20.5 Electromagnetic induction

Name: ______________ Class: __________ Date: ____________ **Total: 31 marks**

KEY WORDS flux linkage 磁链 • lenz's law 楞次定律 • faraday's law 法拉第定律 • magnetic field 磁场 • magnetic flux 磁通量

Objective

Build the skills to answer exam questions on **electromagnetic induction**.

You must be able to:

- use **magnetic flux** $\Phi = BA$ and **flux linkage** $N\Phi$
- apply **Faraday's** and **Lenz's** laws

1 Worked examples

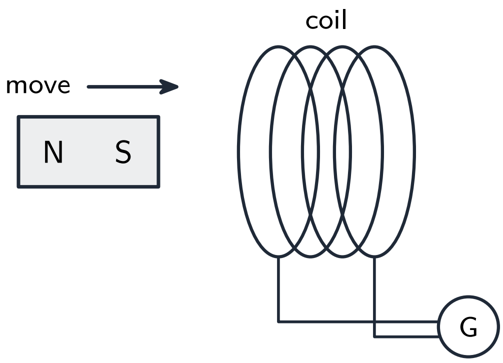
Study these first. Each one shows the method for a question type used later — follow the steps and you can do the Practice and Exam-style questions yourself.

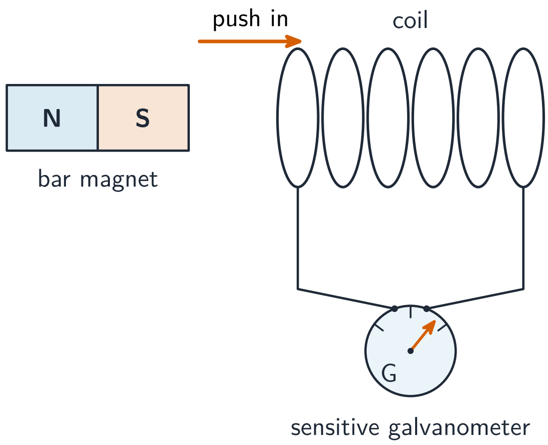
Flux and flux linkage

$$\Phi = BA \quad \text{(weber, Wb)}, \qquad \text{flux linkage} = N\Phi = NBA.$$

Induction

A **changing** flux linkage induces an e.m.f.:





Inducing an EMF by changing flux

- **Faraday's law:** the induced e.m.f. $\propto$ the **rate of change of flux linkage**: $E = \dfrac{\Delta(N\Phi)}{\Delta t}$.
- **Lenz's law:** the induced e.m.f. **opposes the change** producing it (from conservation of energy).

Worked example. $N = 200$ turns, $A = 0.010\ \text{m}^2$, B changes from 0.10 to 0.30 T in 0.50 s: $E = N\dfrac{A\Delta B}{\Delta t} = 200 \times \dfrac{0.010 \times 0.20}{0.50} = 0.80$ V.

■ A moving conductor (motional e.m.f.)

A straight conductor of length L moving at speed v **perpendicular** to a field B **cuts** field lines, sweeping out area at the rate Lv. So flux is cut at the rate $B\,Lv$, inducing:

$$E = BLv.$$

The flux **cut** in a time Δt is then $\Phi = E\,\Delta t$ (since $E = \Delta\Phi/\Delta t$).

Worked example. A rod of length 0.30 m moves at 5.0 m s^{-1} across a 0.40 T field: $E = BLv = 0.40 \times 0.30 \times 5.0 = 0.60$ V.

2 Practice

Now apply the methods above.

