EXPERIMENT 12

Current Balance

Introduction

The current balance is used to measure the force of repulsion between identical, oppositely directed, currents in parallel conductors. In this experiment you will:

1) Determine how the magnetic force of one current-carrying conductor on a parallel current-carrying conductor depends on: the current in the conductors; the length of the conductors and the separation of the conductors.

2) Obtain a value for μ_o, the magnetic permeability of free space.

3) Measure the horizontal component of the Earth's magnetic field.

Theory

The force on a straight current-carrying conductor in a magnetic field is given by,

$$\overrightarrow{F} = L\overrightarrow{I_1} \times \overrightarrow{B_2}$$

where $\overrightarrow{I_1}$, is the current in the conductor, L is the length of the straight conductor that is immersed in the magnetic field, and $\overrightarrow{B_2}$, is the strength of the magnetic field (Fig. 12.1).

The magnetic field, $\overrightarrow{B_2}$, is produced by the second long straight conductor and is given by

$$\overrightarrow{B_2} = \frac{\mu_0 \overrightarrow{I_2}}{2\pi r}$$

where: μ_0 is the magnetic permeability of free space (1.26 $\times 10^{-6}$ H/m); r is the centre-to-centre distance between the conductors, and $\overrightarrow{I_2}$ is the current in the second wire. Thus, the magnitude of the force on one conductor due to the other parallel conductor is given by

$$F = LI_1 \frac{\mu_0 I_2}{2\pi r}$$

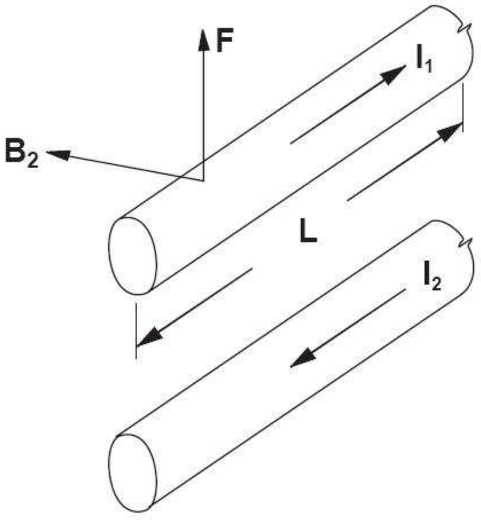


Figure 12.1: *Parallel Conductors*

Since $I_1 = I_2 = I$, the magnitude of the force is

$$F = \frac{\mu_0 L I^2}{2\pi r} \tag{12.1}$$

Experimental Apparatus

This apparatus is extremely delicate and must be handled with a very light touch. The current balance consists of a rectangular conducting frame through which current passes by entering and exiting through liquid gallium (Fig. 12.2). The entire frame is suspended by a 0.006-inch diameter high strength torsion wire. The rectangular frame is counter-balanced by a long beam having a movable counter-balance mass on it and a magnetically damped vane on its end. The vane also serves as a zero-position indicator.

Directly below the long side of the rectangular frame is a parallel conductor carrying the same current in the opposite direction. The height of this conductor is adjustable to allow different separations between the conductors. Each end can be lowered or raised independently of the other to make the two conductors parallel.

The separation adjustment screws have a 1 mm pitch and are used to adjust the centre-to-centre conductor separation from 3.2 mm to 15 mm in increments of 0.05 mm.

One end of the torsion support wire is fastened to a rotatable degree dial which can be rotated a total of three revolutions, one-and-a-half revolutions in either direction from the centre equilibrium position. The other end of the torsion wire can be rotated only about 200 degrees and is used to make fine adjustments in the zero equilibrium position.

The torsion balance has a sensitivity of about 3 degrees per milligram of force. A change of less than 2 degrees on the degree dial is discernible. The balance has a 20 Amp fuse to protect the equipment from damage. Good measurements can be made with a current of 5 A and a maximum working current of 15 A is recommended.

