OCR
Oxford Cambridge and RSA

Thursday 14 October 2021 – Morning

A Level Physics B (Advancing Physics)

H557/02 Scientific literacy in physics

Time allowed: 2 hours 15 minutes

You must have:
- a clean copy of the Advance Notice Article (inside this document)
- the Data, Formulae and Relationships Booklet

You can use:
- a scientific or graphical calculator
- a ruler (cm/mm)

Please write clearly in black ink. **Do not write in the barcodes.**

Centre number | | | | | | Candidate number | | | | |

First name(s) ____________________

Last name ____________________

INSTRUCTIONS
- Use black ink. You can use an HB pencil, but only for graphs and diagrams.
- Write your answer to each question in the space provided. If you need extra space use the lined pages at the end of this booklet. The question numbers must be clearly shown.
- Answer **all** the questions.
- Where appropriate, your answer should be supported with working. Marks might be given for using a correct method, even if your answer is wrong.

INFORMATION
- The total mark for this paper is **100**.
- The marks for each question are shown in brackets **[ ]**.
- Quality of extended response will be assessed in questions marked with an asterisk (*).
- This document has **24** pages.

ADVICE
- Read each question carefully before you start your answer.

SECTION A

Answer **all** the questions.

1 (a) Gravitational potential of a point mass and electrical potential of a point charge are both examples of inverse relationships.

(i) State what is meant by the term **gravitational potential**.

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.... **[1]**

(ii) Explain why gravitational potential is always a negative quantity.

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.... **[2]**

(iii) Explain why electrical potential can be positive or negative.

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.... **[1]**

(b) The gravitational potential at the surface of the Earth is about $-6.3 \times 10^{7}\,\mathrm{J\,kg^{-1}}$.

Write down the minimum initial kinetic energy required for a 1 kg body to escape the gravitational field of the Earth when projected vertically from the surface. Explain your reasoning and suggest why this is a minimum value.

minimum initial kinetic energy = ... J

Explanation:

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Suggestion:

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[3]

(c) The Voyager 1 spacecraft was launched in 1977. It has travelled further into space than any other human-made device. In May 2019 it was more than 2.2×10^{13} m from the Sun, moving at a velocity of $1.7 \times 10^{4}\,m\,s^{-1}$.

Calculate its total energy at this distance and explain the significance of your answer.

mass of Sun = 2.0×10^{30} kg

mass of Voyager spacecraft = 720 kg

total energy = ... J

Explanation:

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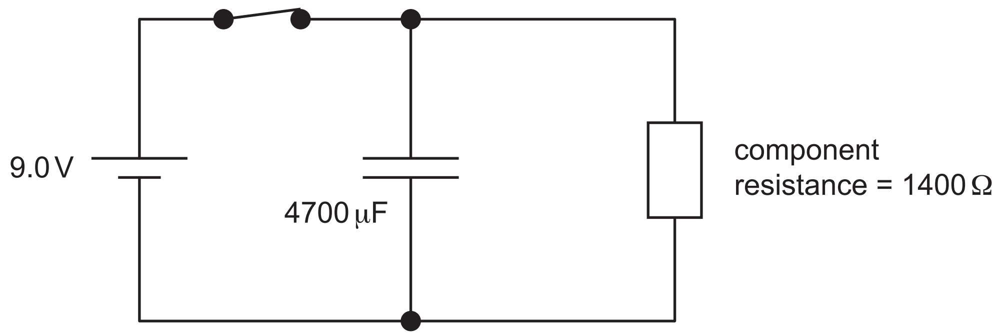
[4]

2 This question is about using capacitors as energy storage devices.

The diagram below shows a simple circuit which models how a capacitor can be used as a back-up power supply. The component is modelled as a single resistor.

In normal use the switch is closed and the p.d. across the component is 9.0 V. Opening the switch models a failure in the power supply.



(a) **(i)** The operating range of the component is 5.2 V to 9.0 V.

Show that 3.5 s after the switch is opened the p.d. across the component will be about 5.3 V.

