The Current Balance

Introduction:

The purpose of this lab is to study the force exerted on one current-carrying conductor by another. Classical electromagnetic theory explains this force in terms of the magnetic field $\boldsymbol{B}$. The current in one of the conductors is viewed as producing a field. The current in the other conductor experiences a force due to the magnetic field. In this lab, the magnetic field is produced by a solenoid. A short straight conductor placed inside the solenoid will experience the magnetic force.

The apparatus is shown in figure 1. A plastic balancing blade with a U-shaped piece of copper on one end is balanced half in and half out of the solenoid. A current I flows through the conductor from point X to Y. The solenoid can be set up to produce a magnetic field pointing from left to right. The current flowing through the base of the U will experience a downward magnetic force; the sides of the U do not experience a magnetic force. Small weights, mg, placed on the right end of the balancing blade balance the magnetic force on the left end.

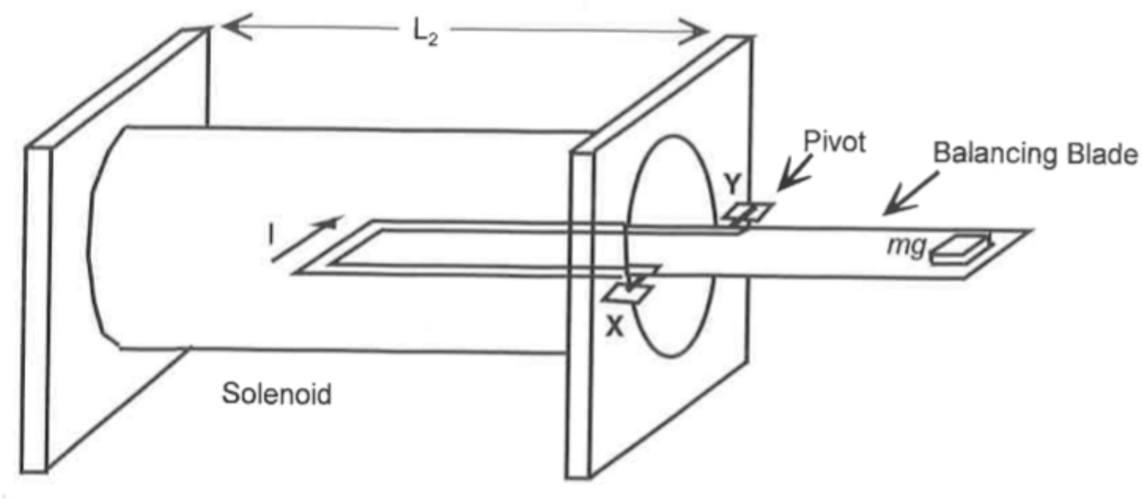

figure 1

Question 1: Explain why the sides of the U will not experience a magnetic force, even when they carry current.

There are two basic equations that apply to this experiment. One gives the magnetic force on a current-carrying wire in a magnetic field. A straight wire of length L_1 carrying a current I through a uniform magnetic field $\boldsymbol{B}$ will experience a force of magnitude

$$F = IL_1 B \sin\theta \qquad (1)$$

in which θ is the angle between $\boldsymbol{B}$ and the wire.

The other equation gives the magnetic field produced inside the solenoid. The magnitude of the field near the center of an N turn solenoid of length L_2, carrying a current I is

$$B = \mu_0 \frac{N}{L_2} I \qquad (2)$$

The constant μ_0 has a value of 4π x 10^{-7} T·m/A. In this experiment, the current in the conductor and solenoid will be the same, so I in equations (1) and (2) are the same. Also, the angle θ will be 90°.

We can combine equations (1) and (2) by eliminating B to give a third useful equation:

$$F = \mu_0 N \frac{L_1}{L_2} I^2 \qquad (3)$$

Equation (3) tells us that, in this experiment, we should expect the magnetic force to be directly proportional to the square of the current. An experimental test of equation (3) is a test of magnetic field theory since it was derived from equations (1) and (2).

Procedure:

As explained above, the downward magnetic force on one end of the balancing blade is balanced by weights placed near the other end. For the currents used in this experiment (less than 3 amps), the balancing weights required will be less than about 10^{-3} N, corresponding to masses of less than 100 milligrams.

Part 1: Making weights

You will need a set of identical weights of approximately 10 milligrams for your experiment. In the following instructions, keep in mind that it is more important that the weights be the same than that they be exactly 10 mg.

The weights can be made from strips of paper. Find the mass of an ordinary sheet of 8.5" x 11" printer paper by measuring, say, 10 identical sheets and divide by 10. Using this mass measurement, calculate the number of milligrams/cm^2 of a single sheet of paper (1 inch is 2.54 cm). Next, determine the area of a 10 milligram strip of paper. Then, make weights with a mass of about 10 milligrams by cutting 5 mm or 1 cm wide strips to the proper length. You'll need around eight to ten weights in all.

Part 2: Electrical connections

You will connect the variable power supply in series with the solenoid and balancing blade. Make sure the power supply is off before starting to make connections. First, connect the + terminal of the power supply to the red terminal in the upper left corner of the solenoid. Connect The black terminal in the upper right corner to the terminal on the back of the solenoid. Finally, connect the terminal in the lower left corner on the front of the solenoid to the – terminal of the power supply.

By inspecting how the terminals are connected to the solenoid and the copper plates for the balancing blade, and using the right-hand rules, convince yourself that this wiring will cause current to flow such that the magnetic field inside the solenoid is directed to the front, and that current will flow through the balancing blade such that the magnetic force on the blade is downwards.

