

Current Balance Lab 6

Equipment Current balance apparatus, laser on tripod, paper and tape, Fluke multimeter, leads, 14 V DC from wall strip, 5Ω 9.2 A rheostat, two 6 inch flat 1 mm thick rulers, weights (50 mg, 100 mg, 200 mg)

Reading Your textbook. Review the vector product (also known as the cross product).

Important Information

1. This experiment uses a laser beam as an optical lever arm. **DO NOT LET THE LASER BEAM OR ITS REFLECTION ENTER YOUR EYE. SERIOUS DAMAGE TO YOUR EYE MAY RESULT.**
2. A wire pivots on two knife edges. The knife edges rest on flat surfaces. Both the knife edges and flat surfaces are easily damaged. Please handle them with care, using the centering rod, described below, to center the knife edges and to gently lower the knife edges onto the flat surfaces.
3. A current passes through a rheostat (variable resistor). At the higher currents one end of the rheostat gets quite hot. **DO NOT TOUCH THIS END OF THE RHEOSTAT.**

1 Introduction

The French Physicist Andre Marie Ampere noticed that when one wire carrying an electrical current is brought near a second wire also carrying a current the two wires experience forces. The force is proportional to the product of the two currents and depends on the relative orientations of the wires. A moving charge in one wire must exert a force on a moving charge in the other wire. The force between the two wires is the sum of the individual forces between the moving charges. This force has distinctly different characteristics from the well-known Coulomb force between charged particles. The force between charged particles due to their motion is called the "magnetic" force. In this experiment you will verify that the force between two wires is proportional to the product of the currents, and estimate the proportionality constant involved.

2 Description of the Experiment

The experiment is similar in principle to the Coulomb balance and indeed uses the same platform. See Fig. 1. A single horizontal rod or wire is pivoted so that it can move freely up and down. Below this wire is a long 10 turn rectangular coil whose long sides are horizontal and parallel to the single wire. One long side of the coil is substantially closer to the single wire than the other long side of the coil. The single wire and coil are connected in series and a current passed through them so that this current is in opposite directions for the single wire and nearby long side of the coil, and in the same direction for the single wire and faraway long side of the coil. The net force between wire and coil is a repulsion. With zero current, the vertical position of the single wire is adjusted to a convenient value. A weight is then added to a pan on the single wire and a DC (steady) current established so that the position of the single wire returns to its initial value. This procedure is repeated for a number of weights. This determines the force on the single wire as a function of the current.

3 Theory

As in the case of the Coulomb force, it is necessary to assume that the magnetic force between two wires A and B is brought about by each wire producing a vector field at all points of the other wire. This field is called the magnetic field \vec{B} . The S.I. unit of magnetic field is the tesla (T), a rather large unit. Consider a differential length of wire $d\vec{\ell}$, where this vector coincides with the wire and points in the direction of the current in the wire. The differential magnetic field $d\vec{B}$ produced a distance r from $d\vec{\ell}$ is given by

$$d\vec{B} = \frac{\mu_0 I d\vec{\ell} \times \hat{r}}{4\pi r^2}, \quad (1)$$

where I is the current, \hat{r} is the unit vector that points from the wire element to the field point and μ_0 is a constant called the vacuum permeability. For almost all purposes, the permeability of air can be taken as μ_0 . This constant is defined so that $\mu_0/4\pi$ is exactly equal to 10^{-7} . In principle, Eq. 1 can be used to calculate the magnetic field produced by one wire at all points in another wire. No matter how complicated the geometry, this magnetic field will be proportional to the current I .

If a wire element $d\vec{\ell}$ with current I is in the magnetic \vec{B} it will experience the force $d\vec{F}$ given by

$$d\vec{F} = I d\vec{\ell} \times \vec{B}. \quad (2)$$

Eq. 2 can be integrated to give the total force on the wire. Using Eq. 1 and Eq. 2 it can be shown that the magnitude of the force F between a length L of two thin infinitely long parallel wires separated by the distance D is given by

$$F = \frac{2\mu_0 I_A I_B L}{4\pi D}, \quad (3)$$

where I_A is the current in one wire and I_B is the current in the other wire. The force is attractive if the currents are in the same direction and repulsive if the currents are oppositely directed. Notice that the force is proportional to the product of the currents. One cannot perform an experiment using infinite wires, but we would expect that the error in using Eq. 3 for finite wires would get smaller as the distance D between the wires became smaller and the length of the wires becomes longer.