[2]

(ii) Estimate the average power delivered to the component during this time.
Explain why the value is an average.

average power = ... W

Explanation:

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[3]

In recent years, **supercapacitors** have been developed. These components charge and discharge in a similar manner to standard capacitors but can have capacitances of more than 10 000 F.

These can be used as back-up power supplies in many circumstances.

(b) A 120 F supercapacitor has an internal resistance of 30 mΩ. At time t = 0.0 s it stores 300 J.

Calculate the minimum time taken for the capacitor to transfer 250 J through discharging. Suggest why this is a minimum value.

time = ... s

Suggestion:

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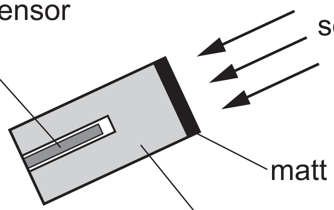
[4]

3 This question is about the power output of the Sun.

A student places an aluminium block with a matt black face in direct sunlight, facing the Sun so that the solar radiation strikes the face as shown in the diagram below. The block has a temperature sensor embedded within it.



After ten minutes the temperature of the block has risen by 2.1 K.

(a) Use the data below to calculate the power per square metre of the radiation incident on the block. You may assume that all the energy incident on the face is retained as internal energy of the block.

Mass of block = 0.28 kg

Area of matt black face = 0.0013 m^2

specific thermal capacity of aluminium = 920 $J\,kg^{-1}\,K^{-1}$

power per square metre = ... $W\,m^{-2}$ **[2]**

(b) The power per m^2 of solar radiation of all wavelengths striking the top of the Earth's atmosphere is 1.4 $kW\,m^{-2}$. The distance from the Earth to the Sun is 1.5×10^{11} m.

Show that these figures suggest that the power output of electromagnetic radiation of the Sun is about 4×10^{26} W.

[2]

(c) The ultimate source of the Sun's energy is the fusion of hydrogen into helium. This is a three-stage process which can be summarised in the single equation below.

$$4\,{}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{0}_{1}\mathrm{e} + 2\,{}^{0}_{0}\gamma + 2\,{}^{0}_{0}\nu$$

(i) Explain how the equation shows that lepton number is conserved in the fusion reactions.

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.... **[2]**

(ii) Use the data below to calculate an estimate of the number of fusion three-stage reactions occurring in the Sun each second. 98% of the energy released in the process consists of electromagnetic radiation in the form of gamma ray photons.

power output of Sun (electromagnetic radiation) = 3.8×10^{26} W

mass of electron = 0.000549 u

mass of proton = 1.007276 u

mass of helium-4 nucleus = 4.001506 u

number of fusion reactions per second = ... **[4]**

SECTION B

Answer **all** the questions.

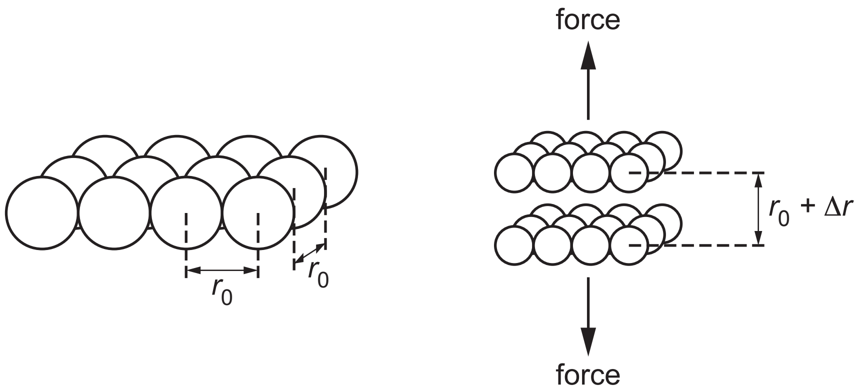
4 This question is about the macroscopic behaviour of a metal under tension and a model of the microscopic structure of the metal.

A 3.951 m length of copper wire with cross-sectional area $5.90 \times 10^{-8}\,m^2$ extends to a length of 3.953 m when a tensile force of 3.43 N is applied.

(a) Calculate the Young modulus of the sample.

Young modulus = ... Pa **[2]**

(b) The microscopic structure of copper can be pictured as planes of atoms as shown in the diagram.



