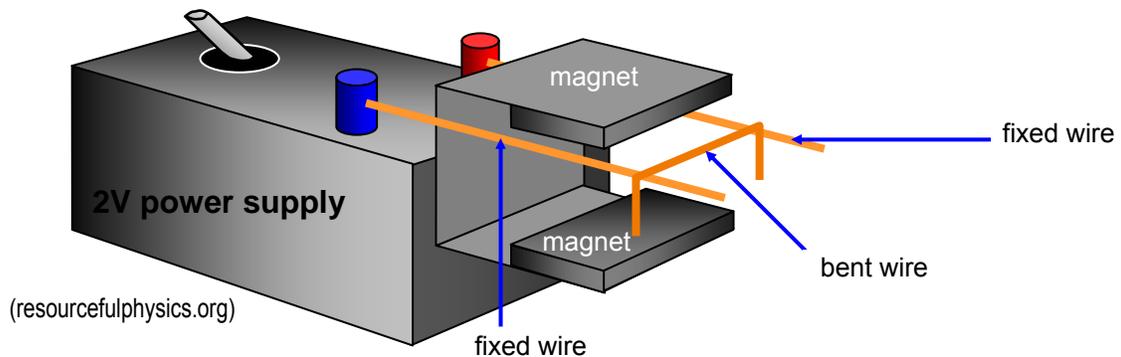


Episode 412: The force on a conductor in a magnetic field

Having reminded your students that magnetic fields can be found near permanent magnets and in the presence of an electric current, the next step is to show how the 'field' can be quantified. Again, students should know that a conductor carrying a current in a magnetic field will experience a force and will probably remember that Fleming's Left Hand Rule can be used to find the direction of that force.



Summary

Demonstrations: Leading to $F = BIL$. (15 minutes)

Discussion: Factors affecting the force. (15 minutes)

Discussion: Formal definitions. (20 minutes)

Student questions: BIL force calculations. (20 minutes)

Demonstrations:

Leading to $F = BIL$

Several quick experimental reminders are possible.

Tap 412-1: Forces on currents

TAP 412-2: An electromagnetic force

These lead on to a further experiment in which the relationship $F=BIL$ can be established.

TAP 412-3: Force on a current-carrying wire

Discussion:

Factors affecting the force

The experiments above lead to the conclusion that the force **F** on the conductor is proportional to the length of wire in the field, **L**, the current **I** and the 'strength' of the field, represented by the flux density **B**. (There is also an 'angle factor' to consider, but we will leave this aside for now.)

Combining these we get **F = BIL**

(It can help students to refer to this force as the '**BIL** force'.)

Students will probably know that electric and gravitational fields are defined as the force on unit charge or mass. So by comparison, **B = F/IL**, and this gives a way of defining the 'magnetic field strength'. Physicists refer to this as the **B**-field or magnetic flux density which has units of

$\text{N A}^{-1} \text{m}^{-1}$ or tesla (T).

A field of 1T is a very strong field. The field between the poles of the Magnadur magnets that are used in the above experiment is about 3×10^{-2} T while the Earth's magnetic field is about 10^{-5} T.

If your specification requires, you will need to develop the 'angle factor' seen in the experiment into the mathematical formula: **F = BIL sin θ** .

For the mathematically inclined, it can be shown that the effective length of the wire in the field (i.e. that which is at right angles) is $L \sin \theta$. If students find this difficult, then it can be argued that the maximum force occurs when field and current are at right angles, $\theta = 90^\circ$ ($\sin \theta = 1$), and that this falls to zero when field and current are parallel, $\theta = 0^\circ$ ($\sin \theta = 0$).

Discussion:

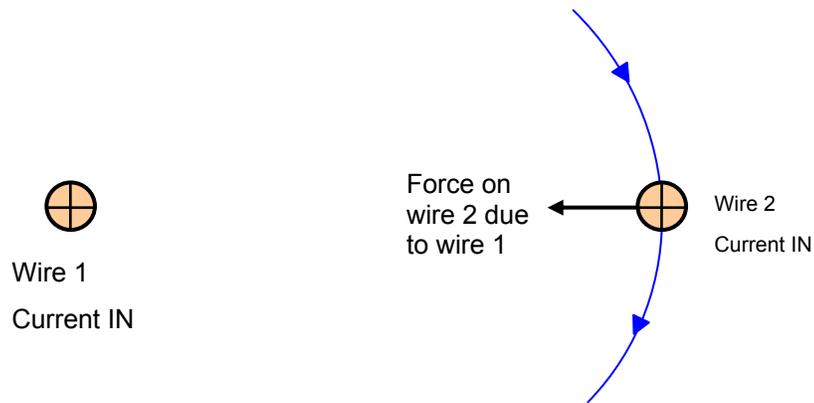
Formal definitions

Some specifications require a formal definition of magnetic flux density and/or the tesla.