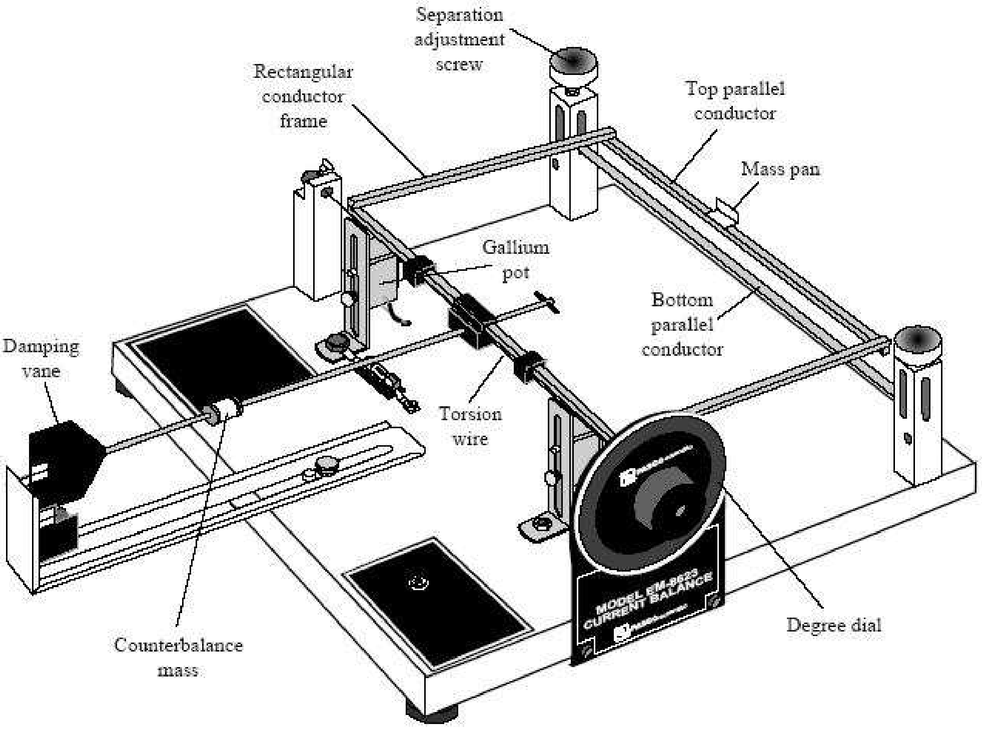


Figure 12.2: *Experimental Apparatus*

The two gallium pots can be raised to the operating position or lowered and capped for storage. Electrical contact is made through the gallium, which has a melting point of 29.78°C. A heater is provided to ensure the gallium is molten during the experiment.

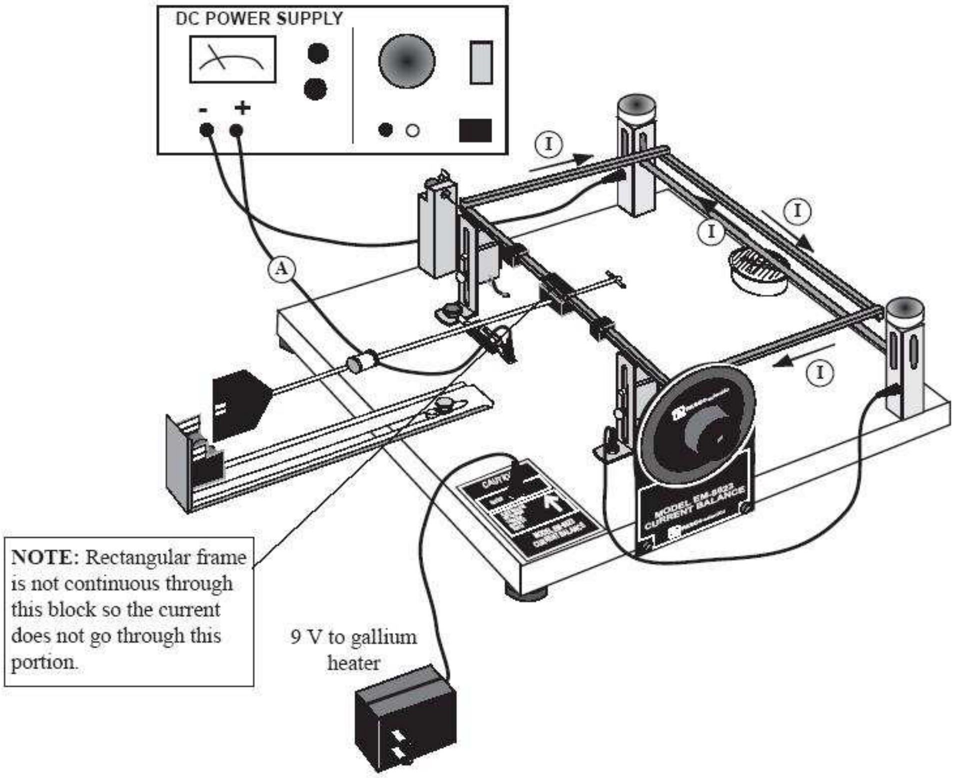
Experiment Setup

The following steps must be performed at the beginning of the experiment:

- Wiring
- Balancing the rectangular frame so it is not touching the lower conductor and is supported only by the wire suspension, and
- Zeroing the balance so the parallel conductors are a known distance apart which then can be used as a reference for all other desired separations.