The distance between the centres of neighbouring atoms, r_0, is 2.3×10^{-10} m.

When the copper wire is not under tension the distance between the planes is also 2.3×10^{-10} m.

The bonds between the atoms can be considered to act like microscopic springs. When the copper is put under tension the separation between the planes increases to $r_0 + \Delta r$.

(i) Using data from the question, calculate the number of atoms in one plane of area $5.90 \times 10^{-8}\,m^2$ and use this value to calculate the tension force between pairs of atoms in neighbouring planes when the wire experiences a tension force of 3.43 N.

tension = ... N **[3]**

(ii) Using data from the question, calculate the increase in distance of separation Δr of the planes of copper atoms when the wire experiences a tension force of 3.43 N.

increase in separation = ... m **[2]**

(iii) Use your answers to **(b)(i)** and **(b)(ii)** to calculate the force constant *k* between a pair of copper atoms.

force constant = ... $N\,m^{-1}$ **[2]**

(c)* This simple model of the microscopic structure of copper cannot be used to predict its yield stress.

Describe how an improved model can predict the way in which metals under stress fail in different ways.

You should include an explanation of the term **yield stress** in your answer and describe how the macroscopic properties of metals can be changed by making changes to their microscopic structure. You may include diagrams in your answer. **[6]**

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Additional answer space if required.

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Question 5 begins on page 12

5 This question is about oscillations.

A 0.84 kg mass is attached to two springs as shown in **Fig. 5.1**. The mass is displaced 0.24 m from the equilibrium point and released. There is negligible friction between the mass and the surface.

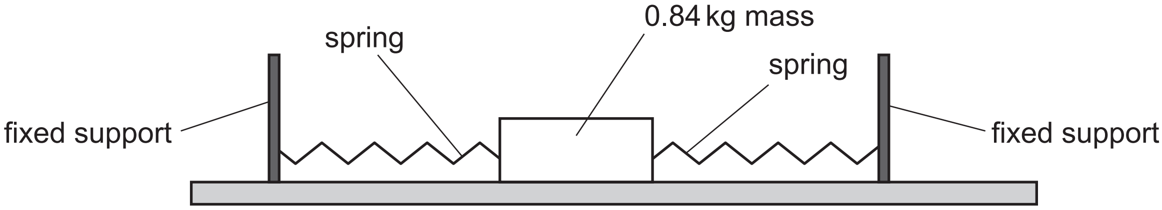

Fig. 5.1

(a) The mass oscillates between the springs with a time period of 1.3 s.

Calculate the spring constant *k* of the system.

spring constant = ... $N\,m^{-1}$ **[2]**

(b) Calculate the maximum velocity of the mass.

maximum velocity = ... $m\,s^{-1}$ **[3]**

(c) Explain why the kinetic energy of the oscillator will equal the elastic potential in the system when its displacement = $\frac{\text{maximum displacement}}{\sqrt{2}}$.

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.... **[2]**

(d) Calculate the time interval between releasing the mass from its position of maximum displacement and the first time the kinetic energy of the mass is equal to the elastic potential energy of the system.

time = ... s **[2]**

(e) A powerful magnet is fixed to the side of the mass as shown in **Fig. 5.2**. An aluminium sheet is placed below the mass. The friction between the mass and the metal surface is still negligible.

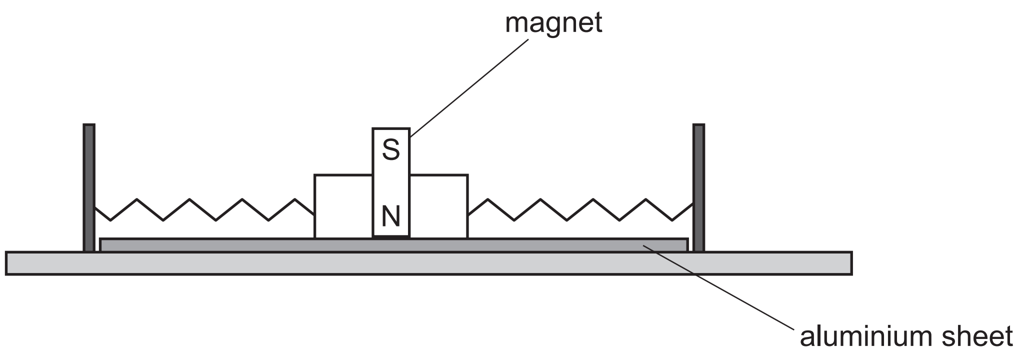

Fig. 5.2

When the experiment is repeated with the magnet and sheet present, the amplitude of oscillations falls rapidly due to eddy currents in the sheet.

