Current Balance:
Measuring the Force Between Two Current Carrying Wires

Introduction

Parallel wires transporting electrical current interact with each other. The interaction is strong enough so that the interaction force can easily be determined in an introductory laboratory. The design of this apparatus is based on the experiment that defines the mks unit of electrical current, the ampere (A).

Equipment

- Current Balance
- Fractional Weight Set
- Reversal Switch
- He-Ne Laser and scale
- 3-10A Ammeter
- Vernier Calipers (metric)
- 3-10A Power Supply
- Leads
- Screens to block light and display position

Safety Issues:

Lasers are potentially dangerous. Even a reasonably low power laser can cause damage to your eyesight. Under no circumstances should you direct the laser light toward a classmate or yourself. Always direct the light away from the rest of the class. Reflected light should be intercepted with the screens provided.

Most of the work performed in this lab uses power supplies outputting small voltages (<18V), so shock hazards are minimal. However, it is always important to turn off the current through the circuit when making any modifications to the experiment. This will eliminate any possibility for shock and improve you experimental results since ohmic heating will be minimized.

Before the Lab

Read and *understand* the theory section of this document. Answer the questions at the end of the theory section. Read the procedure section once.

Theory

When a charged particle moves in a magnetic field, it experiences a force known as the Lorentz Force given by the expression

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

where q is the charge on the particle, v is the velocity of the particle and B is the magnetic field. If the charged particle is an electron and the direction of motion of the charge is perpendicular to the magnetic field (on average), then the cross product reduces to

$$F=evB. \tag{2}$$

Generalizing this expression for a current carrying wire in a magnetic field is accomplished by adding the force on each of the moving charge carriers. In fig. 1, we will count all of the charged particles in the volume of wire $V=AL$, where L is the length of the wire and A is the cross sectional area of the wire. If the density of charge carriers in this volume is n (#/m^3), then the total number of charged particles in this volume is $N=nAL$. Equation 2 can then be modified to give the Lorentz force acting on a length of wire L long

$$F=nALev_dB, \tag{3}$$

assuming that B is uniform throughout the region of the wire. The drift velocity of the charged particles, v_d, has been substituted for the velocity of the electrons in free space.

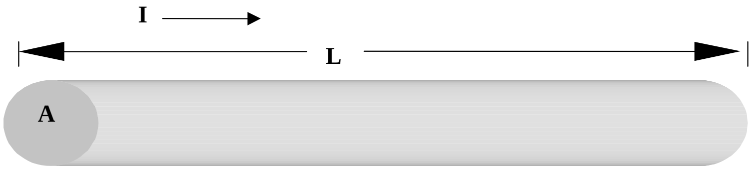

Fig. 1. Schematic diagram of a current carrying wire.

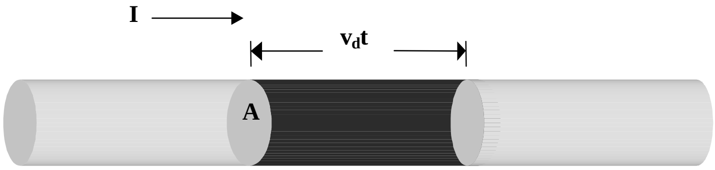

Fig. 2. Schematic diagram of the volume used to calculate the current.

The current is the amount of charge that passes any cross-section of the wire per unit time. In this case, we determine the number of charged particles (number of electrons) contained in the shaded region. The charge in this region passing any cross-section in time t is

$$Q=nev_d tA,$$

where the parameters are as they were defined above. The current in the steady state is

$$I=dQ/dt=Q/t= I = \frac{dQ}{dt} = \frac{Q}{t} = \frac{nev_\mathrm{d}tA}{\mathrm{t}} = nev_d A. \qquad (4)$$

The force, eq. 3, acting on the current carrying wire can be rewritten by substituting eq. 4 into eq. 3 as

$$F=(nAev_d)LB=-ILB \qquad (5)$$

which is the force acting on a wire carrying uniform current I.