Each is now described in turn:

- **Wiring**
  1. Connect the balance to the variable DC power supply as shown in Fig. 12.3 using banana plug lead wires. Use long lead wires and keep them as far away from the



NOTE: Rectangular frame is not continuous through this block so the current does not go through this portion.

9 V to gallium heater

Figure 12.3: *Wiring diagram for the apparatus*

rectangular frame as possible (minimum distance 25 cm). This is so the magnetic field produced by the current in the lead wires will have a negligible effect on the balance.

2. Place the compass on the current balance base under the two parallel conductors. To eliminate the effect of the Earth's magnetic field, orient the parallel conductors in the magnetic N-S direction as indicated by the alignment of the compass needle. Remove any ferromagnetic materials from the vicinity of the current balance.
   NOTE: To eliminate the effects of all extraneous magnetic fields, bypass the fixed conductor and complete the current loop with a lead wire. Then orient the current balance until there is no deflection of the beam when a large current is turned on and off.
3. A 9V transformer is supplied with the current balance to power the gallium heater. To keep the gallium liquid, plug it into the jack (Fig. 12.3).

- **Balancing**

1. Turn the degree dial to zero degrees, making sure that the dial is in the centre of its range by looking in the back of the degree dial to see if the peg sticking through the large gear is halfway through the range of the gear slot (Fig. 12.4a). Rotate the rear wire clamping thumb screw so it is vertical (Fig. 12.4b).

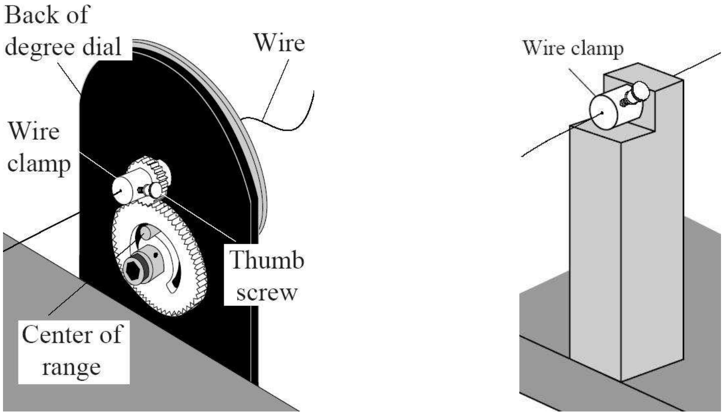


Figure 12.4: *(a) Back of degree dial* *(b) Wire clamp*

2. Slide the counterbalance mass (Fig. 12.2) until the balance beam is horizontal. Fine adjustments in balance can be made by turning the rear wire thumb screw (Fig. 12.4b) slightly, which twists the back portion of the torsion wire. Because there is so little friction in the pivot, air currents may cause the balance to move. Avoid drafts.
3. Position the slideable damping magnets so that when the balance beam is horizontal, the index reads zero (all three index lines line up as in Fig. 12.5).

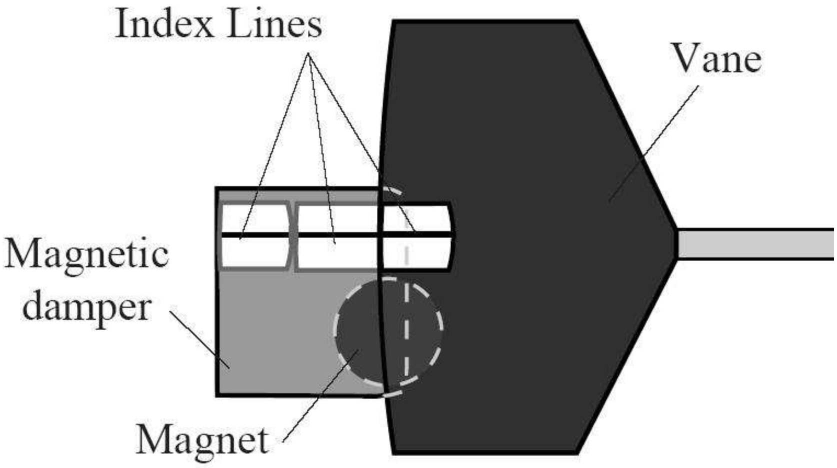


Figure 12.5: *The damper vane*

- **Zeroing**

  In the following steps the separation between the parallel conductors is calibrated by first making the two conductors touch each other, at which point the separation is known (the diameter of the conductor = 3.2 mm). Then the additional separation is determined by keeping track of how many revolutions are made on the 1 mm pitch screw as the bottom conductor is lowered away from the top conductor.

