Magnetic flux and electromagnetic induction solutions

Electromagnetism 4 A warehouse docking sensor

Matching answers and examiner-style commentary

OCR A H556 | A-level physics | Module 6 | 42 marks

Specification points covered

6.3.3(a–b) Magnetic flux, flux linkage and the weber.

6.3.3(c), 6.3.3(d)(i–ii) Faraday's and Lenz's laws; e.m.f. and search-coil investigations.

Graph gradients and pulse areas are used without requiring calculus.

Use $\Phi = BA\cos\theta$, $\lambda = N\Phi$ and $\varepsilon = -\Delta\lambda/\Delta t$. The angle θ is between B and the area normal.

1 Read the pickup sensor

A permanent magnet on a warehouse shuttle approaches a fixed pickup coil, pauses before it, then withdraws along the same axis. Its north pole faces the coil during this movement.

The coil has N = 250 turns and area A = 6.00 cm^2 per turn. Initially the field is normal to its plane. Treat B as uniform over each turn. The sensor measures open-circuit e.m.f.; appreciable current flows only in a separately stated closed-loop test.

For signed graph calculations, positive flux is along the stated rightward normal and the e.m.f. reference is defined by $\varepsilon = -\Delta\lambda/\Delta t$. No terminal polarity is inferred from an unmarked winding.

The positive area normal points right along the magnet–coil axis.

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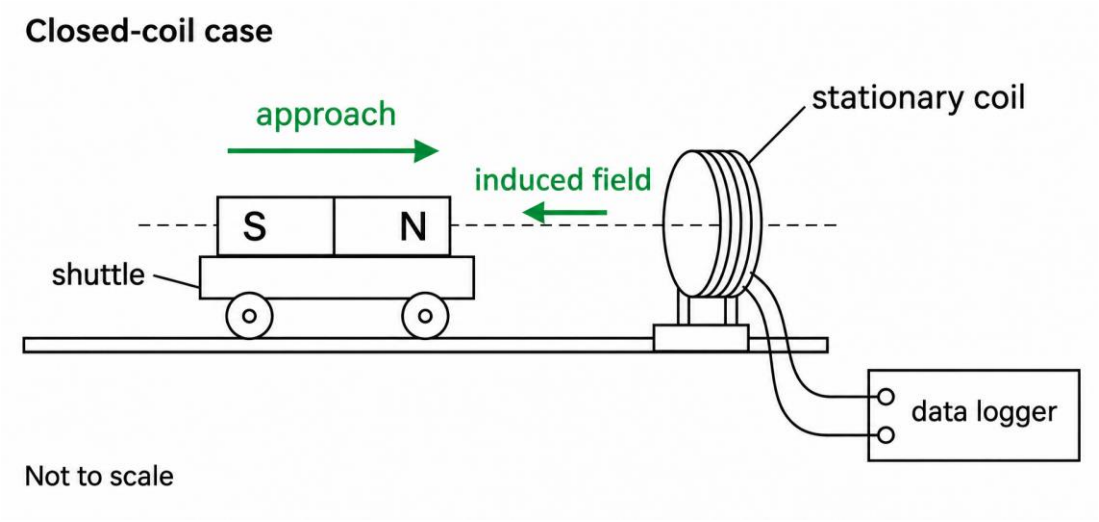


Figure 1 Lenz's-law field for the separately stated closed-coil approach case

1(a) Distinguish magnetic flux density B, flux Φ through one turn, and flux linkage λ for this coil.
[2 marks]

B describes the magnetic field and is measured in tesla. For a uniform field, single-turn flux is $\Phi = BA\cos\theta$, measured in weber.

Flux linkage accounts for all N turns: $\lambda = N\Phi$. For N dimensionless, its SI unit is also Wb; "Wb turns" is often used to make the distinction clear.

Marking guidance 1: B distinguished from single-turn flux. 1: linkage is N times single-turn flux.

1(b) If the coil's plane is perpendicular to the field, what is θ in $\Phi = BA\cos\theta$? State the SI unit of flux.
[1 mark]

The area normal is then parallel to B, so $\theta = 0°$. The flux unit is the weber, Wb.

Marking guidance 1: 0° and weber/Wb.

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2 Calculate magnetic linkage

2(a) At B = 40.0 mT with θ = 0°, calculate the flux through one turn. **[2 marks]**

Area is an area conversion: 6.00 cm^2 = 6.00 × 10^{-4} m^2. B = 0.0400 T.

Φ = BA cos 0° = (0.0400)(6.00 × 10^{-4}) = 2.40 × 10^{-5} Wb.

Marking guidance 1: correct area conversion. 1: 2.40 × 10^{-5} Wb.

2(b) Calculate the corresponding flux linkage. **[1 mark]**

λ = NΦ = 250(2.40 × 10^{-5}) = 6.00 × 10^{-3} Wb.

Marking guidance 1: 6.00 × 10^{-3} Wb.

2(c) At the same B, the area normal is turned to 60.0° from the field. Calculate the new linkage. **[1 mark]**

λ = NBA cos 60.0° = (6.00 × 10^{-3})(0.500) = 3.00 × 10^{-3} Wb.