The strength of a magnetic field or magnetic flux density **B** can be measured by the force per unit current per unit length acting on a current-carrying conductor placed perpendicular to the lines of a uniform magnetic field.

The SI unit of magnetic flux density **B** is the tesla (T), equal to $1 \text{ N A}^{-1} \text{m}^{-1}$. This is the magnetic flux density if a wire of length 1m carrying a current of 1 A as a force of 1 N exerted on it in a direction perpendicular to both the flux and the current.

Study of the force between parallel conductors leading to the definition of the ampere may be required. Students may already have seen the effect in your initial experiments but this may need to be repeated here. The effect can be explained by considering the effect of the field produced by one conductor on the other and then reversing the argument.



(The most common alternative approach relies upon field lines only and describes a 'catapult effect' from regions where the field lines are tightly packed into regions where the lines are more widely spaced.)

The force between parallel conductors forms the basis of the definition of the unit of current, the ampere. A formal definition is not usually required but students should realise that in a current balance (such as was used above) measurement of force and length can be traced back to fundamental SI units (kg, m, s) leaving the current as the only 'unknown'.

Some students are likely to be interested in the formal definition which is "that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible cross-section, and placed 1m apart in a vacuum, would produce a force of 2×10^{-7} Newton per metre of length".

Student questions:

BIL force calculations

TAP 412-4: Forces on currents in magnetic fields

Although the electric motor could be discussed here, it is probably better to leave this until after electromagnetic induction has been covered so that the back emf can be included.

Tap 412-1: Forces on currents

These activities allow qualitative investigation of the forces on currents.

You will need:

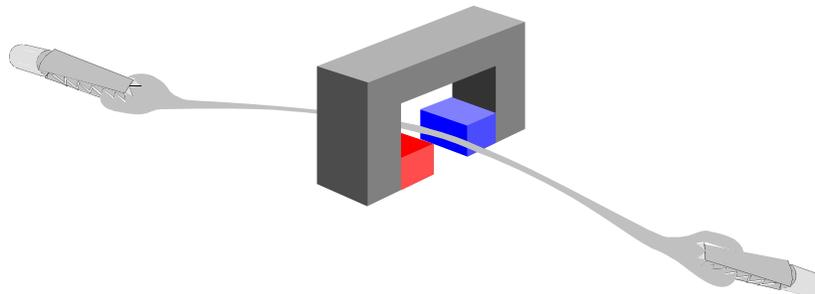
- ✓ aluminium foil
- ✓ scissors
- ✓ large horseshoe magnet
- ✓ two clip component holders
- ✓ four long 4 mm leads
- ✓ power supply, 0–12 V plus rheostat (4 A) (or Westminster Very Low Voltage power supply)

| | |
|---|---|
|  | Safety If the current is too large then the foil will get hot and the forces will be too large and tear the foil. When using two strips of foil be aware that if they touch sparking may occur. Care is needed, and the pd must remain modest |
|---|---|

You will be making some general observations about forces on currents. As force is a vector, you will be interested to see how large the force is and in what direction it acts. Systematic observations will be essential.

The force on a current in a magnetic field

The current passes through a strip of aluminium foil. The movement of this foil shows the size and direction of the force. The foil is placed in the magnetic field of a large permanent magnet and connected to the power supply.



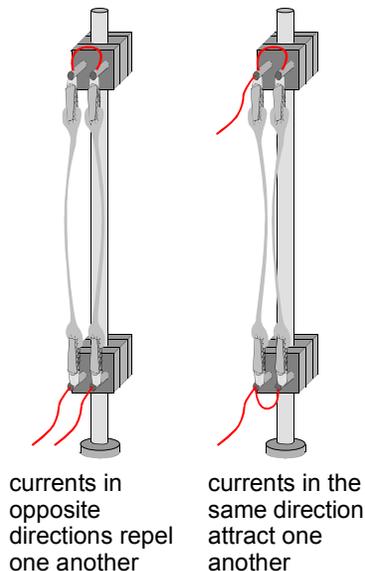
1. Set the power supply to 1 V, switch on, and observe what happens to the foil.
2. Increase the power supply to 2 V. What happens?
3. Now reverse the connection to the power supply. What happens?
4. Finally, reverse the magnet. What happens to the foil?