Explain how these currents are formed and how they transfer energy away from the oscillation.

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.... **[4]**

(f) At a height of 632 m, the Shanghai Tower is the world's second tallest building. A huge pendulum which oscillates at the natural frequency of the building reduces the effect of the wind. The oscillations of the pendulum are damped with hydraulic pistons and electromagnetic dampers. **Fig. 5.3** shows the tower with its electromagnetic damper.

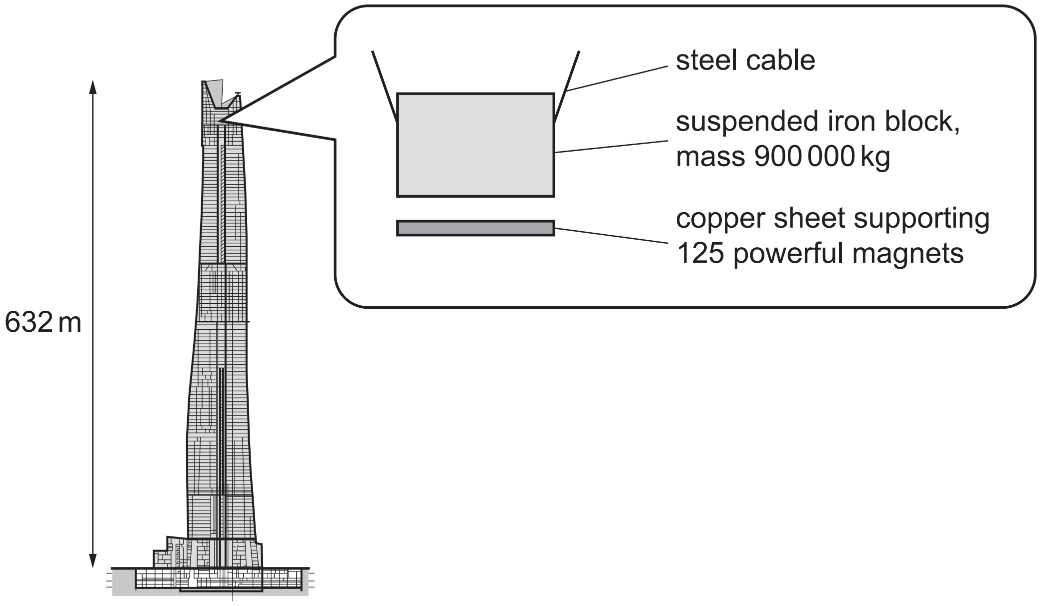

Fig. 5.3 Shanghai Tower. Pendulum diagram not to scale. Hydraulic dampers not illustrated.

Suggest how this system reduces the motion of the building in winds and explain the purpose of the damping systems.

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6 This question is about the conductivity of metals.

Fig. 6.1 shows a circuit used to determine the conductivity of nichrome wire.

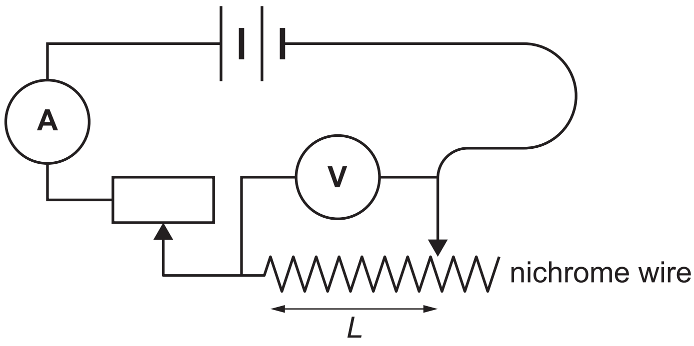

Fig. 6.1

The length L of nichrome wire the current passes through is varied. The variable resistor is used to keep the current in the circuit constant.