NOTE: To lower the conductor, turn the screws clockwise.

1. To make the bottom conductor parallel (level) with the top conductor, place a mass (200 mg) on the mass pan (Fig. 12.2) and/or twist the degree dial clockwise to bring the conductors together. Rotate the two separation adjustment screws alternately until there is no gap between the conductors at either end.
2. Remove the mass from the pan and/or return the degree dial to the centre zero position. Now the bottom conductor is parallel to the top conductor and the zero position can be determined by moving the bottom conductor up so it just barely touches the top conductor. Raise the bottom conductor by rotating the separation adjustment screws counterclockwise alternately one turn at a time until the bottom conductor just barely touches the top conductor. This should keep the conductors parallel as the bottom conductor is raised. When the conductors are just touching, the balance beam should still read zero. When this is complete, the centre-to-centre separation between the two conductors is equal to one rod diameter (3.2 mm).
   NOTE: If the bottom conductor cannot be raised enough by turning the separation screws, rebalance the top conductor so that it is slightly lower. This may require moving the counterbalance mass and the damping magnets.
   Now whenever the balance is in the zero position, the centre-to-centre separation of the conductors is known to be 3.2 mm. Then any other desired separation can be known by keeping track of the number of rotations of the separation adjustment screws which move the bottom conductor one millimeter for each complete rotation.
3. There is a circular scale on the top of each screw marked off in divisions of 1/20 of a complete rotation. To keep track of the rotation of the screw, line up a corner of the square post (below the screw) with the scale. For example (Fig. 12.6), the number 4 is lined up with the outer corner of the square post, so one total rotation is complete when the 4 is once again lined up with the same corner and then the conductor has been raised or lowered 1 mm. Or, if it is desired to move the conductor only 0.5 mm, the screw can be rotated until the 9 is in the position formerly occupied by the 4. Rotate both screws the same amount to maintain a parallel separation of the conductors.

You are now in a position to carry out the experiments to meet the objectives outlined in the Introduction.

Part 1: Force versus Current

Introduction

The magnetic force of one current-carrying conductor on a parallel current-carrying conductor depends on the current in the conductors, the length of the conductor, and the separation between the centres of the conductors. In this experiment the separation and the length of the conductor are held constant while the current is varied to find how the force depends on the current.

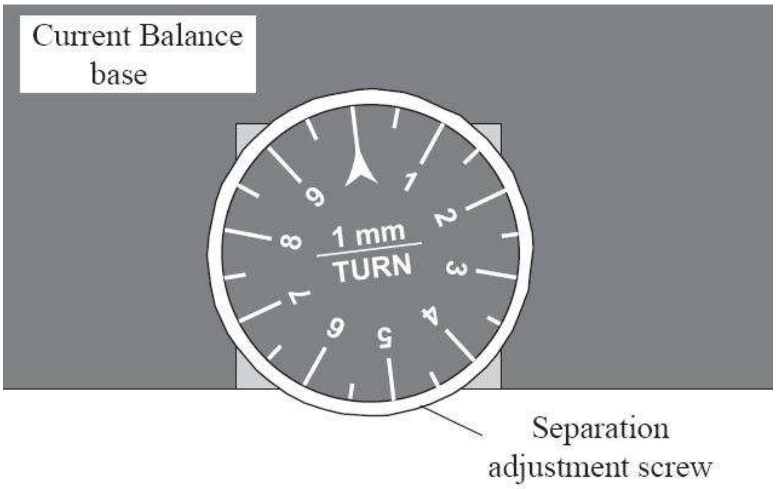


Figure 12.6: *Top view of separation adjustment screw*

Procedure

1. Set the separation of the parallel conductors to about 8 mm, by following the instructions in the Theory section.
   Record the constant separation = Number of turns $\times 10^{-3}$ m + 3.2 $\times 10^{-3}$ m. Measure and record the length of the conductor.

2. Apply a known downward force by placing a 5 mg mass on the centre of the mass pan.

3. Adjust the current until the balance returns to zero. Record the current. Now the magnetic force lifting the top conductor is equal to the weight of the known mass pushing it down. This is the most critical measurement in the experiment. Make sure that the balance is exactly zeroed, and measure the current carefully.

