4.5 Magnetic forces and electromagnetic induction

Name: _____ Class: _____ Date: _____ **Total: 28 marks**

KEY WORDS Magnetic flux density • Fleming's left-hand rule • Magnetic flux • Flux linkage • Electromagnetic induction • Faraday's law • Lenz's law

Objective

Develop the methods for magnetic forces and electromagnetic induction before the curated WPH14 questions. Use $g = 9.81$ m s^{-2} where needed. These are original training questions, not copied past-paper questions.

1 Key knowledge and worked examples

■ Directions, flux and force

Magnetic flux density B describes the field's force effect. For a straight wire of length l in a uniform field:

$$F = BIl\sin\theta$$

Here θ is between conventional current and field. Only the length inside the field counts. For one charged particle:

$$F = |q|vB\sin\theta$$

Use **Fleming's left-hand rule** : first finger along field, second along conventional current, thumb gives force. A positive charge moves with conventional current. Reverse the result for an electron's motion. Dot symbols mean out of the page; crosses mean into it.

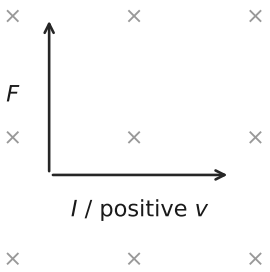
Magnetic force is perpendicular to velocity, so it changes direction without doing work. It cannot, alone, increase the particle's kinetic energy. If **v** is parallel to **B**, magnetic force is zero.

Magnetic flux through a flat area in a uniform field is:

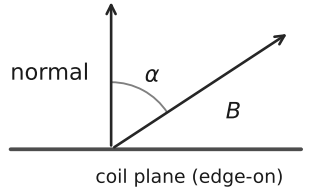
$$\phi = BA\cos\alpha$$

Here α is between field and the area's normal, not the plane itself. The unit is the weber. **Flux linkage** is $N\phi$ when the same flux links each of N turns.

Field into page; force upwards



Flux uses angle to area normal



$\phi = BA\cos\alpha$

Worked example. A coil has 40 turns and radius 0.015 m. A uniform 0.020 T field is perpendicular to its plane. Find flux linkage.

$$A = \pi r^2 = \pi(0.015\text{ m})^2 = 7.07\times10^{-4}\text{ m}^2$$

$$N\phi = NBA = 40\times0.020\text{ T}\times7.07\times10^{-4}\text{ m}^2 = 5.65\times10^{-4}\text{ Wb}$$

Use radius, not diameter, and multiply by turns only when finding linkage. A balance under magnets measures the opposite reaction to a force on a separately supported wire. Convert a balance reading change Δm to force Δmg, not Δm itself.

■ A changing linkage induces an e.m.f.

Electromagnetic induction occurs when flux linkage changes. Relative movement of a coil and magnet can cause it. Rotating the coil or changing current in another linked coil can also cause it. A stationary coil in a constant field has no induced e.m.f. merely because flux is present.

Faraday's law relates e.m.f. magnitude to rate of flux-linkage change. **Lenz's law** gives the opposing direction:

$$\mathcal{E} = -\frac{\mathrm{d}(N\phi)}{\mathrm{d}t} \qquad |\mathcal{E}_{\text{average}}| = \frac{|\Delta(N\phi)|}{\Delta t}$$

Induced current, if the circuit is closed, produces a magnetic effect opposing the change that caused it. It does not always oppose the existing field: when that field decreases, the induced effect helps maintain it. This opposition is consistent with energy conservation.

Worked example. Flux through each of 50 turns decreases from 6.0×10^{-5} to 2.0×10^{-5} Wb in 0.020 s. Find average induced e.m.f. magnitude.

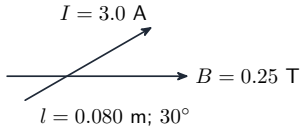
$$|\mathcal{E}| = \frac{N|\phi_2 - \phi_1|}{\Delta t} = \frac{50 \times |2.0 - 6.0| \times 10^{-5}\ \text{Wb}}{0.020\ \text{s}} = 0.10\ \text{V}$$

Faster movement, stronger field, more turns or larger linked area can increase the rate. Explain which quantity actually changes. In a magnetic-strip reader, reversing pole orientation reverses signal direction. For a straight boundary swept across an area of width L at speed v, $\Delta A/\Delta t = Lv$, giving $|\mathcal{E}| = NBLv$ under that uniform-field model.

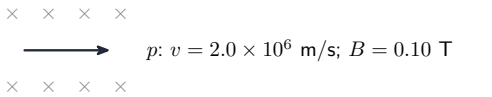
Wireless charging uses alternating current in one coil, producing changing magnetic field and changing linkage in the phone coil. That induces an e.m.f. The receiving circuit can then charge the battery. Equal turn counts do not ensure equal voltages: some flux may fail to link the other coil, especially with separation or without an iron core.