We will use Eq. 3 as a starting point for analyzing this experiment. First assume that the force on the single wire is due entirely to the the current in the long side of the rectangular coil that is nearest the single wire. The experiment is wired so that the current through the single wire also passes through each turn of the coil. The coil has $N=10$ turns, so that Eq. 3 can be written

$$F = \frac{2\mu_0 N I^2 L}{4\pi D}, \quad (4)$$

where I is the common current in the single wire and each wire of the coil. Second, we will break the the distance D into two parts such that $D = d + b$. The distance d will be known, and will be either a or $2a$, where $a=1.0$ mm. The distance b will be obtained from the data, and $(a+b)$ or $(2a+b)$ will be approximately but not exactly equal to the distance between the single wire and the longer side of the coil nearest the single wire. In other words, the distance b , obtained experimentally, will compensate to some degree for the inaccuracies of

Eq. 4. Two sets of data will be obtained, one with $D = a + b$ and denoted by subscript 1, and the other with $D = 2a + b$ and denoted by subscript 2. The following two equations are derived from Eq. 4.

$$F_1 = \frac{2\mu_0 NI_1^2 L}{4\pi (a+b)} \quad \text{and} \quad F_2 = \frac{2\mu_0 NI_2^2 L}{4\pi (2a+b)} \quad (5)$$

where I_1 is the current that will result in the Force F_1 on the single wire, and so forth. For each of the two spacings $(a+b)$ and $(2a+b)$ a series of weights are added to the single wire and the current necessary to bring the single wire back to its original position determined. The two sets of data are plotted on the same piece of linear graph paper, force on the vertical axis and current squared on the horizontal axis. The two sets of data have different slopes, S_1 and S_2 . Eqs. 5 then give

$$\frac{F_1}{I_1^2} = S_1 = \frac{2\mu_0 NL}{4\pi (a+b)} \quad \text{and} \quad \frac{F_2}{I_2^2} = S_2 = \frac{2\mu_0 NL}{4\pi (2a+b)}. \quad (6)$$

These two equations can be solved to give b .

$$b = \frac{a(2S_2 - S_1)}{S_1 - S_2}. \quad (7)$$

We can use this value of b in either of Eqs. 5 to obtain a value of $\mu_0/4\pi$. Using the first of these equations, we have

$$\frac{\mu_0}{4\pi} = \frac{S_1(a+b)}{2NL}. \quad (8)$$

4 A Remark About The Speed of Light

With the introduction of the vacuum permeability μ_0 it is of interest to note that Maxwell showed in the mid-19th century that by combining his equations containing the electric and magnetic fields he could predict the existence of propagating waves containing both types of fields. He predicted that the speed c of "electromagnetic" waves in vacuum is given by

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = 3.00 \times 10^8 \text{ m/s}. \quad (9)$$

The coefficient is not exactly three. If it is written out with more decimal places it is slightly less than three.

5 The Apparatus

Fig. 1 is a sketch of the apparatus. It uses the same basic board as the Coulomb balance experiment except that the capacitor plates have been replaced by a wire and a coil. The long rectangular coil is fixed in position. The single wire is held by two rods that are attached to a "pivot arm" that pivots on two knife edges. This allows the single wire to freely move toward and away from the coil. This single wire assembly has a balance adjustment weight that allows the equilibrium vertical position of the single wire to be adjusted. There is a mirror attached to the pivot arm. A laser beam is directed onto the mirror and then reflected

back to a piece of paper taped to the front of the laser. This allows you to return the top plate to a given position with great accuracy.

The "period adjustment" weight changes the oscillation period of the single wire. Moving this weight down makes the period of oscillation longer, and lengthens the times necessary for the wire to stop oscillating. This weight, being below the pivot points, also serves to make the equilibrium position of the wire stable. The lower this weight is, the more stable the mechanical equilibrium of the wire.

There is a "centering rod" (not shown) that is a rod with two knobs at the ends and two off-set points. When the centering rod is rotated, the two points fit into two tapered holes in the bottom of the pivot arm, and one can lift the pivot arm a bit. When the pivot arm is lowered back down, the knife edges should be centered on their supports. This should be done gently so as not to damage the knife edges.

You will be provided with 2 small plastic rulers that are quite close to 1.0 mm thick. They are used as spacers to set the distance between the single wire and coil.

A metal plate attached to the pivot arm is positioned in the gap of a small permanent magnet. As the pivot arm swings back and forth, this arrangement provides eddy current damping.

6 Apparatus Set-Up

This apparatus is sensitive. Once you start adjusting it and taking data, take care not to disturb the bench or apparatus so as not to move the wire set it into oscillation.

