Ampere's Law & the Magnetic Properties of Materials

PHYS 296

Your name___________________ **Lab section**_________________

PRE-LAB QUIZZES

1. What will we investigate in this lab?

2. Write down the formula for the magnetic field inside a current-carrying solenoid. Specify each symbol.

3. Define the relative permeability constant and classify three basic types of magnetic materials based on the magnitude of the relative permeability constant.

4. Describe the hysteresis for the magnetization curve and the difference between the soft and hard magnetic materials.

Ampere's Law & the Magnetic Properties of Materials

PHYS 296

Name____________________________ **Lab section**______________________

Lab partner's name(s)____

Objective

Investigate Ampere's law and the magnetic properties of materials.

Background

In 1820, Oersted observed that needles in magnetic compasses changed direction when brought near current-carrying wires. Consequently, he discovered that electric current generates magnetic field. For a straight current-carrying wire, as Oersted determined, the produced magnetic field on a circle perpendicular to and centered at the wire has uniform strength at every point on the circle and the direction of the magnetic field is tangential to the circle. Oersted's observation is described in a more generalized form as Ampere's Law

$$\int \vec{B} \bullet d\vec{l} = \mu_o I, \qquad (1)$$

which states that the line integral of the magnetic field $\vec{B}$ (in *Tesla*) over a closed loop equals the net current I passing through the loop multiplied by the permeability in vacuum, $\mu_0 = 4\pi\times10^{-7}$ *Tesla meters per ampere* ($T{\cdot}m/A$). For a straight wire of infinite length carrying current I, Ampere's law yields the strength of the magnetic field at a distance R from the wire as

$$B_0 = \frac{\mu_o I}{2\pi R}. \qquad (2)$$

In this lab, we investigate another important example, namely, the magnetic field inside a current-carrying solenoid. By Ampere's law, for a solenoid densely wound with wire carring current I, the magnetic field inside the solenoid is given by

$$B_o = \mu_o n I. \qquad (3)$$

where n is the number of turns of wire per unit length of the solenoid. Following Equation (3), the magnetic field inside a solenoid is proportional to the current it carries. The field is uniform inside the solenoid (note: the uniformity is only approximately correct).

Note: the subscript of B_0 implies that Equations (2) and (3) apply only when the straight wire and the solenoid are placed in vacuum. The cases with other media are discussed in Part II.

PART I Ampere's Law

In part I, we measure the direction and the magnitude of the magnetic field induced in a current-carrying solenoid.

PROCEDURES

1. Following Figure 2, connect the solenoid to the *Output* of the ***750 Interface*** and *Input Channel B* of the ***750 Interface*** through *the provided current sensor*. First, you need to calibrate the current sensor.
2. Select *triangular wave* for *Output* with the frequency set to *0.5 Hz* and the amplitude to *5.0 V*. Set the sample rate to *100 Hz* or higher.
3. Insert *the provided magnetic sensor* into the solenoid such that the end of the sensor is approximately at the center of the solenoid. Select the field-direction arrow on the magnetic field sensor that is parallel with the solenoid.
4. Connect the magnetic field sensor to *Input Channel A* of the ***750 Interface***. Use the zero button on the magnetic sensor to zero the sensor reading when no current is passing through the solenoid.
5. Open graph display and set the *y-axis* to display magnetic field in *gauss* and set the *x-axis* to display current.
6. Press the start button and collect the data for at least one cycle of the triangular wave.

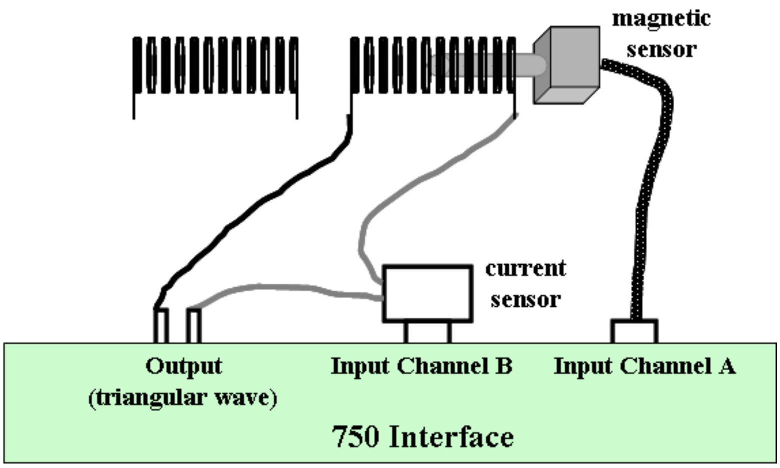

Figure 1 The setup for measuring the magnetic field inside a solenoid.

QUESTIONS

1. What kind of curve do you anticipate for *B-versus-I*? Explain why the measured *B-versus-I* curve agrees or disagrees with your prediction.

