from EMF to B -field using the calibration constant, c .
- Plot a graph a magnetic field as a function of distance from the center.
- Find the point on your graph where the curve changes from convex to concave (point of inflection). Mark it on your graph.
- Figure 2 is a graph of the calculated field of the solenoid. The field is in arbitrary units. The shape of your graph should look like this.

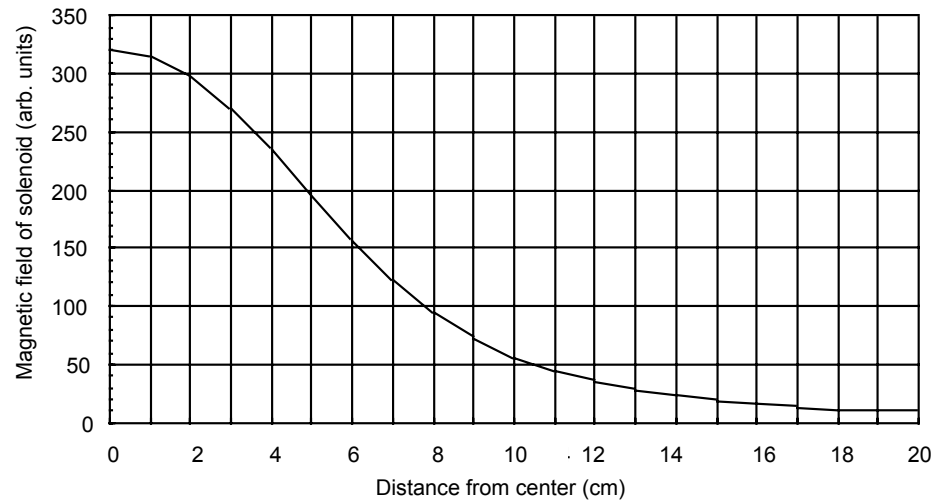


Figure 2. Calculated variation of field with distance from center

4. Verification of Ampere's Law

Introduction

Ampere found a relationship between the magnetic field around a closed loop and the current enclosed by that loop. The relationship is known as Ampere's law

$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 i. \quad (2)$$

- $\oint \mathbf{B} \cdot d\mathbf{s}$ is the line integral of the \mathbf{B} -field around a closed loop.
- i is the current enclosed by that loop.
- μ_0 is the permeability of free space.

But, what is the left-hand side of equation (2)? We can approximate

$\oint \mathbf{B} \cdot d\mathbf{s}$ by measuring the magnetic field at various locations around a closed loop. We will approximate $\mathbf{B} \cdot d\mathbf{s}$ as $B_{\parallel} \Delta s$, where B_{\parallel} is the average parallel component of the magnetic field, and Δs is the length of the segment over which the average is taken. We will then sum all the products. That is,

$$\oint \mathbf{B} \cdot d\mathbf{s} \cong \sum B_{\parallel} \Delta s.$$

In the experiment we will choose our own closed loop and measure the parallel components of the magnetic field around that loop. Since the length of all segments is the same,

$$\sum (B_{\parallel} \Delta s) = (\sum B_{\parallel}) \Delta s.$$

The magnetic field will be determined by measuring the *EMF* induced in the search coil. The calibration constant will then be used to convert this voltage to the magnitude of the magnetic field. In this way we will experimentally determine the left hand side of equation (2).

We then use Ampere's law to predict the enclosed current,

$$i_{\text{predicted}} = \frac{(\sum B_{\parallel}) \Delta s}{\mu_0} \quad (3)$$

To check Ampere's law, we measure the current with an ammeter. The magnetic field is produced by a solenoid, and the measured current enclosed by the loop is equal to the current through the ammeter multiplied by the number of turns in the solenoid, $N = 3400$. That is,

$$i_{\text{measured}} = i_{\text{ammeter}} N \quad (4)$$

Our verification of Ampere's law then consists of comparing the predicted and measured currents defined in equations (3) and (4).