2 Practice

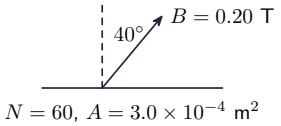
2.1 A wire carrying 3.0 A has 0.080 m in a 0.25 T field at 30° to the field. Calculate force. Explain what happens if wire and field become parallel. [3]



2.2 A proton travels rightwards at 2.0×10^6 m s^{-1} in a 0.10 T field into the page. Find force magnitude and direction. Explain the change for an electron with the same velocity, and whether magnetic force alone changes speed. [5]

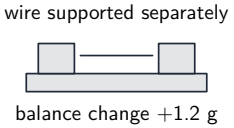


2.3 A 60-turn coil has area 3.0×10^{-4} m^2. A 0.20 T field makes 40° with its normal. Find flux linkage. Explain why using the angle to the plane would give the wrong result in the cosine formula. [3]

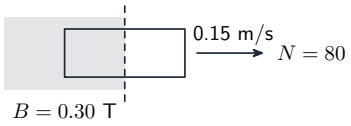


3 Exam-style questions

3.1 Magnets rest on a balance; a wire is supported independently between them. The balance reading increases by 1.2 g when a 4.0 A current flows through 0.060 m of wire perpendicular to the field. Find magnetic flux density and the force direction on the wire. Explain the error in setting force equal to 1.2. [5]



3.2 A rectangular 80-turn coil is pulled at 0.15 m s^{-1} out of a uniform 0.30 T field normal to its plane. Its edge parallel to the straight field boundary is 0.040 m long. Find induced e.m.f. while the boundary crosses the coil and explain its direction using Lenz's law. State what happens once the coil is wholly outside. [5]



3.3 Explain wireless charging from the current in the supply coil to the induced e.m.f. in the receiving coil. Explain why d.c. after switching settles gives no sustained induction, and why equal turn counts do not guarantee equal voltages. During one interval the flux through each of 120 receiving turns falls from 5.0×10^{-5} to 1.0×10^{-5} Wb in 0.0080 s; calculate average induced e.m.f. magnitude. [7]

supply coil

receiver

Solutions

Original-task marks: M1 = method, A1 = accuracy, B1 = stated reasoning point.

2.1 Use the angle between wire current and field.

$$F = BIl\sin\theta = 0.25\ \text{T} \times 3.0\ \text{A} \times 0.080\ \text{m} \times \sin 30^\circ = 0.030\ \text{N}$$

Magnitude. Parallel gives $\sin 0 = 0$, hence zero force.

2.2 Perpendicular particle force.

$$F = qvB = 1.60 \times 10^{-19}\ \text{C} \times 2.0 \times 10^{6}\ \text{m s}^{-1} \times 0.10\ \text{T} = 3.20 \times 10^{-14}\ \text{N}$$

Magnitude. Proton force is upwards. Electron force is downwards with equal magnitude. Force is perpendicular to instantaneous velocity, doing no work and leaving speed unchanged.

2.3 Multiply flux per turn by turn count.

$$N\phi = NBA\cos\alpha = 60 \times 0.20\ \text{T} \times 3.0 \times 10^{-4}\ \text{m}^2 \times \cos 40^\circ = 2.76 \times 10^{-3}\ \text{Wb}$$

Linkage. Cosine takes the angle to the normal; the angle to the plane is its complement and would require sine.

3.1 Convert reading change to weight change.

$$F = \Delta mg = 1.2 \times 10^{-3}\ \text{kg} \times 9.81\ \text{m s}^{-2} = 1.18 \times 10^{-2}\ \text{N}$$

Use equal and opposite wire/magnet forces with $F = BIl$.

$$B = \frac{F}{Il} = \frac{1.1772 \times 10^{-2}\ \text{N}}{4.0\ \text{A} \times 0.060\ \text{m}} = 0.0491\ \text{T}$$

Field. Increased balance reading means force on magnets downwards, so force on wire upwards. The balance change is a mass in grams; 1.2 alone is neither converted mass nor force in newtons.

3.2 Area leaves at rate Lv, so linkage changes at $NBLv$.

$$|\mathcal{E}| = NBLv = 80 \times 0.30\ \text{T} \times 0.040\ \text{m} \times 0.15\ \text{m s}^{-1} = 0.144\ \text{V}$$

Magnitude. Linked external flux decreases; induced current, if the circuit is closed, produces field in the original field direction to oppose that decrease. Outside, linkage no longer changes, so induced e.m.f. is zero.

3.3 Alternating current produces changing magnetic field in the transmitting coil. Changing flux links the receiving coil and induces e.m.f. by Faraday's law. Steady d.c. gives constant linkage after the switching transient, so no sustained e.m.f.. Some flux misses the receiver because of separation/alignment or lack of a shared core; equal turns do not imply equal linkage rates. Use change in linkage per time, not flux alone.

$$|\mathcal{E}| = \frac{N|\phi_2 - \phi_1|}{\Delta t} = \frac{120 \times |1.0 - 5.0| \times 10^{-5}\ \text{Wb}}{0.0080\ \text{s}} = 0.60\ \text{V}$$

Value. Lenz direction opposes the flux change, consistent with energy conservation rather than creating energy from nothing.