2. Fit the *B-versus-I* curve as a straight line and record the fitting equation. Write down the slope with the appropriate unit. Note: the conversion between the units is *1 Tesla = 10^4 Gauss*. Since the magnetic field in this lab is measured in *Gauss*, we should rewrite Equation (3) to describe the magnetic field inside the solenoid as $B(Gauss) = 10^4 \mu_0 n I = 10^4 \times (4\pi \times 10^{-7} T \cdot m / A) n I = (4\pi \times 10^{-3} Gauss \cdot m / A) n I$. Accordingly, the slope should be $(4\pi \times 10^{-3}) n$.

3. Use the obtained slope to calculate n. The given value of n by the manufactory is *26,564 turns/meter*. Calculate the % error of your measurement.

PART II The Magnetic Properties of Materials

In atoms the electrons constantly rotate around the nuclei. The rotating electrons resemble ring currents and produce magnetic field. Electrons also possess another important intrinsic property, which is called spin and also produces magnetic field. For “non-magnetic” materials, if there is no external magnetic field the sum of “the electronic ring currents” and the electron spins vanish in all directions. Thus, “non-magnetic” materials do not produce macroscopic magnetic field when no external magnetic field is applied to them. When an external magnetic field is applied on the “non-magnetic” material, to a small degree “the electronic ring currents” and the electron spins tend to align with or against the external magnetic field. As a result, the “non-magnetic” materials produce a magnetic field parallel or anti-parallel to the external field, namely, the effective magnetic field inside the materials is respectively increased or decreased. In the former case, the materials are called paramagnetic and, in the latter case, diamagnetic. By contrast, for some materials the electron spins (and sometimes “the electronic ring currents”) can automatically align in a certain direction even when the external magnetic field is zero. It can thus spontaneously produce a magnetic field. These materials are called ferromagnetic.

To determine the magnetic property, a specimen of the material can be placed in an external magnetic field of B_0, for instance inside a current-carrying solenoid. The magnetic field, B, within the specimen is measured and is compared with B_0,

$$B = \kappa_m B_0. \qquad (4)$$

The *relative permeability* of the material, κ_m, is a dimensionless factor and is an important parameter to describe its magnetic property.

For diamagnetic materials, $\kappa_m < 1$ and usually $1-\kappa_m < 0.001$.

For paramagnetic materials, $\kappa_m > 1$ and usually $\kappa_m - 1 < 0.01$.

Thus, diamagnetic materials slightly reduce the magnetic field inside the materials, whereas paramagnetic materials slightly increase the magnetic field. For diamagnetic and paramagnetic materials, κ_m can be taken as a constant, not dependent on B_0. Thus, the *B-versus-B_0* curve should be a straight line. Particularly, the curve should pass through the origin ($B = 0$, $B_0 = 0$).

By contrast, for ferromagnetic materials κ_m depends not only on B_0 but also on the history of how B_0 is changed. Thus, the *B-versus-B_0* curve for the ferromagnetic material is not a straight line and depends on how the applied external magnetic field varies. As illustrated in Figure 2, initially the ferromagnetic material is not magnetized and the external magnetic field is zero. When the external field B_0 increases from 0 to $B_{0,up}$, the net magnetic field inside the material varies accordingly as depicted by curve ***ab***. Then, when B_0 decreases from B_0 to 0, the net magnetic field follows curve ***bc***. Note: curve ***bc*** does not retrace curve ***ac*** and does not pass through the origin. When B_0 is reversed to the opposite direction and changes from 0 to $-B_{0,up}$ and subsequently changes from $-B_{0,up}$ to 0, the total magnetic field follows curve ***cd*** and curve ***de***, respectively. When B_0 changes again from 0 to $B_{0,up}$, the magnetization curve follows curve ***eb***, which is often different from curve ***ab***. The lack of retraceability shown in Figure 2 is the signature of *hysteresis*. The curve ***bcdeb*** is called a hysteresis loop. (The textbook offers one explanation for hysteresis using magnetic domains). Note that at point ***c*** and point ***e*** the magnetic material is magnetized even though B_0 is 0. This is the familiar phenomenon exhibited by permanent magnets.

For ferromagnetic materials: κ_m varies from $+\infty$ to $-\infty$.

Particularly, $|\kappa_m| = \infty$ at points ***c*** and ***e*** and $|\kappa_m| = 0$ at points ***c′*** and ***e′***.

Usually, $|\kappa_m|$ is much larger than 1 at point ***b*** and points ***d***, especially when $B_{0,up}$ is not too large or too small.

The area of the hysteresis loop, ***bcdeb***, is proportional to the energy needed for the magnetic material undergoing a complete magnetization-demagnetization cycle. The area of the loop is much larger for hard ferromagnetic materials than for soft magnetic materials, rendering the latter as the better materials to use as a transformer core. On the other hand, the magnetization at point ***c*** and point ***e***, known as the remnant magnetization, is larger for hard materials rendering them as the better choice to make permanent magnet.

