Force on a Current-Carrying Wire

PRE-LAB

Review Purcell section 6.1 on the magnetic field. Skim section 11.11 on ferromagnetism.

Pre-lab Question 1: In Part I of this lab, you will measure the force on a wire in an external magnetic field as a function of the current running through it. Therefore the external field will be held constant. This external field is produced by an electromagnet. Will you choose a high value or a low value for the magnet current I_m, which will produce the external magnetic field? Explain your reasoning.

Pre-lab Question 2: Ferromagnetic substances like iron generally do not have an overall net magnetization. They appear "unmagnetized" until they are in the presence of an external magnetic field. Briefly explain why this is so.

INTRODUCTION

Force on a current.

The Lorentz force law gives the force on a charged particle in a magnetic field. In SI units:

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B} \tag{1}$$

This can be rewritten in terms of current rather than charges since

$$q\vec{v} = \frac{d}{dt}\left(q\vec{l}\right) = \frac{dq}{dt}\vec{l} \tag{2}$$

If the direction of current flow changes, then equation 1 is written in a differential form in terms of a current element I d***l***.

$$d\vec{F} = Id\vec{l} \times \vec{B} \tag{3}$$

Hysteresis.

The magnetic field at a point P inside a coil of wire (Fig. 1) is directly proportional to the current through the coil. A graph of field vs. current would look like the line FOG of Fig. 2. If a ring of magnetic material is introduced as shown dashed in Fig. 1, the magnetic moments of the atoms tend to align with the applied field and so add their magnetic field to that produced directly by the current. For strongly magnetic (ferromagnetic) materials, such as iron, the total field at the point P rises far above OG. The point A in Fig. 2 is close to the limit that all the atomic magnetic moments are aligned parallel to the field of the magnetizing current. It represents the maximum field (saturation) for any current I.

The actual magnetization curve exhibits hysteresis. As I is raised from zero for an initially unmagnetized sample, the total field follows the dashed curve shown in Fig. 2 from O to

A. As the current is then decreased from maximum, the magnetic field follows the curve AC. That is, the iron remains partially magnetized when the current once again reaches zero. Increasing the current with reversed direction (“negative” current) carries the field to a reversed maximum along the curve CD, and so on. Thus the value of field depends not only upon the existing current I but also upon previous values of the current. The iron has a "magnetic memory."

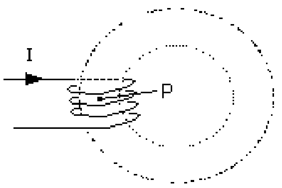

Fig. 1. Magnetic field produced by current I in a coil.

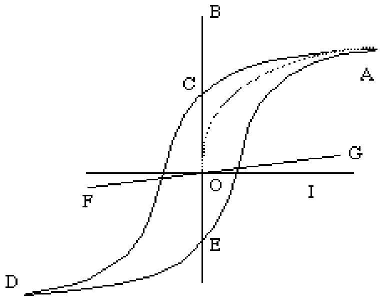

Fig. 2. Hysteresis Loop.

APPARATUS

In Fig. 3 a rectangular loop of heavy wire (seen edge on in the front view, extended in the side view) hangs from one arm of a sensitive balance (not shown) with its lower side in the center of the narrow air gap of an iron core electromagnet. The loop current I_l flows around the loop in the sense indicated (downward in the near side), entering and leaving by leads so flexible that the balance swings freely. The magnet's field is produced by the magnet current I_m flowing in the indicated sense. Two representative lines of **B**-field are shown (dashed). Note that the outer of these lines is linked with the loop and forms part of the flux through it, while the inner line does not contribute to the flux.

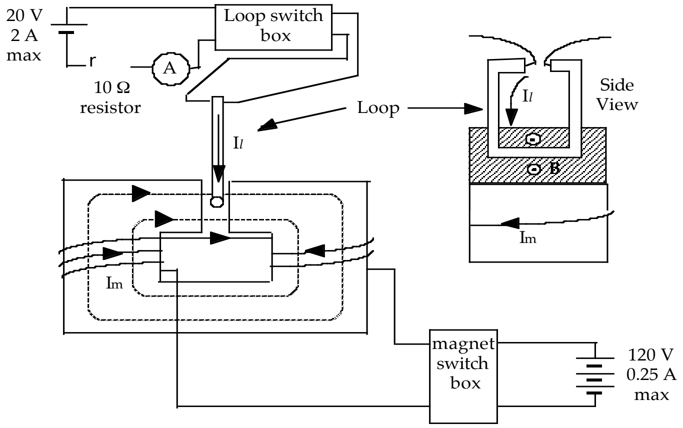

Fig. 3. Circuit diagram.