What you have seen

1. The size of the force on a current in a magnetic field depends on the size of the current.
2. The direction of the force depends on the direction of the current and the direction of the magnetic field.
3. The direction of the force is at right angles to the current and to the magnetic field. (Fleming's left-hand rule.)
4. You have not seen that the size of the force also depends on the size of the magnetic field. But you can show that the magnetic field is essential to the force by removing the magnet!

The force between two currents

Set up two strips of foil as shown in the diagram and connect the power supply.



1. First, arrange the connections so the current is passing down both strips of foil. Set the power supply to 1 V. Switch on and describe what happens.
2. Increase the power supply to 2 V. What happens now?
3. Arrange the connections so that the current is passing up both strips of foil. What happens?
4. Finally arrange the connections so the current is passing up one foil and down the other. What is the result?

What you have seen

1. The size of the force between currents depends on the size of the current.
2. The direction of the force depends on the current directions. If they are in the same direction they attract. If they are in opposite directions, they repel. Like currents attract, unlike currents repel.

Practical advice

The main point is that currents experience forces in a magnetic field, which can be due to either a permanent magnet or another current. The size of the force depends on the sizes of the current and the magnetic field. Depending on your circumstances this may well be revision of pre-16 level work. You might like to extend the tasks. How does the force between currents depend on distance? What happens when alternating current is put through the foil in the field? What has this got to do with a possible loudspeaker or microphone?



Safety

If the current is too large then the foil will get hot and the forces will be too large and tear the foil. When using two strips of foil be aware that if they touch sparking may occur. Care is needed, and the pd must remain modest

Technician's note:

Westminster power supplies are ideal for the first two experiments. If these are not available it may be necessary to put a high-current rheostat in the circuit to prevent the cut-out operating.

Alternative approaches

The option is to select one activity and to demonstrate it, with class discussion, as a revision exercise.

External reference

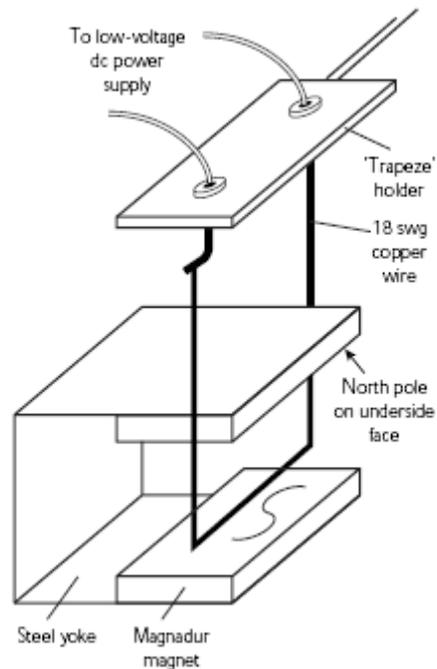
This activity is taken from Advancing Physics chapter 15, 290E

TAP 412-2: An electromagnetic force

Use the arrangement shown below to explore the force on a current-carrying conductor when it is inside a magnetic field.

You will need:

- ✓ trapeze holder
- ✓ 18 swg bare copper bent to make trapeze
- ✓ Magnadur magnets (2) (as from Westminster Electromagnetic kit)
- ✓ steel yoke
- ✓ low-voltage dc supply (e.g. Westminster pattern)
- ✓ leads



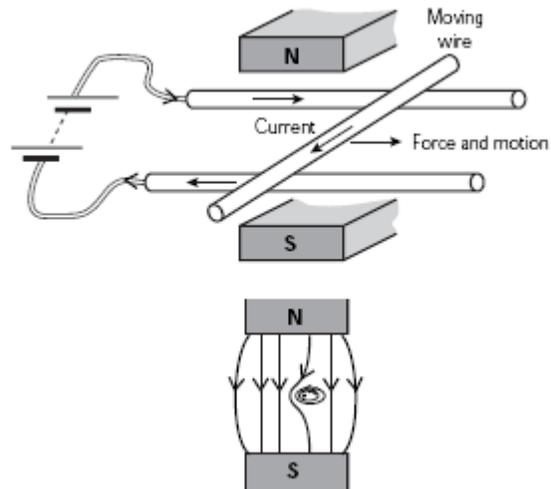
Identify the north and south poles of your magnet.