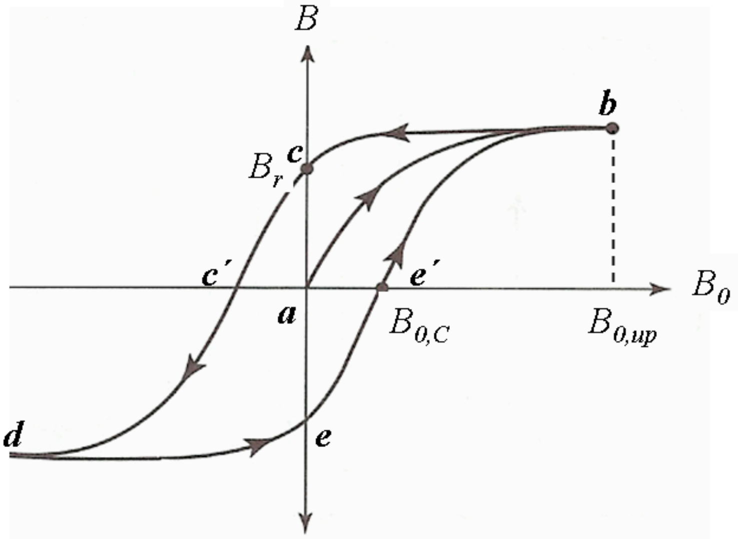

Figure 2 The hysteresis loop of ferromagnetic materials.

(A) "Non-magnetic" Materials

In Part II (A), we study the magnetic properties of stainless steel rods.

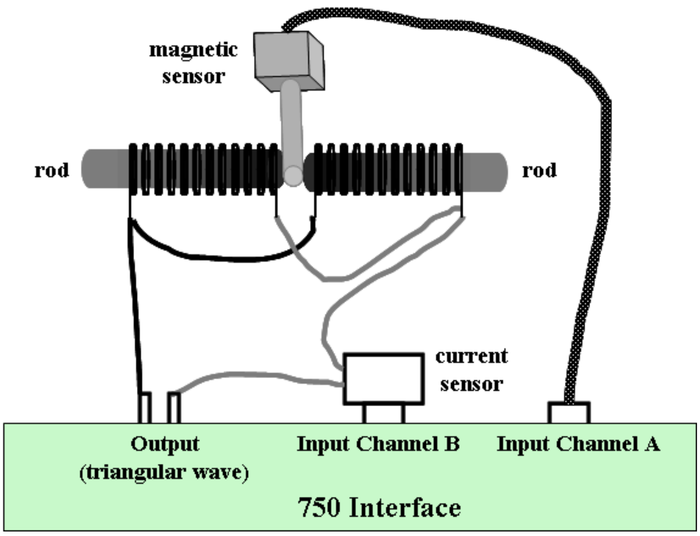

Figure 3 The setup for measuring the relative permeability.

PROCEDURES

1. Set up the system as shown in Figure 3. Note that the magnetic sensor should now be placed between the two solenoids. Select the field-direction arrow which points parallel to the solenoids (Note: is this the direction of the magnetic field between the solenoids?)

2. Rotate the double-solenoid set on the table until the B_0-*versus-I* curve gives the smallest intercept. This should be the direction with the least interference from Earth's magnetic field. Keep the double-solenoid set aligning along this direction for the following experiments.
3. Obtain the magnetization curve of the solenoid (with only air inside the solenoids). Measure B versus I.

Record: slope = intercept =

Note: in air $\kappa_m = 1.00034$ which can be approximately taken as 1. Therefore, the measured *B-versus-I* curve in air can be used as the B_0-*versus-I* curve in vacuum. To use this relationship later, convert the current to B_0 by double clicking the "Calculate" button on the tool bar of ***Data Studio***. The *Calculator* window pops up. Type in "*B0(Gauss) = slope*I + intercept*". Use the fitted values for *slope* and *intercept*. Click "Accept". Define I as the current. Click "Accept" and close the *Calculator* window. Now, you can use *B0(Gauss)* as B_0 for the following experiment. Note: now you should not rotate the solenoid set.

4. Insert the stainless steel rods into the solenoids, making sure that they touch the sensor. Measure B versus I.

Record: slope =

5. With the stainless steel rods inside the solenoids, measure *the B-versus-B0(Gauss)* curve for stainless steel.

Record: slope =

QUESTIONS

1. Show that $\kappa_{m,steel}$ = the slope for the stainless steel divided by the slope for air. Hint: use $B = \kappa_m B_0$.

2. Use the slopes of the *B-versus-I* curve curves measured in Steps 3 and 4 to obtain $\kappa_{m,steel}$, and compare with the measured $\kappa_{m,steel}$ in step 5. Calculate the percent of difference.

(B) Ferromagnetic Materials

In Part II (B), we study the hysteresis loops for two ferromagnetic materials using the two provided pairs of rods (labeled as "soft iron" and "1045").

PROCEDURES

Follow the same procedure described in Part II (A), measure the *B-versus-* B_0*(Gauss)* curves for the two sets of ferromagnetic rods. *Because you will not get straight lines, do not try to linear-fit the measured magnetization curves as done in Part II (A)*.

QUESTIONS

1. Calculate the κ_m values at the applied maximum current for both materials. Show derivation.

For the "soft iron" rods:

For the "1045" rods:

2. Which rod is made of hard ferromagnetic material? Which rod wastes more energy to complete one cycle of magnetization?

3. Which material is better to be used as a transformer core? (Note: the primary transformer coil undergoes tens of cycles of current variation per second).