There are two independent circuits in this apparatus. Make sure that you understand the difference.

(1) The loop has very low resistance and is connected to a low-voltage, high-current power supply. A 10 Ω resistor in series with the loop is used to limit the current (preventing a short circuit). This supply will also be operating in constant current mode.

(2) The magnet has high resistance due to many turns of fine wire and operates from the Hewlett-Packard power supply. You will adjust the current through the circuit by using the current control knob on the supply. The digital read-out on the supply acts as the ammeter. To set the power supply, first turn the current knob all the way up (clockwise) then turn up the voltage coarse adjustment until the maximum voltage is reached. From this point on, the supply should be working in constant current mode (the green light next to "CC" should be lit on the panel).

On the older balances, there is a knob that lowers the balance beam onto the knife-edge bearing. This bearing is quite fragile, so handle the apparatus gently and raise the beam off the knife-edge when not in use. The newer Ohaus balances do not have this feature, so you have to be especially careful. Check the zero adjustment of the balance, and make sure the loop does not rub against the magnet pole faces. Once these adjustments have been made, be careful not to bump into the coiled flexible leads connecting to the loop.

WARNINGS

- Do not touch any of the metal spade lugs or the wire loop unless the power supplies are turned off. The magnet circuit is high-voltage, and the loop circuit is high-current. Both can be dangerous!
- For reasons that will be more clear once we've studied Faraday's Law, don't use the magnet switch box while current is flowing in the magnet.
- Keep computer disks, credit cards, and other magnetic material away from the electromagnet.

EXPERIMENT

Part I. Lorentz force law.

1. You want to verify that the force F is linearly dependent on the loop current I_l. Therefore, the magnetic field B needs to be constant throughout this part of the experiment. This is achieved by holding the magnet current I_m constant. Because the resistance of the magnet wire may change as it heats up, you should monitor the magnet current to make sure it is constant. For this reason, you do not want to set the power supply at its maximum setting, since you may need to make adjustments.
2. Weigh the force on the loop as a function of the loop current I_l. Take enough data points to plot force vs. I_l in Kaleidagraph. Use the "General" curve fit option to fit a straight line to your data. Record the slope and uncertainty data from the Equation Box displayed on the graph.
   What does the slope of this line represent?

3. The length of the bottom of the loop, *l*, is labeled in centimeters on the base of the balance. With the slope of the F vs. I_l curve and *l*, find the magnetic field B of the electromagnet.

   Quote your result as $B = B \pm \sigma_B$.
   What are the units of B (in MKS)?

Part II. Hysteresis.

Now with the loop current I_l held constant close to but not exceeding 2 A, you are going to vary the magnet current I_m to obtain data for a hysteresis loop similar to ACDEA of Fig. 2. Your hysteresis loop will be straighter and narrower than that of the figure because the air gap of your magnet reduces the effect of the iron. Be sure to record the (constant) loop current.

1. Start with the magnet current I_m at the maximum available (point A). This current is (very nearly) sufficient to saturate the iron's magnetization and hence to erase its previous history. Then reduce I_m to zero (point C of Fig. 2) incrementally, being careful always to decrease the current monotonically. This means that if you accidentally pass a desired current value, do not attempt to go back. Record the force at each value of I_m.
2. After recording point C ($I_m = 0$), throw the magnet circuit switch to reverse the connections at the magnet terminals. Current will now flow in the opposite (negative) direction. Decrease the magnet current **very slowly and monotonically**, but make sure you at least find the current necessary to return the field to zero.
3. When the field is zero, switch the direction of the loop current I_l, since the force is going to be in the opposite direction for points to follow. Measure negative forces on the loop through point D and then to point E. (The force at point E is negative and should be approximately equal in magnitude to the force at point C.)
4. At point E the magnet current is zero again, so throw the magnet circuit switch to reverse the connections at the magnet terminals. Decrease the magnet current **very slowly and monotonically**, but make sure you at least find the current necessary to return the field to zero.
5. At this point switch the direction of the loop current I_l and collect data until you are again at point A.
6. Plot the full (four quadrant) hysteresis graph.

LAB BOOK CHECKLIST

You should have:

- plot of force vs. current with a linear fit
- determination of the magnetic field (in tesla).
- plot of the complete hysteresis curve (with B field in tesla as a function of current in amps). Your hysteresis curve should identify points C and E as well as the values of current necessary for zero field.