Procedure

- We first must define the closed loop. To do this trace a rectangle on the graph paper. One side of the rectangle must pass through the inside of the solenoid. Make the length of each side of the rectangle some multiple of 2 centimeters (i.e. one side may be 14 cm or 10 cm or 18 cm, etc.).
- Draw lines that divide each side of the rectangle into two centimeter segments.
- Place the search coil in the middle of one segment, making sure the coil axis is parallel to the line segment.
- Record the value of the EMF you found in the table.
- Repeat the measurement at each line segment
- Convert the voltage to the magnetic field by multiplying by the calibration constant, c .
- Calculate the sum of the magnetic field components over the entire rectangle.
- Multiply the sum by the length of a single segment, 0.02 m. The units of the result should be tesla· meters.
- Use equation (3) to find the predicted current enclosed by the rectangle, i_p .
- Measure the current by placing an ammeter in series with the function generator and the solenoid.
- Record the measured value of the current given by equation (4), i_m .
- Record the percent error between the measured and predicted values.

Name _____

Partner _____

Section _____

Faraday's and Ampere's Laws

2. Calibration

Current through 20-turn loop $i =$ (_____) A

Coil diameter $2a =$ (_____) m

Voltage measured with oscilloscope at center of loop (_____) V

Calculated magnetic field $B = \mu_0 N i / 2a =$ (_____) T

Calibration constant $c =$ (_____) T/V

3. Variation of Field Strength with Distance

Note: in the table below calculate each value of the magnetic field, B by multiplying the measured EMF by the calibration constant, c . You can also have the computer do this calculation instead.

Distance (cm)	EMF (V)	B (T)	Distance (cm)	EMF (V)	B (T)
0.0			8.0		
0.5			8.5		
1.0			9.0		
1.5			9.5		
2.0			10.0		
2.5			11.0		
3.0			12.0		
3.5			13.0		
4.0			14.0		
4.5			15.0		
5.0			16.0		
5.5			17.0		
6.0			18.0		
6.5			19.0		
7.0			20.0		
7.5					

Questions

1. In part 1 you found the orientation of the search coil that produced the largest voltage. Describe this orientation of the axis of the search coil with respect to the axis of the solenoid.
2. What is the ratio of the magnetic field at the end of the solenoid to its value at the center? Compare with the ratio predicted by Figure 2.
3. Where is the inflection point in your graph? Compare with its location on Figure 2.
4. A solenoid is often used to make a constant magnetic field. Over what length is the field inside your solenoid constant to within 10%?
5. Pat, Leslie, and Robin were arguing over the effect of Earth's magnetic field on the measurement of the field of the solenoid. **Pat** said that, because Earth's field is so small, its effect would be so small that it could be neglected. **Leslie** said that, because Earth's field is mostly vertical, its effect could be neglected. **Robin** said that, because Earth's field is constant, it couldn't produce an *EMF* in the coil.

Which, if any, student is correct? Write a short explanation to the students who are wrong why they are wrong, describing how experiments you have done in the laboratory support your reasoning.

4. Verification of Ampere's Law

Note: in the table below calculate each value of the magnetic field, $B_{||}$ by multiplying the measured EMF by the calibration constant, c , found in part 2.

Line segment	Rectangle side							
	I		II		III		IV	
	EMF (V)		EMF (V)		EMF (V)		EMF (V)	
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								

$$\sum B_{||} = c \sum EMF (V) = \text{_____ T}$$

$$\sum B_{||} \Delta s = \text{_____ T}\cdot\text{m}$$

$$\text{Predicted current } i_{\text{predicted}} = \sum B_{||} \Delta s / \mu_0 = \text{_____ A}$$

$$\text{Measured current } i_{\text{measured}} = i_{\text{ammeter}} N = \text{_____ A}$$

$$\text{Percent difference between predicted and measured current} = \text{_____ \%}$$