If a second wire is close to the first carrying the same magnitude current I, this one will “create” a magnetic field (choosing this wire to create the magnetic field is arbitrary, we could have chosen the other wire as the magnetic field generator). If the wires are exactly parallel, the magnetic field “sensed” by the first wire is uniform and B is a constant along the length of the wire. The magnetic field created by the second wire at a distance *r* from the center of the second wire is by Ampere’s Law

$$\oint \vec{B} \bullet d\vec{l} = \mu_o I \ .$$

Constructing a Gaussian surface as shown in fig. 3, the path integral reduces to $2\pi r$and I is the current in the wire. The uniform magnetic field is given by

$$B(2\pi r) = \mu_0 I \Rightarrow B = \frac{\mu_0 I}{2\pi r}. \qquad (6)$$

Placing this result in eq. 5 yields

$$F = ILB = IL\frac{\mu_o I}{2\pi r} = \frac{\mu_o L}{2\pi r} I^2 \qquad (7)$$

where *L* is the length of the wire and *r* is the separation between wires (center to center distance). This is the expression we will verify in today’s laboratory.

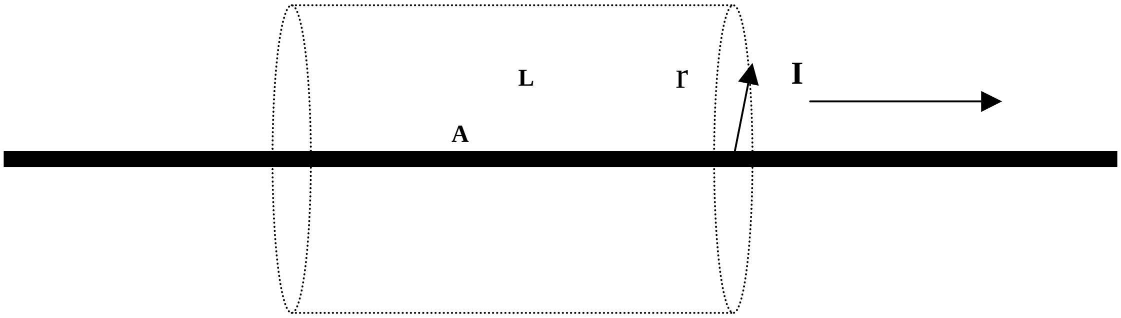

Fig. 3 Image showing the "Gaussian" surface used to determine the magnetic field from Ampere's Law.

Prelab Questions:

If the force between two current carrying wires has increased by a factor of four and the wire has not changed its position, by how much has the current in the wires increased?

If the force between two current carrying wires has decreased by a factor of four and the current has not changed, by how much has the distance between the wires changed?

The magnetic field generated by the current in the stationary wire is a constant. The direction of the current is from left to right in fig. 4. As shown in fig.4, with the movable wire running parallel to the stationary wire, which direction is the magnetic field at the position of the moveable wire?

Procedure:

Setup the simple circuit as shown in Fig. 4. The switch will allow reversal of the current in the moveable wire resulting in a change in the sign of the force. The battery should be replaced with the HP dc power supply provided.

It is very important that lead wires connected to binding posts on the balance leave them at right angles with the conductors that are part of the frame. The circuit shown in fig.4 provides the configuration for a repulsive force between the two parallel bars as required in the experiment. By suitably interchanging the wires connected to the balance, the bars may be made to attract each other.

Caution:
The Earth's magnetic field can lead to errors. This problem can be avoided by orienting the conducting bars parallel to the earth's field.

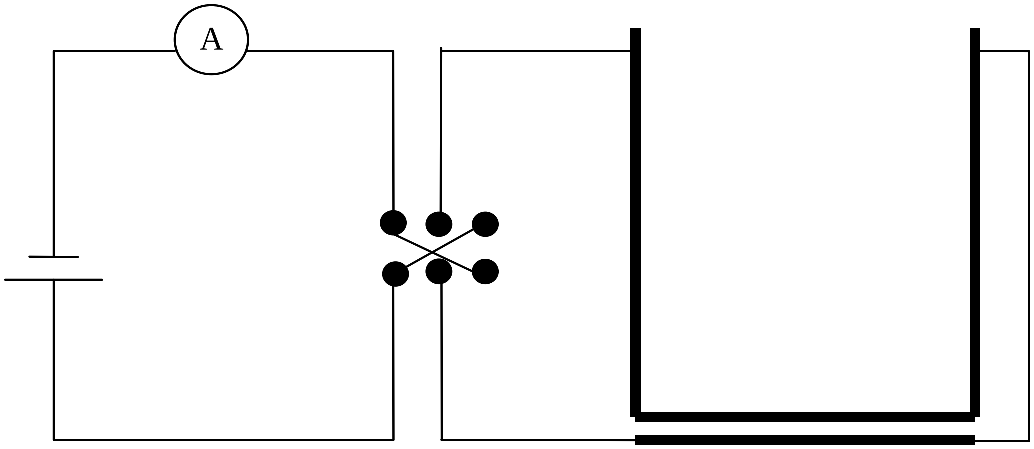

Fig. 4 Schematic of circuit to be constructed with current reversal switch

Remove the frame from the balance and clean the knife-edges, bearings, and the two parallel bars carefully to prevent sticking. The knife-edges have been honed and checked for burrs at the factory. Further honing by the user should be avoided. Be careful to protect these pivot surfaces from accidental scratching. Use only the lifting arms to place and remove the balance assembly from the bearing posts.