(a) State and explain why it is important to keep the current constant when determining the resistivity of the nichrome wire.

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.... **[2]**

(b) **Fig. 6.2** shows a graph of the results obtained using the apparatus.

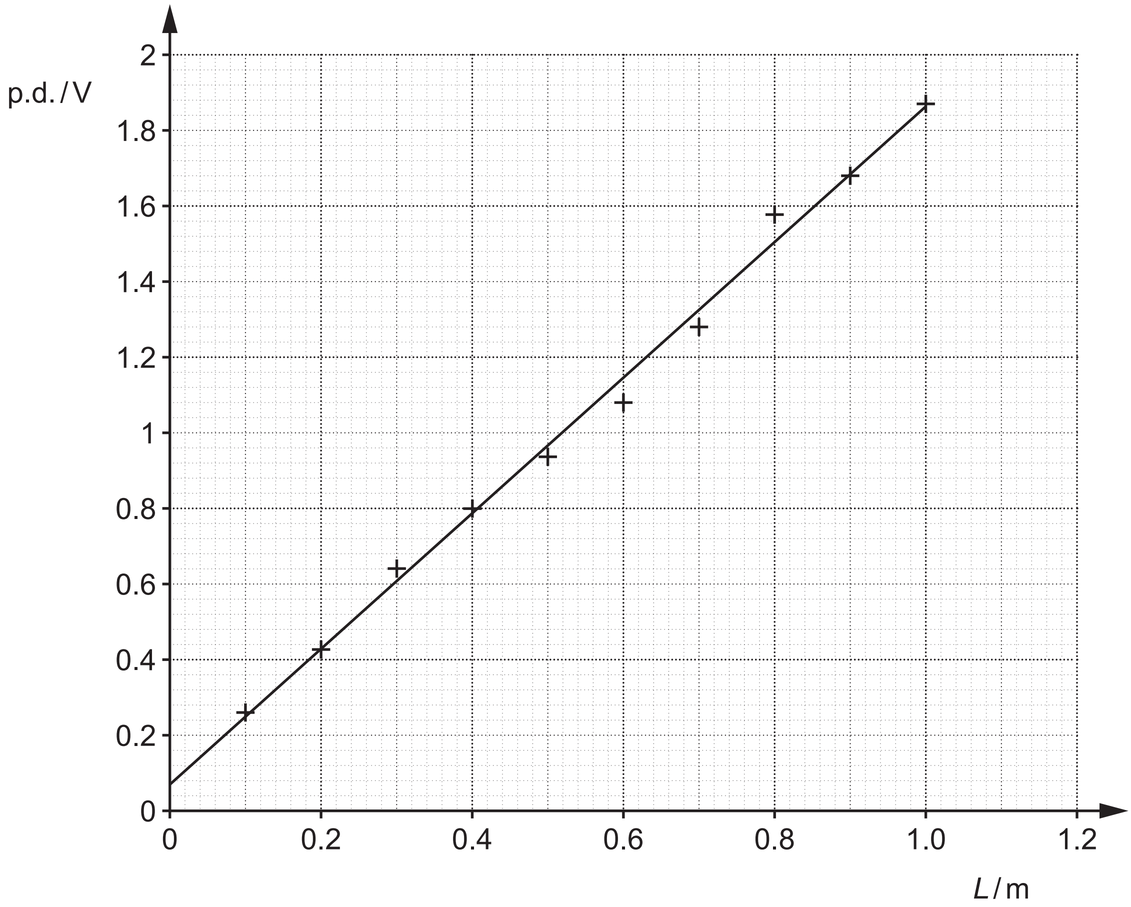

Fig. 6.2

(i) State how the graph shows that there is a systematic error in the data and suggest a possible cause of the error.