2.1 Define **magnetic flux**. [1]

2.2 Write $\Phi = BA$ and the **flux linkage** for a coil of N turns. [2]

2.3 State **Faraday's law**. [1]

2.4 State **Lenz's law**. [1]

3 Exam-style questions

3.1 The induced e.m.f. in a coil is proportional to the: [1]

- **A** magnetic flux
- **B** rate of change of flux linkage
- **C** area of the coil
- **D** current in the coil

3.2 A coil of 200 turns and area 0.010 m^2 is in a field that changes from 0.10 T to 0.30 T in 0.50 s. Calculate the induced **e.m.f.** [3]

3.3 State **Lenz's law** and explain how it follows from **conservation of energy**. [3]

3.4 Describe an experiment to show that a **changing magnetic flux** induces an e.m.f. [2]

3.5 An aircraft of wingspan 30 m flies horizontally at 250 m s^{-1} through the vertical component of the Earth's magnetic field, $B = 4.5 \times 10^{-5}$ T.

(a) Calculate the e.m.f. induced between the wingtips. [2]

(b) Calculate the magnetic flux **cut** by the wings in 15 s. [2]

3.6 An aircraft with a wingspan of 34 m flies horizontally through the Earth's magnetic field. The **vertical** component of the field is 4.4×10^{-5} T. An e.m.f. of 0.55 V is induced between the wingtips P and Q.

(a) **State** Faraday's law of electromagnetic induction. [2]

(b) **Calculate** the magnetic flux cut by the wings in 15 s. Give a **unit** with your answer. [2]

(c) **Determine** the area swept by the wings in that time. [2]

(d) Hence **determine** the speed of the aircraft. [2]

(e) Use **Lenz's law** to explain how you would decide which wingtip is at the higher potential. [3]

(f) **State and explain** what happens to the induced e.m.f. if the aircraft flies at the same speed directly over the magnetic **equator**, where the field is horizontal. [2]

Solutions

2.1 The product of the **magnetic flux density** and the **area perpendicular** to it ($\Phi = BA$).

2.2 $\Phi = BA$; flux linkage $= N\Phi = NBA$.

2.3 The induced e.m.f. is **proportional to the rate of change of flux linkage**.

2.4 The induced e.m.f. (or current) is in a direction that **opposes the change** that produces it.

3.1 **B** — rate of change of flux linkage.

3.2 $E = N\dfrac{\Delta\Phi}{\Delta t} = N\dfrac{A\Delta B}{\Delta t} = 200 \times \dfrac{0.010 \times (0.30 - 0.10)}{0.50} = 0.80$ V.

3.3 The induced e.m.f./current **opposes the change** producing it; if it aided the change, the current would grow without an energy source — impossible; so opposing it conserves energy (work must be done against the force).

3.4 Move a **magnet into a coil** connected to a galvanometer; the galvanometer **deflects** while the flux changes (and reads zero when the magnet is still).

3.5 (a) $E = BLv = (4.5 \times 10^{-5})(30)(250) = 0.34$ V.

3.5 (b) $\Phi = E\,\Delta t = 0.34 \times 15 = 5.1$ Wb.

3.6 (a) The magnitude of the induced e.m.f. is **proportional to the rate of change of magnetic flux linkage**; the flux linkage is the flux through the circuit multiplied by the number of turns.
(b) $\Phi = \varepsilon t = 0.55 \times 15 = 8.25$ Wb — the weber, equal to a volt second.
(c) $\Phi = BA$, so $A = \dfrac{\Phi}{B} = \dfrac{8.25}{4.4 \times 10^{-5}} = 1.9 \times 10^{5}\ \text{m}^2$.
(d) The wings sweep an area $A =$ (span) $\times$ (distance), so distance $= \dfrac{1.875 \times 10^{5}}{34} = 5.5 \times 10^{3}$ m; $v = \dfrac{5515}{15} = 3.7 \times 10^{2}\ \text{m s}^{-1}$.
(e) The induced e.m.f. drives a current in the direction that **opposes the change producing it**. Imagine completing the circuit: the induced current must create a magnetic field opposing the change in flux through it, and the wingtip that the conventional current flows **towards** inside the wing is the one at the higher potential — apply the right-hand rule to the field direction and the aircraft's velocity to decide which.
(f) The e.m.f. becomes **zero**. Only the component of the field **perpendicular** to the swept area cuts through it, and a horizontal field is parallel to the area a horizontally-flying wing sweeps out, so no flux is cut.