1 AIMS

1.1 Physics

In this experiment you should study the force between parallel current-carrying conductors. You should find a value for the magnetic permeability of free space.

1.2 Skills

The particular skills you will start to acquire by performing this experiment are:

- Working with a low magnetic field and eliminating the effect of the earth’s field.

- Careful adjustment and zeroing of a torsion balance and its use to measure very small forces.

- Derivation of equations and numerical substitution.

- Graphing skills and error assessment.
2 INTRODUCTION

A Danish physicist Hans C. Oersted noticed that a compass needle was deflected when placed near to a current carrying wire. This was the first empirical connection between electricity and magnetism although Ampère had noticed that a force existed between two wires carrying a current\(^{(1)}\).

Coulomb’s Law describes the electric force between charges separated by a distance \( r \). This is the total force experienced by the charges when they are at rest. When they are moving with respect to each other there is an additional force acting on the charges. This extra force is the magnetic force given by\(^{(2)}\)

\[
\mathbf{F} = -\frac{\mu_0 q q'}{4\pi r^2} \mathbf{v} \mathbf{v}'
\]

for two charges \( q \) and \( q' \) moving with velocities \( v \) and \( v' \) parallel to each other and separated by a distance \( r \). For charges of the same sign the force is attractive if the velocities are parallel and repulsive when they are antiparallel. Notice that the force is zero unless both velocities are non-zero. The value of the constant \( \mu_0 \) is exactly \( 4\pi \times 10^{-7}\) H.m\(^{-1}\). Its value depends on the definitions of current and charge in the SI system of units. According to equation (1) for modest speeds the magnetic force between point charges is small compared to the electric force and consequently this might imply that it has only a small effect. However, the magnetic force can be very important, even at low speeds. This occurs when the electric forces due to the charge distribution cancel. Does this happen in the current balance?

3 THEORY

Using the standard formulae, which state that the magnetic flux density at a distance \( r \) from an infinitely conductor carrying a current \( I \) is given by\(^{(1)}\)

\[
B = \frac{\mu_0 I}{2\pi r}
\]

and that the force on a conductor of length \( L \) carrying a current \( I \) perpendicular to a flux density \( B \) is

\[
F = BIL
\]

derive the expression for the force between two parallel conductors of length \( L \) each carrying a current \( I \) when the distance between the centres of the two conductors is \( r \).

This is the expression you will test in the following experiments.

What difference does it make that in your experiment \( L \) is finite rather than infinite?
4 DESCRIPTION OF THE APPARATUS

The Pasco current balance consists of a rectangular conducting frame through which a direct current from a power unit can be passed. The frame is suspended on a torsion wire and counterbalanced by a long beam fitted with a moveable mass and a magnetically damped vane. At this stage you should examine Figure 1 below and identify the various parts of the equipment.

![Diagram of the Pasco Current Balance apparatus.](image)

**Figure 1:** Diagram of the Pasco Current Balance apparatus.

The current under investigation is passed through two conductors that are physically parallel to each other but are connected in series electrically. The current flows in opposite directions in the two conductors so that they repel each other. The force of repulsion may be measured either by using the torsion head to twist the suspension or by placing a small mass in the mass pan on the top conductor.

The separation of the parallel conductors can be adjusted by means of the two 1mm-pitch screws that raise or lower the bottom conductor. The current enters and leaves the conductor frame through two contacts that dip into molten gallium. This material presents no hazard and can be maintained as a liquid by means of a low power heater.
In order to isolate the equipment as far as possible from stray magnetic influences it is mounted on a wooden supporting box that raises it well above bench level. Metal frames or other equipment associated with a magnetic field must be kept away from the apparatus to minimise magnetic interference.

5 EXPERIMENTAL PROCEDURE

5.1 Setting up the Apparatus

Before any observations can be made the current balance must first be carefully zeroed. In particular you should decide how you are going to avoid backlash problems when adjusting the various screw dials on the apparatus.

The apparatus has already been aligned so that the parallel conductors lie in a N-S direction, to eliminate the effect of the earth’s magnetic field. You should not alter the orientation of the equipment.
Connect up the circuit shown in Figure 2, using the special heavy-duty current cables provided. Keep the lead wires as far from the rectangular frame as possible (at least 0.25m) in order that the field due to these wires will not affect the balance. Note the inclusion of the digital ammeter to enable the currents to be measured with high precision.

Plug in the low voltage heater and turn it on to warm up the gallium pots.

### 5.2 Zeroing Procedure

With the power supply turned off, carry out the balancing and zeroing procedures described below. Do this as carefully as possible to ensure that your experimental results are both accurate and precise.

Turn the torsion head degree dial to zero degrees. Making sure that the dial is in the centre of its range by inspecting the back of the dial to see if the peg sticking through the large gear is about halfway through the range of the slot as shown in Figure 3.

Rotate the wire clamping screw at the other end of the torsion wire so that it is vertical.