Switch on the current to the 'trapeze' wire and note how the 'trapeze' behaves.

- Repeat with the magnetic field alone reversed.
- Repeat with the electric current alone reversed.
- Repeat with both the magnetic field and the electric current reversed.

Practical advice

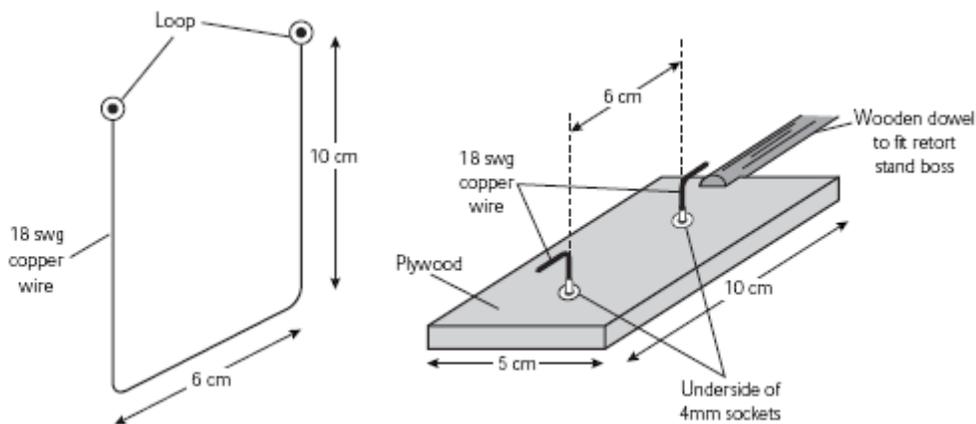
When considering the direction of the force, some students might appreciate an explanation in terms of a 'catapult field' (below) in which the interaction of the field of the permanent magnet with that of the current-carrying wire gives rise to an attraction on one side of the wire and a repulsion on the other. The resulting field-line pattern can be likened to a catapult – the wire is 'kicked' as it would be if the lines were pieces of stretched elastic. The direction is as described by Fleming's left-hand rule.



The term 'magnetic flux density' will probably need some discussion, as it has connotations of flow.

Technician's note

Trapeze and trapeze holder construction details:



Requirements:

- ✓ plywood 10 cm x 5 cm (DIY store),
- ✓ 18 swg bare copper wire (Philip Harris Y94804/7),

- ✓ 4 mm sockets white (2) (JPR 705-210),
- ✓ dowel rod 15 cm (DIY store),
- ✓ retort stand and boss

External reference

This activity is taken from Salters Horners Advanced Physics, section TRA, activity 9

TAP 412-3: Force on a current-carrying wire

Here you measure the force on a current-carrying wire placed in a uniform magnetic field. This is the origin of the 'motor force'.

You will need:

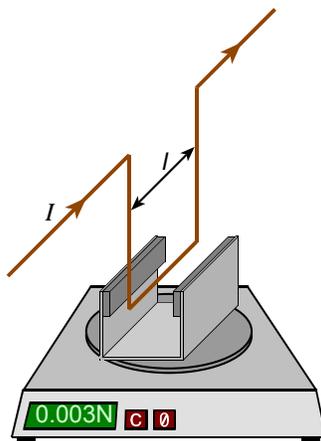
- ✓ two mild steel yokes
- ✓ four slab magnets
- ✓ rheostat rated at least at 4 A, 6 A is better
- ✓ digital multimeter, used as an ammeter
- ✓ power supply, 0–12 V
- ✓ leads, 4 mm; three are required, two need to be at least 0.5 m long
- ✓ mass balance, electronic, 0–2 kg, ± 10 mg
- ✓ two retort stands with boss and clamp
- ✓ metre rule (used for holding wire in position)
- ✓ shaped bare wire, six samples



Safety

Large currents will heat the wires and care should be taken when handling them

What to do



The 'top pan balance' is a straightforward way of investigating the factors affecting the force on a wire carrying a current in a magnetic field. The 'wire' is clamped so that it remains stationary and the balance measures the 'change in weight' of the Magnadur magnets placed on its pan.