1. Check that the board on which the apparatus is mounted does not wobble. If it does, adjust one of the two thumbscrews on the front of the board.
2. Check that the apparatus is wired as shown in Fig. 2, but leave one of the wires unplugged so that there is no current. A DC voltage of 14 V will be provided from the wall strip. A Fluke multimeter will be used to measure the current. Use the Com and 10 A jacks on the Fluke. To turn the Fluke on, rotate the dial to the "A" that has a solid and dashed line above it. The A stands for amperes and the dotted and dashed lines signify DC (direct or steady current). In so far as feasible, keep the wires and rheostat away from the apparatus so as to minimize the effect of their magnetic fields.
3. Try setting the period adjustment weight toward the lower end of its range. If you decide to move it later, you will have to realign the apparatus as described below.
4. Center the pivot arm by gently raising it and lowering it with the centering rod.
5. Check that the single wire rotates freely. The damping plate should not touch the magnet, and the points on the centering rod should not touch the pivot arm.
6. Hold one of the 6 inch rulers near the middle by the edge. Place the ruler on top of the plastic that holds the coil and then drop a quarter on the weight pan of the single wire to bring the wire down onto the ruler. The ruler should not rest on the aluminum strip that holds the plastic coil form. This procedure sets the distance between the wire and the top of the coil form at 1.0 mm.
7. WITH THE LASER OFF, familiarize yourself with the knobs on the tripod mount so that you can raise, lower, and rotate the laser with ease. In adjusting the laser beam,

you may also have to move the tripod sideways. Tape a piece of paper to the front of the laser.

8. REMINDER. DO NOT LET THE LASER BEAM OR ITS REFLECTION ENTER YOUR EYE. Turn on the laser, open the shutter, and adjust the position and orientation of the laser so that the laser beam reflects off the mirror and back onto the paper taped to the laser. Make a horizontal mark where the laser beam strikes the paper. Rather than making the mark in the middle of the laser beam, you might consider making the mark at the very top or bottom of the laser beam. Your ultimate goal will be to return the laser beam to its original location.
9. Remove the quarter and the ruler, taking care not to disturb the position of the wire assembly. Rotate the balance adjustment weight until the laser beam hits the mark you have already drawn on the paper attached to the laser. The wire should now be in the same position it was in when the ruler was in place.

7 Procedures

Place a 50 mg mass on pan attached to the wire. Turn the Fluke multimeter on to DC amperes. Adjust the rheostat for maximum resistance by moving the slider to the proper end of the rheostat. IMPORTANT. Examine the rheostat carefully so that you know which end the slider should be at for maximum resistance in the circuit. Complete the circuit. Increase the current by slowly moving the rheostat slider until the laser beam hits the mark on the paper. Record the current and the weight. Repeat this procedure for masses from 100 mg to 300 mg in steps of 50 mg. DO NOT EXCEED 9 A. Make a four column table of mass in mg, force in newtons, current in A, and the square of the current in A^2 .

Repeat the above measurements but with a distance between the wire and the top of the plastic coil form of 2 ruler thicknesses (2.0 mm).

8 Analysis

On the same sheet of linear graph paper, plot your two sets of data, force in newtons on the vertical axis and current squared in A^2 on the horizontal axis. Can the two sets of data be reasonably represented by straight lines? Draw two straight lines through the data. Each line should go through the origin. Does your data support the statement that for a given spatial configuration, the force is proportional to the square of the current?

Calculate the slopes S_1 and S_2 of your two lines and use Eq. 7 to calculate b . Then use Eq. 8 with $L=0.30$ m to obtain a value of $\mu_0/4\pi$. Compare your value to 10^{-7} .

9 Questions

1. It is much easier to obtain the balance point in this experiment than in the Coulomb Balance experiment. Why?
2. The two wires that support the single wire also carry current. Will there be forces on these two wires due to the magnetic field of the coil, and if so, how will they effect the experiment?

10 Finishing Up

Please leave the bench as you found it. Thank you.