![Figure 3: Reverse view of Torsion Dial.](image)

![Figure 4: Diagram of Damping Vane with Index Lines lined up.](image)

Slide the counterbalancing mass until the beam is approximately horizontal (the counterbalance arm itself will sag below the horizontal). Fine adjustments in balance can be made by turning the rear wire thumbscrew.

Position the damping magnets so that when the beam is horizontal the index reads zero, and all three index marks line up as in Figure 4.

Raise the bottom conductor by turning the adjustment screws until the two conductors just touch over as much of their length as possible. If the bottom conductor can not be raised sufficiently using the adjustment screws repeat steps F and G to set the beam slightly lower.
**H** Place a 200mg mass in the mass pan to force the conductors together.

**I** Finally use the two separation adjusting screws to adjust the beam position so that while the conductors continue to touch over the whole of their length the index marks are lined up. This is the zero balance condition. **Note the positions of both screws.**

It is helpful to hold a sheet of white paper behind the conductors while setting them in contact to make the gap more visible.

When this adjustment is complete the separation of the conductors is exactly equal to one rod diameter (3.1mm).

**J** Remove the 200mg mass from the mass pan.

From now on whenever the balance beam is in the zero position the centre-to-centre separation of the two conductors is known to be 3.1mm. Any other desired separation can be obtained by turning the two calibrated adjustment screws. Since these screws have a pitch of 1mm, three complete clockwise turns on each screw, for example, will produce a conductor separation of $3 + 3.1 = 6.1$mm, and so forth. It is essential to always turn both screws by the same amount to keep the conductors parallel.

### 5.3 Experiment 1: Variation of Force with Current

In this experiment the currents $I$ required to restore the beam to zero are measured when various forces $F$ are applied to deflect the beam.

**A** With the apparatus carefully zeroed, set the separation of the conductors to 4.1mm.

**B** Apply a known downward force $F$ to the beam by placing a load $m$ of 20mg to the centre of the mass pan.

**C** Switch on the power unit and adjust the current $I$ in the conductors until the beam is again zeroed (three marks in line at the damping magnets). The magnetic force between the conductors will now be equal to $F$.

**D** Repeat the last two steps with different values of $m$, measuring the force for as wide a range of currents as the power unit will permit.

**E** Tabulate $m$ in mg, $F$ in Newtons and $I$ in amps.

**F** Repeat steps A to E for at least two other values of the separation $r$ of the conductors.

What does the derivation above suggest that the relationship between $F$ and $I$ should be?

**G** Plot a suitable graph to test this relationship for each of your values of $r$. 

*Page 6 of 8*
By finding the gradients of your “best fit” lines and putting the values into your derived formula it is possible to find the value of $\mu_0$, the magnetic permeability of free space. You will need to measure $L$, the length of the parallel conductors. Find the mean value of $\mu_0$ from your observations and compare with the accepted value.

**Note:** Be particularly careful over units and powers of 10 in your working. What are the major sources of error in this experiment? Are the errors greater at large or small values of $F$. Is this what you would expect?

### 5.4 Experiment 2: Variation of Force with Wire Separation

The current is now held constant and the force $F$ will be determined using the torsion head rather than discrete masses, in order to permit $F$ to be varied continuously. It is therefore first necessary to calibrate the torsion head.

**Calibration of the Torsion Dial:**

A Using the vane index lines, ensure that the balance is zeroed with no current flowing. Lower the bottom bar a few millimetres away from the top conductor. Top conductor. Place a 20mg mass on the mass pan, ensuring that it is centred over the conductor. Restore the beam to zero by turning the degree dial anti-clockwise until the marks are in line. Note the angle $\theta$ through which the dial has been rotated.

B Repeat the above procedure with masses $m$ up to 100mg. Tabulate your results, and plot a graph of force $F$ in Newtons against angle $\theta$ in degrees. Find the gradient $k$ of the best fit line to this graph. Does your graph have a non-zero offset – is this expected? You can then use $k$ to find the force equivalent to any angle of rotation.

**Measurement of Force vs Separation:**

C Remove the masses from the pan, choose a current of around 7A and keep this constant from now on. Take care it may drift with time you will need to check the value at regular intervals.

D Using the torsion head, measure the force $F$ required to return the balance to zero for several different values of separation $r$, from 4.1mm upwards.

E Tabulate, $F$ in Newtons, and $r$ in m.
As before, plot a suitable graph to test your derived relationship between $F$ and $r$. Use the gradient of the graph to find a value for $\mu_0$.

Is your relationship verified? How does the accuracy of this experiment compare with that of experiment 1?

Is this what you would expect? Why?

By reference to any standard textbook of electromagnetism, see how highly accurate current balances differ from the one you have been using. Can you account for these differences?

6 REFERENCES


2) The general version of equation (1) for charges travelling in arbitrary directions is

$$\hat{F} = \frac{\mu_0}{4\pi} \frac{qq'}{r^2} \hat{\mathbf{v}} \times (\hat{\mathbf{v}}' \times \hat{\mathbf{r}})$$