Part 3: Further setup

Place the balancing blade on the two copper plates at the end of the solenoid while the power supply is off. If it does not balance, place some small additional weight on the end outside the solenoid. Use a ruler to measure the distance between the end of the blade and the table top. Further adjust the added weight so that this distance corresponds to a convenient tick mark on the ruler. This is your **base position**. You will have to rebalance the blade several times while taking data, and the magnetic forces in this experiment are quite small, so it is very important that you make it as easy as possible to determine when the blade is rebalanced.

Next, turn the voltage adjustment knobs on the power supply clockwise, about half a rotation from the off position. Turn the current adjustment knobs fully counterclockwise. Turn the power supply on and turn the current adjustment knobs while watching the current readout on the power supply. Do not touch the voltage adjustment knobs (this will keep the power supply in constant-current mode). You should be able to adjust the current from 0 to 3 amps, and the end of the balancing blade inside the solenoid should move down as the current is changed. **Do not allow the current to exceed 3 amps!**

Part 4: Measurements

Place one of your 10 milligram weights near the end of the blade – there should be a line drawn across the blade that you can use to align the strip (also see figure 2). Increase the current (remember, only use the current adjustment knobs) until the blade returns to the base position. Record the current. Continue to add weights, one at a time in the same location (make a stack), rebalance the blade by increasing the current, and record the balancing current. Repeat this procedure until you reach 3 amps. Make a table that contains the number of weights and the corresponding balancing current.

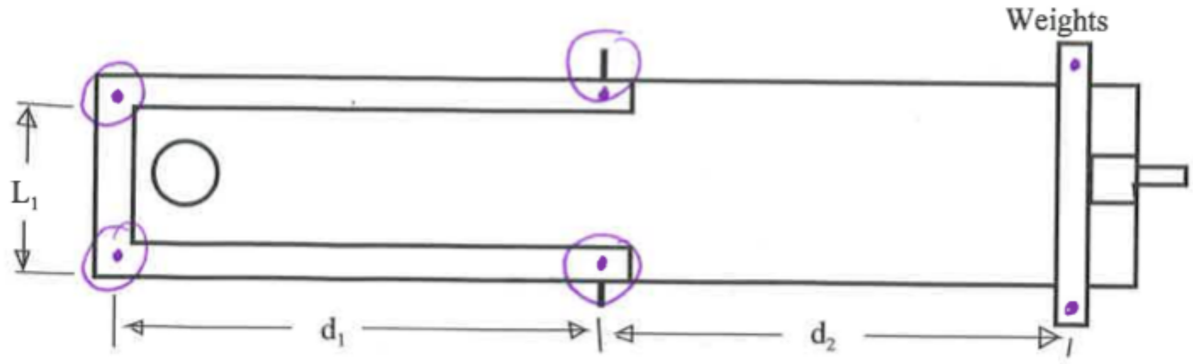

Figure 2

You will need some additional information to analyze your data. Turn off the power supply and remove the balancing blade from the solenoid. Measure the three distances d_1, d_2, and L_1 (see figure 2). Count the number of turns of wire on the solenoid and measure its length L_2. There are actually five layers of turns, so N is five times the number of turns you counted. Be sure to record uncertainties on these five directly measured quantities.

Data Analysis:

The most important part of the data analysis is to see if your data agrees with equation (3). However, since you do not actually measure the magnetic force, we will need to derive from equation (3) a different equation instead. Since the magnetic force and gravitational force are what balance the blade, it is the torques of these forces about the pivot point that must be equal. Recall that torque is the lever arm times force; the lever arms are the distances d_1 (for the magnetic force) and d_2 (for gravity) in this situation. If you used n masses of m kilograms to balance the magnetic force F, then the following equation sets the torques equal:

$$Fd_1 = nmgd_2$$

Solve this equation for F, plug it into equation (3) and solve for n to get:

$$n = \left(\frac{\mu_0 N d_1 L_1}{m g d_2 L_2}\right) I^2 \qquad (4)$$

Where n is the number of 10-milligram weights. This equation suggests that a plot of n vs. I^2 will give a straight line if equation (3) is true. Make this plot and see if it forms a straight line.

Question 2: Is your data consistent with equation (3)? Explain.

The slope of the plot should be equal to the collection of terms inside the parentheses of equation 4. Do a linear fit to your plot to find the slope, and use the LINEST function to find the standard error on the slope. Use your other measurements to calculate the slope (in SI units) from the terms in parentheses in equation (4). There are seven measured values (including g)

that go into this calculation, and hence, seven sources of error, so you are not required to do the full error propagation. Instead, calculate the fractional uncertainty of the seven measurements (the fractional uncertainty is the error divided by the measured value) and only propagate the two sources of error that have the largest fractional uncertainty (in other words, assume that the other five uncertainties are negligible).

Question 3: Are the two values for the slope consistent within uncertainties? If not, propose a reasonable explanation – either an error source that is not accounted for, or an error that you suspect was underestimated.

Informal Lab Report Guidelines

On a separate piece of paper, include the following material in this order:

1) Your full name, your partners' full names, the name of the lab, and the date.

2) State the dimensions of the strips you made in part 1 of the procedure, and show all measurements and calculations used to determine the strip size.

3) The measurements, with uncertainties, of N, d_1, L_1, m, d_2, and L_2. Also, state the value of g you used and its uncertainty.

4) The table of n and I measurements from part 4.

5) The plot of n vs. I^2 that you created for the data analysis. Include the linear fit line on the plot.

6) State the slope of your plot with its uncertainty from LINEST (and include the units!). Also state the slope that you calculated from equation (4) with an uncertainty that includes the two largest sources of fractional uncertainty. Show all calculations you did to propagate the uncertainties.

7) Answer the three bolded questions in the lab procedure.