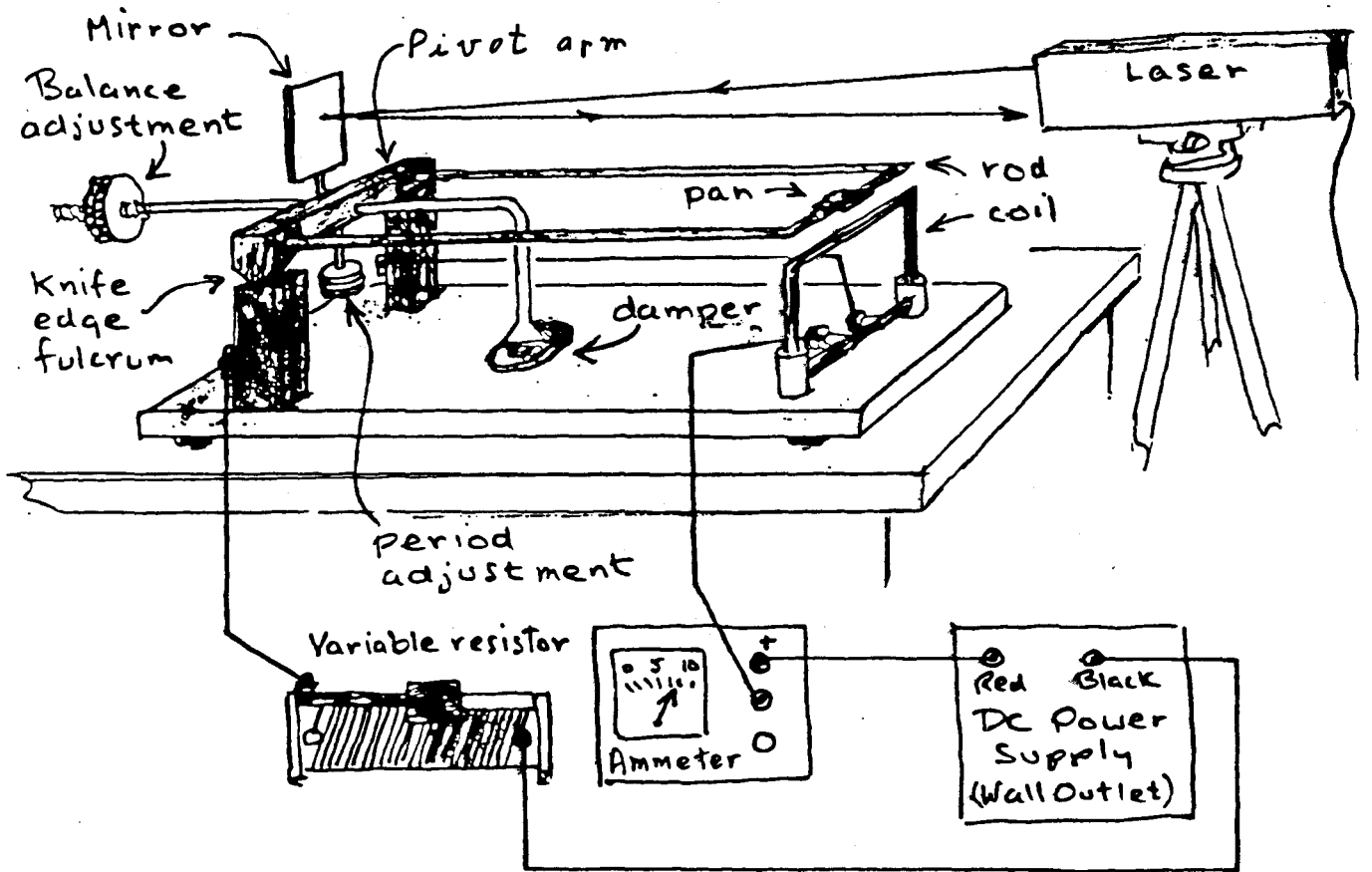


Figure 1
Setup for the experiment.

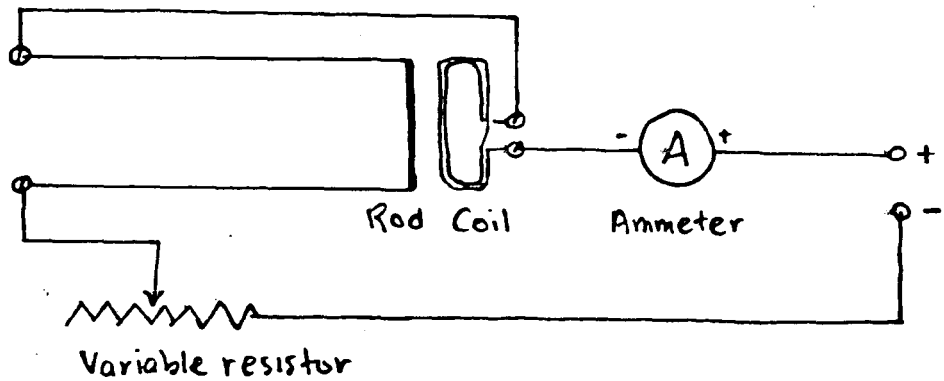


Figure 2
Schematic of the electrical circuit.