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.... **[2]**

(ii) Calculate the gradient of the line, making your method clear.

gradient = ... $V\,m^{-1}$ **[2]**

(iii) Use the value from **(ii)** and the data below to calculate the conductivity of the wire.

current through wire = 0.30 A
diameter of wire = 5.6×10^{-4} m

conductivity = ... $S\,m^{-1}$ **[3]**

(c) The experiment was repeated with nichrome wire of diameter 4.2×10^{-4} m carrying the same current of 0.30 A. The repeated experiment gave a different value for the conductivity of nichrome.

Suggest and explain why the second experiment gave a different value.

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.... **[2]**

(d) Metals have far higher electrical conductivities than insulators.

Explain this difference by referring to the microscopic properties of both classes of materials.

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.... **[3]**

SECTION C

Answer **all** the questions.

This section is based on the Advance Notice Article, which is an insert.

7 This question is about the longitudinal resolution of ultrasound pulses used in medical imaging (lines 112–124).

An ultrasound scanner emits an ultrasound pulse into tissue which reflects at the boundary between tissue and a layer of fat. The time interval between the emission of the pulse and return is 15.5 μs.

(a) Calculate the distance between the scanner and the layer of fat.

velocity of sound in tissue = $1540\,m\,s^{-1}$

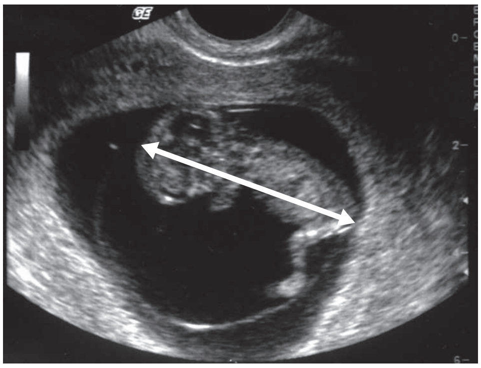
distance = ... m **[1]**

(b) The frequency of the ultrasound used is 3.5 MHz and each pulse lasts 1 μs.

Calculate the longitudinal resolution of the pulse.

longitudinal resolution = ... m **[3]**

8 The figure below reproduces the ultrasound scan shown in the article on page 5.



The length of the foetus indicated by the double-headed arrow is 39 mm. The whole image measures 920 × 700 pixels.

(a) Calculate the resolution of the image.

resolution = ... mm **[2]**

(b) The image size is 644 000 bits.

Explain why this suggests that each pixel in the image is either white or black and suggest how the image appears to show shades of grey.

Explanation:

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Suggestion:

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[2]

9 This question is about the spreading and attenuation of sound in air (lines 39–60).

(a) (i) A bat emits a pulse from a single point. The intensity of the sound emitted varies with distance from that point in an inverse square relationship. The pulse strikes an object at distance *R*. The reflected pulse also spreads in an inverse square manner.

State what is meant by the term **inverse square relationship** and explain why the intensity of the echo the bat receives is given by the equation

intensity of echo = intensity of original pulse / R^4.

You can assume that there is no absorption or scattering of the sound by the air and that all the energy incident on the object is reflected.

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.... **[2]**

(ii) A pulse emitted by the bat returns after reflection from a small object at a distance of 2.4 m.

Calculate the change in power in decibels (dB) of the pulse from its emission to its return, assuming that there is no absorption or scattering of the sound and that all the energy incident on the object is reflected.

change in power = ... dB **[3]**

(b) **(i)** Ignoring the effects of spreading, the power of a sound wave of frequency 100 kHz falls to 93% of its original value after travelling 0.1 m.

Show that the attenuation coefficient of air for sound of frequency 100 kHz is about $0.7\,m^{-1}$.

[2]

(ii) By considering only the effects of spreading **and** attenuation calculate the difference in power in decibels between the transmitted pulse and detected echo when a bat sends an ultrasound pulse of frequency 100 kHz which strikes a moth at a distance of 3.0 m. Assume that the bat and the moth each acts like a point source of sound and that all the energy incident on the moth is reflected.

power difference = ... dB **[4]**

Turn over for question 10

10* Explain how superposition is used by bats and in ultrasound scanners to increase the **power** of the ultrasound beam in a desired direction or location. You should include in your answer an explanation of the term **wave superposition**. You may include diagrams in your answer. **[6]**

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Additional answer space if required.