Place the balance directly on the laboratory bench. Adjust the leveling screws to position the base firmly. Replace the frame and adjust the counter weight behind the mirror until the frame oscillates freely and comes to rest with the front horizontal bar a few millimeters above the stationary bar. Adjust the counter poise below the mirror until the period of oscillation of the frame is 1 to 2 seconds. It should come to rest in 10 to 15 seconds when the poles of the damping magnets are about 2 mm apart.

To check the two conducting bars for alignment, place a coin on the scale pan to bring the bars into contact without distortion. Thumbscrews on each front post permit either end of the lower bar to be raised or lowered. Similar thumbscrews on each block at the rear permit either end of the upper bar to be moved forward or backward. The two bars should be aligned as accurately as can be determined by the unaided eye when viewed from the front and from the top. When viewed from the front, with a white paper behind the bars, the two bars may appear to be slightly bent. If this is serious, correct by gently bending one bar or the other by hand until both appear to be straight. It is difficult to get them so straight that no light may be seen between them, and this is not essential for good quantitative results. Nevertheless, the bars are rather easily bent and this inspection should be made before every trial. In general, the bars should always be handled gently and as little as necessary.

Setup the laser and scale 1to 1.5 meters from the mirror. Remove the coin from the weight pan and record the rest point indicated by the position of the laser spot on the scale. Note that a screw behind the mirror permits its angle of tilt to be adjusted so that spot height reading is convenient.

Engage the beam lift gently; the release it and again record the rest point. If it deviates from the first observation, the knife edges may not be clean, the base or table may be unsteady, or the balance or laser may have been jarred.

Determine the length of the wire to be used in the calculation of the force. Record this value as L_o.

Measure the distance from the pivot to the center of the front bar on each side and record the average of these two as a_o.

Measure the distance from the mirror to the scale and record this number as b.

The separation of the two bars at equilibrium is determined in the following the manner. The scale reading at equilibrium is noted. Then the upper bar is depressed (by placing a coin on the scale pan) until it is in contact with the lower bar, and a new scale reading is noted. Geometry will show that the separation is given by (ask your instructor if you should derive this expression):

$$d_o=a_oD/2b$$

where D is the difference in position on the scale. The center to center distance d is the sum of d_o and the two radii of the current carrying rods, i.e. $d=d_o+r_1+r_2$. The radii should be measured with a vernier caliper.

Caution:
The purpose of the beam lift is to relocate the knife-edges to their proper positions on the bearing posts so that the front moveable conductor will always be in the same vertical plane as the fixed conductor below it. Lifting the beam each time a weight is added or removed avoids the risk of jarring the beam and damaging the knife edge.

Begin a trial by adding a weight to the pan. Increase the current until the beam returns to its equilibrium position, and read the ammeter. Change the weight on the pan and again adjust the current and read the ammeter. Continue this process until you have recorded at least 10 values between 10 and 150 mg. (Do not exceed 10A. If the current must be increased to more than 10A, decrease the weight. Higher currents will tend to drift due to ohmic heating of the wire increasing the resistance of the rod.)

Plot the weight on the plate (mg) versus the current squared. Perform a linear fit and determine the slope of the line. This slope is related to measured quantities and $\mu_o = 4\pi \times 10^{-7}$H/m = $4\pi \times 10^{-7}$Vs/A. Compare your slope to the predicted value.

For a second trial, change the couterpoise slightly to make the separation of the conducting bars slightly different. Record the scale readings at contact and at equilibrium, and take another series of readings.

Data Tables

	Trial 1	Trial 2
Mirror to scale, b		
Radii of bars, r_1+r_2		
Lever arm, a_o		
Length of upper bar, L		
Scale reading at contact		
Scale reading at equilib.		
Difference, D		

Trial 1:

Force , mg (N)	**I(A)**	**$I^2(A^2)$**	**F/I^2**

Trial 2:

Force , mg (N)	**I(A)**	**$I^2(A^2)$**	**F/I^2**

Summarize the experiment and provide samples of all calculations.