Marking guidance 1: 3.00 × 10^{-3} Wb.

2(d) A replacement coil has twice as many turns but half the area per turn. At the same field and angle, what happens to its flux linkage? **[1 mark]**

Linkage stays unchanged because the product NA stays unchanged. Single-turn flux halves, but twice as many turns link it.

Marking guidance 1: unchanged with product reasoning.

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3 Read a docking trace

For this prescribed docking motion, B along the positive normal varies linearly between successive readings. Use the actual table values for numerical work.

Table 1

t / ms	B along positive normal / mT
0	0
20	40.0
50	40.0
90	0

3(a) Using Table 1, sketch λ against time. Label the linkage values and the times at each change of gradient. **[2 marks]**

Multiply the supplied B values by NA = 250(6.00 × 10^{-4}) = 0.150 m^2.

Join (0 ms, 0), (20 ms, 0.00600 Wb), (50 ms, 0.00600 Wb) and (90 ms, 0) with straight lines.

The graph rises linearly, stays constant, then falls linearly. These idealised straight sections are supplied data, not a general field–distance law for a magnet.

Marking guidance 1: correct labelled linkage values and times. 1: appropriate connected shape.

3(b) Calculate the signed e.m.f. during each of the three time intervals. Sketch the corresponding e.m.f.–time graph in blank space. **[3 marks]**

Faraday's law uses the gradient of linkage, with the defined negative sign. Convert ms to s.

0–20 ms: ε = −(0.00600 − 0)/0.0200 = −0.300 V.

20–50 ms: linkage is constant, so ε = 0.

50–90 ms: ε = −(0 − 0.00600)/0.0400 = +0.150 V.

Draw horizontal levels at those values over the stated intervals. Ideal sharp changes are part of the model; real traces have rounded transitions.

Interval / ms	Linkage behaviour	ε / V
0–20	Linear: 0 to 0.00600 Wb	−0.300
20–50	Constant: 0.00600 Wb	0
50–90	Linear: 0.00600 to 0 Wb	+0.150

Marking guidance 1 each: correct signed e.m.f. and corresponding interval; include the zero section.

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3(c) Calculate the average e.m.f. from 0 to 50 ms. Explain why it differs from the largest e.m.f. magnitude during that interval. **[2 marks]**

Use the net linkage change over the entire chosen interval, including the pause.

$\varepsilon_{average} = -(0.00600 - 0)/0.0500 = -0.120$ V.

The largest magnitude is 0.300 V during approach. The average is smaller in magnitude because the 50 ms interval also includes 30 ms with zero e.m.f.

Marking guidance 1: −0.120 V. 1: pause/average-versus-peak explanation.

3(d) The same approach and withdrawal changes occur in half the time, with the pause also halved. State the effects on pulse heights, widths and area magnitudes. **[2 marks]**

The linkage change is unchanged but the rate doubles, so the e.m.f. magnitudes double. Each pulse lasts half as long.

Each area magnitude stays at 0.00600 V s because it represents the same magnitude of linkage change.

Marking guidance 1: doubled heights and halved widths. 1: unchanged areas linked to unchanged linkage changes.

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4 Explain the induced direction

4(a) For 4(a) and 4(b), close the coil through a resistor. Viewed from the approaching magnet towards the coil, state the induced current direction and explain using Lenz's law. **[2 marks]**

As the north pole approaches, the source field through the coil increases. The induced current produces a field opposing that increase.

The coil face towards the magnet acts as a north pole, opposing approach. Viewed from the magnet, its current is anticlockwise.

Marking guidance 1: anticlockwise for the specified view. 1: opposing increase/near face N with causal explanation.

4(b) State and explain the current direction from the same viewing side while the north pole withdraws. **[2 marks]**

The source flux through the coil decreases. The induced field acts to maintain it, opposing the decrease.

The near face is now S and attracts the withdrawing N pole. Viewed from the magnet, current is clockwise.

Marking guidance 1: clockwise. 1: opposing decrease/near face S with causal explanation.

4(c) During the pause, B is 40.0 mT but the measured e.m.f. is zero. Explain. **[1 mark]**

The linkage is non-zero but constant. Faraday's law depends on its rate of change, which is zero during the pause.

Marking guidance 1: constant linkage gives zero rate/e.m.f.

4(d) In the closed-loop test the total resistance is 12.0 Ω and inductance is negligible. Find the approach-current magnitude. Explain the source of the energy dissipated as heat when the shuttle is driven at its prescribed motion. **[2 marks]**

$I = |\varepsilon|/R = 0.300/12.0 = 0.0250$ A.

The magnetic interaction opposes the motion/change. The drive must do mechanical work to maintain the prescribed movement; that energy is transferred to electrical energy and then thermal energy in the resistance.

Marking guidance 1: 0.0250 A. 1: mechanical work against the opposing interaction supplies the heating.