The balance will probably be calibrated in grams and milligrams. One gram is equivalent to a weight of 0.0098 N (0.01 N will probably be accurate enough). The balance should also be capable of being 'tared' or zeroed with the magnets in place, so that when there is no force the reading is zero.

1. A single straight wire, connected to a dc power supply in series with an ammeter and rheostat, is taped to a metre rule and clamped horizontally at right angles to the field. Vary the current gradually up to about 5 or 6 A. (This will depend on your power supply.)
2. How does the force on the wire (or the change in weight of the magnets) depend on the current in the wire?
3. Plot a graph of force against the current in the wire.
4. To investigate how the length of wire in the field affects the force, the single wire can be replaced by wires of different length. These wires have been shaped so that a short horizontal section can be placed in the field. Investigate how changing the length affects the force on the wire. Make sure that the current is the same each time.
5. There are forces acting on the vertical sections of the wire. Why don't these affect the reading on the balance?
6. Plot a graph of force against the length of the wire in the field.

If magnets of different strength are available, you should be able to determine how the force depends on the magnetic field strength, although a quantitative relationship may be very difficult to establish.

Outcomes

1. The two graphs should show that the force is proportional both to the current in the wire and to the length of wire in the field.
2. The force is also proportional to the magnetic field strength, although without measurement you may not be convinced.

Practical advice

Several lengths of shaped bare wire are required, about 0.56 mm diameter or thicker. Bare or tinned copper will do. All apart from one should be shaped so that a known length can be inserted into the field between the magnets ranging from 10 mm up to 60 mm. The ends of these wires could be fitted with 4 mm sockets for ease of use.

This is a slick and easy way to do an experiment that has appeared in different forms, primarily as a current balance, which we want to avoid. We do not think the students' or teacher's time is rewarded by the effort that is often necessary to get results. The top pan balance provides a simple way of measuring force.

It is well worth preparing a set of wires beforehand, although, if time allows, teachers may wish their students to make them. This will mean that suitable tools, good pliers and possibly a small vice, will need to be available as well as the apparatus listed.

Investigating length and current are straightforward and should not cause too many problems. It would be wise to check what range of currents will provide suitable results.

Changing the magnetic field will be less satisfying, unless you have a wide range of suitable magnets with different, known strengths.

There may be a problem with a 100 Hz ripple affecting either the ammeter or the balance; if this is the case a good smoothing unit should be used.

Alternative approaches

We strongly recommend this method: it allows us to concentrate on the relevant physics and avoids the practical intricacies that other methods introduce. This method also gives good accuracy and reliability.

| | |
|---|--|
|  | <p style="text-align: center;">Safety</p> <p>Large currents will heat the wires and care should be taken when handling them</p> |
|---|--|

External reference

This activity is taken from Advancing Physics chapter 15, 300E

TAP 412- 4: Forces on currents in magnetic fields

$$\mu_0 = 4\pi \times 10^{-7} \text{ N A}^{-2} \text{ and } g = 9.81 \text{ m s}^{-2}$$

- (a) Write down the formula for the force on a straight wire of length L placed at right angles to a magnetic field of flux density B .

(b) A pivot arrangement using a wire of length 15 cm is placed in a magnetic field. When a current of 4 A is passed through the wire it is found that a mass of 2.0 g must be hung from the wire to return it to a horizontal position. $g = 9.81 \text{ m s}^{-2}$
Calculate the magnetic flux density of the magnet.
- A horizontal wire 6 cm long and mass 1.5 g is placed at right angles to a magnetic field of flux density 0.5 T. Calculate the current that must be passed through the wire so that it is self-supporting
- A wire of length 0.5 m carrying a current of 2 A is placed at right angles to a magnetic field of 0.2 T. Calculate the force on the wire.
- What is the force between two wires placed 0.2 m apart in a vacuum each carrying a current of 5 A.