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END OF QUESTION PAPER

ADDITIONAL ANSWER SPACE

If additional space is required, you should use the following lined page(s). The question number(s) must be clearly shown in the margin(s).

Oxford Cambridge and RSA

Thursday 14 October 2021 – Morning

A Level Physics B (Advancing Physics)

H557/02 Scientific literacy in physics

Advance Notice Article

Time allowed: 2 hours 15 minutes

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INSTRUCTIONS
- Do **not** send this Advance Notice Article for marking. Keep it in the centre or recycle it.

INFORMATION
- This is a clean copy of the Advance Notice Article you have already seen.
- This document has **8** pages.

Seeing with sound

In the 1790s, the Italian scientist Lazarro Spallanzani performed a rather surprising experiment. He observed the flights of owls and bats in a room lit only by dim candlelight. The birds and mammals both successfully navigated the room without bumping into anything. However, when the candle was blown out the owls could no longer confidently fly around the room whilst the behaviour of the bats was unchanged – the bats could 'see' in the dark. Rather gruesomely, Spallanzani went on to blind his experimental animals only to find that the bats could still 'see' in the dark. It was only when he blocked the bats' ears that the creatures lost their navigational ability. The conclusion – bats 'see' with their ears, but how could this be?

This problem went unanswered for 140 years until the discovery of ultrasound echolocation in the 1930s. Simply put, the bat produces an ultrasonic 'click' and listens for the returning echo. The time delay between click and echo allows the bat to judge the distance to objects. But the reality is much more complicated and impressive than this simple picture. Some species of bat change the frequency of the note they emit for more efficient range finding. Many species have adapted mouth, nose and ears to increase the range and resolution of the echolocation system. When hunting, a bat needs to know more than just the distance of its target (often a moth). The relative speed of the target is required, as is the target's horizontal and vertical position. The methods used for this data capture are given in the table.

measurement	**method**
distance to prey	echolocation: distance = $\frac{1}{2}$ × speed of sound in air × time interval between bat emitting pulse and detecting echo
vertical position of prey	interference patterns of echo signal produced by ridges in the bat's ears (see **Fig. 1**)
horizontal position of prey	comparison of intensity of echo signal in right and left ears
movement of prey	Doppler effect detection
size of prey	intensity of echo signal

Fig. 1 The long-eared bat shows clear ridges on its ears. These act in a similar fashion to a diffraction grating and help the bat determine the vertical position of its prey.

Detecting distance

Waves will reflect from objects which are at least as long as the wavelength. For this reason, the bat must emit short wavelength, high frequency sound. Typically, they use pulses of sounds of around 80 kHz in echolocation – way beyond the upper limit of human hearing. The pulses have to be short in duration so that the spatial length of the pulse (how long it is in metres) is as small as possible to establish the distance to the prey with precision. When searching for prey a bat might produce a pulse every 200 ms; this rises to about one pulse every 5 ms when the bat comes close to the prey.

The problem of power

The power of sound is measured in decibels (dB). Strictly, it measures **differences** in sound power. Sound power difference in decibels is given by the equation

$$\text{difference in sound power (dB)} = 10\log_{10}\left(\frac{P_1}{P_0}\right)$$

where, often, P_0 is the power of a sound that can just be heard and P_1 is the power of the sound produced by the source under consideration. Therefore, a sound that can just be heard will have a power difference of 0 dB. A sound of 3 dB will have approximately twice the power of the smallest audible signal.

The echolocating signal of a bat can be 110 dB at a few centimetres distance from the bat. However, the power diminishes very quickly. Two effects produce this loss of power; the spreading of the sound from the source and absorption and scattering of the sound by the atmosphere. Without absorption and scattering, the power of sound waves from a point source shows inverse square variation. Bats reduce the effects of signal loss through spreading by using high frequency sounds which diffract less on leaving the sound source. Some species project the echolocation signals through their nostrils. This means that there are two sources of waves which superpose constructively in the zeroth-order direction. This concentrates the power of the beam so that it travels greater distances through air.