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5 Use pulse areas and limits

5(a) Find the signed area under the approach e.m.f.–time pulse and the corresponding signed change in flux linkage. **[2 marks]**

The signed area is $\varepsilon\Delta t = (-0.300)(0.0200) = -0.00600$ V s.

Because $\varepsilon = -\Delta\lambda/\Delta t$, $\Delta\lambda$ is the negative of that area: +0.00600 Wb. The positive source linkage has increased.

Marking guidance 1: −0.00600 V s. 1: +0.00600 Wb with correct sign relation.

5(b) A separate 250-turn, 6.00 cm^2 search coil is turned from maximum flux to zero flux in a uniform field. The pulse area magnitude is 0.00590 V s. Infer the field magnitude. **[1 mark]**

For this complete 90° turn, $|\Delta\lambda| = NAB$.

$B = 0.00590/[250(6.00 \times 10^{-4})] = 0.03933$ T ≈ 39.3 mT.

Marking guidance 1: about 39.3 mT.

5(c) The docking sensor triggers only when $|\varepsilon| \geq 0.200$ V and its input accepts up to $|\varepsilon| = 1.00$ V. Choose a 250-turn or 400-turn coil so both approach and withdrawal trigger. Only N changes. Justify using both pulse magnitudes and the input limit. **[3 marks]**

With 250 turns, approach is 0.300 V but withdrawal is only 0.150 V, so withdrawal fails to trigger.

With 400 turns, magnitudes increase by 400/250 = 1.60: approach 0.480 V and withdrawal 0.240 V.

Choose 400 turns. Both magnitudes exceed 0.200 V and the larger, 0.480 V, is below 1.00 V.

Marking guidance 1: 250-turn failure identified. 1: correct 400-turn pulse values. 1: chosen coil checked against trigger and range limits.

5(d) Evaluate: “The signed pulse areas over the full docking cycle add to zero, so electromagnetic induction never occurred.” **[2 marks]**

Zero total signed area means zero net change in linkage between the initial and final states.

It does not mean the rate of change was zero throughout. Non-zero opposite-sign e.m.f. pulses occur during approach and withdrawal and cancel in the signed sum.

Marking guidance 1: zero area interpreted as zero net linkage change. 1: non-zero opposite pulses can cancel.

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6 Plan a search-coil measurement

6(a) A thin rectangular search coil will be used to measure an unknown uniform field. Explain how to determine its effective turn area and suggest one way to reduce area uncertainty. **[2 marks]**

Measure the mean length and width enclosed by the thin winding with a suitable ruler or calipers, then calculate A = length × width.

Use an appropriate resolution and repeated measurements at relevant positions to judge alignment/variation; narrow windings make the mean enclosed area better defined. The required positions depend on the coil, not a universal “three places” rule.

Marking guidance 1: suitable enclosed dimensions and area calculation. 1: relevant justified improvement.

6(b) Suggest a suitable instrument for recording the voltage pulse during a rapid 90° turn and explain one recording or processing control that matters. **[2 marks]**

Use a storage oscilloscope or a voltage logger with sufficient sampling rate and voltage/time resolution to capture the whole pulse.

For example, set an appropriate range and trigger, record the zero baseline before the turn and subtract an offset before calculating the area. Capture the complete pulse rather than only its peak.

Marking guidance 1: suitable time-resolved voltage measurement. 1: relevant recording/processing control with reason.

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6 Plan a search-coil measurement Extended response

6(c) Write a method to determine an unknown uniform magnetic field using a search coil of known N and measured A. The gap permits a full 90° turn while the coil remains in the uniform region. Explain the starting and final orientations, measurements, processing and evaluation. **[6 marks]**

Connect the search coil to a suitably ranged storage oscilloscope or voltage logger. Know N and measure the effective area A. Position the entire coil in the central uniform field, initially with its area normal parallel to B, so linkage is maximum.

Record a zero baseline, then turn the coil through 90° until its normal is perpendicular to B and linkage is zero. Record the complete induced voltage pulse, including its return to baseline. Ensure the turn stays within the uniform region.

Find the magnitude of the baseline-corrected voltage–time area, using the instrument or sufficiently fine geometric/trapezium processing. Convert the time scale to seconds. Faraday's law gives $|\Delta\lambda| = |\text{area}| = NAB$, so calculate $B = |\text{area}|/(NA)$.

Repeat complete turns between the same marked orientations and compare/average the results. Judge limitations from area measurement, angular alignment, pulse capture, baseline and field uniformity. A different turning speed changes pulse height and width but should not change the complete pulse area.

Assessing 6(c) Best-fit marking guidance

Level 3 (5–6): a workable measurement with correct orientations and full pulse capture AND a correct area-to-B calculation route and relevant justified evaluation The argument is clear, linked and scientifically sound.

Level 2 (3–4): a sound account of one strand with limited treatment of the other, or some relevant detail in both; links or evaluation are incomplete.

Level 1 (1–2): limited creditworthy method or analysis, presented as fragments with little connection. 0: no creditworthy response.

Use best fit, then the quality within the level. The exemplar is indicative, not a six-keyword checklist; accept other workable, justified approaches.

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