Questions 5 and 6:

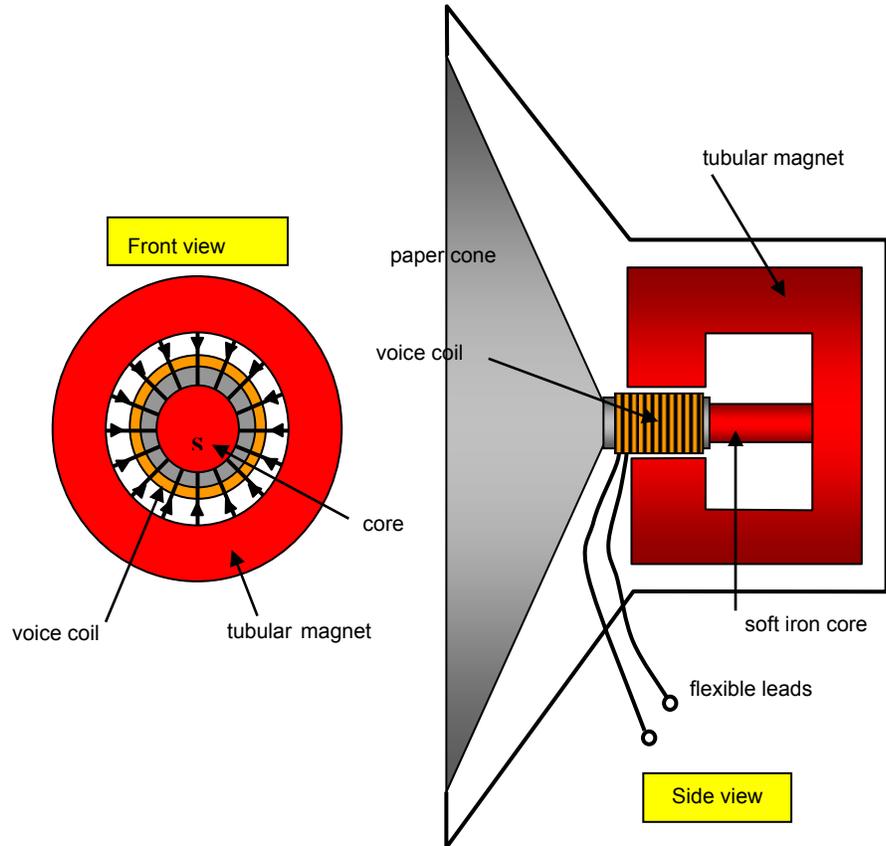
A magnetic field exerts a force of 0.25 N on an 8.0 cm length of wire carrying a current of 3.0 A at right angles to the field.

- Calculate the force the same field would exert on a wire 20 cm long carrying the same current.

6. Calculate the force the same field would exert on three insulated wires, each 20 cm long and held together parallel to each other, each carrying a current of 3.0 A in the same direction.

7. (a) Using the ideas of forces on currents in magnetic fields and the diagram explain the operation of a moving coil loudspeaker.

(b) Calculate the force on the voice coil of a loudspeaker that has a diameter of 2 cm, a 100 turns and carries a current of 20 mA if the field strength of the tubular magnet is 0.1 T.



Answers and worked solutions

1(a) $F = BIL$

(b) $B = F/IL$

$$B = [2.0 \times 10^{-3} \times 9.81] / [4 \times 0.15] = 0.0327 \text{ T (Remember to change grams to kg and centimetres to metres)}$$

2 Weight of mass required = BIL

$$\text{Therefore: } 1.5 \times 10^{-3} \times 9.81 = 0.5 \times I \times 0.06 \text{ giving } I = 0.49 \text{ A}$$

3 $F = BIL = 0.2 \times 2 \times 0.5 = 0.2 \text{ N}$

4 $F = \mu_0 I^2 L / 2\pi r = 4\pi \times 10^{-7} \times 25 \times \frac{1}{2} \pi \times 0.2 = 2.5 \times 10^{-5} \text{ N}$

5 For 20 cm length

$$F = 0.25 \text{ N} \times \frac{20 \text{ cm}}{8 \text{ cm}} = 0.625 \text{ N.}$$

6. If each wire carries 3.0 A this is the same as effective current of 9.0 A, so force $F = 3 \times 0.625 = 1.9 \text{ N}$.

7(a) The wire of voice coil is at right angles to the field. When a varying current from an amplifier current flows in the coil it experiences a force that moves the coil backwards and forwards along the soft iron core.

(b) $F = nBIL = 100 \times 0.1 \times 20 \times 10^{-3} \times \pi \times 2 \times 10^{-2} = 0.013 \text{ N}$

(Note: cm to m and mA to A)

External references

Questions 1-4 and 7 are taken from Resourceful Physics Questions 5 and 6 are from Advancing Physics chapter 15, 250S