4. Holding the separation constant, repeat steps 2 and 3, measuring the current for about 15 different masses, up to a maximum of 200 mg. Record your data in your laboratory notebook in a table of the form shown in Table 15.1.

Mass (kg)	Current (A)	Force (N)

Table 15.1 *Data and Calculations.*

Data Analysis

1. Plot F vs. I^2 to show that the result is a straight-line graph as predicted in the Theory section.

2. Calculate the slope of the best-fit line from the graph using Eq. 25 in 'Notes on Errors'. Using Eq. 12.1, determine the theoretical expression for the slope. Using this expression, solve for the magnetic permeability constant, μ_0 in terms of the slope and hence calculate μ_0. Using Eq. 28 in 'Notes on Errors', determine the error on the slope and hence the error on μ_0, using the propagation of errors formula (Eq. 15 in 'Notes on Errors').

3. Make an estimate of the error on I based on the resolution of the ammeter and hence determine the error on I^2. Overplot the errors on I^2 on your graph.

Part 2: Force versus Separation

In this part of the experiment the current and the length of the conductor are held constant while the separation is varied to find how the force depends on the separation.

Procedure

Calibration of the degree dial:

NOTE: The torsion constant (slope) will vary slightly with wire tension. You will have to recalculate the slope each time the apparatus is set up.

1. Since the current is held constant in this experiment, the force is determined using the continuous degree dial rather than the discrete masses. To calibrate the degree dial, first make sure the balance beam is at the zero-balance position when the degree scale is at the centre zero and there is no current flowing through the balance and then perform the following steps:
   - **(a)** Place a 20 mg mass on the mass pan, making certain it is centred over the conductor. Turn the degree dial counterclockwise to bring the beam back to the zero-balance position and record the degrees of rotation.
   - **(b)** Repeat (a) for 50, 75, 100, 125 and 150 mg loads, compiling your data in your laboratory notebook in a form as shown in Table 15.2.
   - **(c)** Plot the force versus the angle (β) and determine the slope of the best-fit straight line through the data points using Eq. 25 in 'Notes on Errors'. The slope, k, determines the force for any rotation of the degree dial according to the equation $F = k\beta$.

   Force versus Separation

2. Now choose a current in the 5 to 10 A range and keep it constant for all measurements.

3. Measure the force required to return the balance to zero for several separations from 4 to 15 mm, recording your data in the form shown in Table 15.3. The force is calculated from the angle reading on the degree dial and the separation is determined by knowing how many rotations down from the minimum separation the conductor has been lowered.

Mass (kg)	Angle $\beta^{(o)}$	Force (N)

Table 15.2: *Calibration Data*

Number of turns (N)	Separation (r) N $\times 10^{-3}$m + 3.2 $\times^{-3}$m	Angle $\beta^{(o)}$	Force kβ(N)

Table 15.3: *Sample Data Table*

Data Analysis

1. Plot F vs. 1/r to show that the result is a straight-line graph as predicted in the Theory section.
2. Calculate the slope of the best-fit line from the graph using Eq. 25 in 'Notes on Errors'. Determine the theoretical expression for the slope. Using this expression, solve for the magnetic permeability constant, μ_0, in terms of the slope and hence calculate μ_0.
3. Determine the error on your estimate of μ_0. How does it compare with the value you obtained in Part 1?

Part 3: Horizontal Component of the Earth's Magnetic Field

Introduction

In this experiment no current flows through the bottom conductor of the current balance so the only magnetic field lifting the top conductor is the Earth's horizontal field.

Procedure

1. Orient the balance so that the parallel conductors are perpendicular to the N-S magnetic field (i.e., aligned with East-West).
2. Unplug the leads to the bottom conductor and connect them directly together if they are long enough or use a third lead wire if necessary. Make sure these wires are kept away from the balance.

3. Now that the lower conductor has been bypassed, so only the Earth's magnetic field will act on the current flowing in the upper conductor. Use as large a current as possible, up to 15 Amps, for best results. Measure the force required to balance the apparatus.
4. Measure the length of the top conductor that is perpendicular to the Earth's magnetic field.

Data Analysis

Calculate the horizontal component of the magnetic field using the equation $B = \frac{F}{IL}$.

Questions

1. Why does this experiment only measure the horizontal component of the Earth's magnetic field? How is the effect of the vertical component eliminated?
2. In the other experiments using the current balance, why doesn't the Earth's magnetic field cause an error?
3. Where on the Earth would the current balance indicate the Horizontal component of the Earth's magnetic field is zero?