Sound absorption in air is highly frequency-dependent. The power of the signal decreases exponentially with distance. With no spreading, a 100 kHz signal halves its power over a distance of about one metre, a change of 3 dB. The power approximately follows the relationship

$$P_x = P_0 e^{-\alpha R}$$

where P_x is the power at distance R from the source, P_0 is the power at the source and α is the atmospheric attenuation constant.

The Doppler effect

One of the most remarkable adaptations bats have evolved is that of Doppler effect detection. As the figure shows, some species of bats can use the Doppler effect to judge the relative velocity of the object it is locating. A moth flying away from the bat produces an increase in the wavelength of the reflected waves (**Fig. 2 a**). An approaching moth produces reflections of decreased wavelength (**Fig. 2 b**).

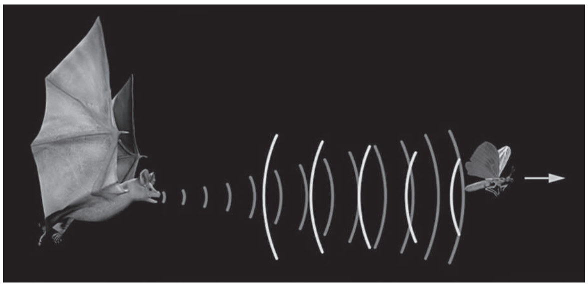

Fig. 2 a

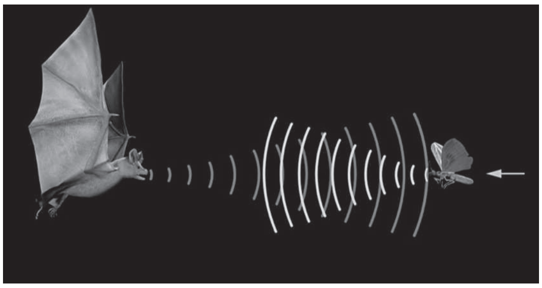

Fig. 2 b

The new frequency f produced by the relative motion of the source and the receiver is given by the Doppler shift equation

$$f = \left(\frac{c - v_r}{c - v_s}\right) f_0$$

where c is the velocity of sound in air (about 340 m s^{-1}), v_r is the velocity of the receiver (the moth) and v_s the velocity of the source (the bat). Even in this one-dimensional case, c, v_r and v_s are vectors, so v_r and v_s are positive if they are in the same direction as c and negative if they are in the opposite direction. This means that in **Fig. 2 a**, a moth flying at 5 m s^{-1} pursued by a bat flying at 40 m s^{-1} emitting ultrasound at f_0 = 100 kHz receives a frequency $f = \left(\frac{340 - 5}{340 - 40}\right) \times 100\,\text{kHz} = 112\,\text{kHz}$ whereas a moth flying at the same speed towards the bat in **Fig. 2 b** receives a frequency of $f = \left(\frac{340 - [-5]}{340 - 40}\right) \times 100\,\text{kHz} = 115\,\text{kHz}$.

To calculate the frequency heard by the bat it is necessary to treat it in two stages: the frequency the moth receives is calculated using the bat as the source and then the reflection the bat receives from the moth is calculated using the moth as the source, emitting sound at the frequency it received.

Some species of bat have developed this form of echolocation to the extent that they can identify the species of moth by the Doppler shift produced by the manner in which the moths flutter their wings.

Medical ultrasound

Many babies in the world are scanned before birth using ultrasound echolocation, another example of seeing with sound.

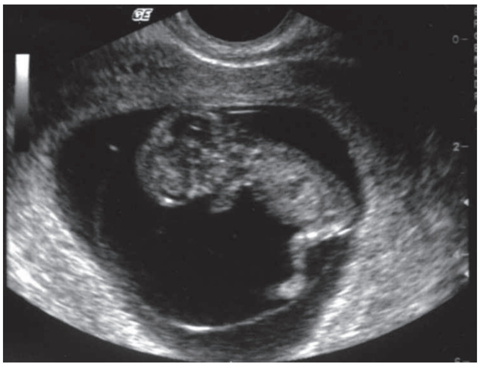

Fig. 3 Ultrasound scan of a healthy 10 week-old foetus

Ultrasonic waves used in medical imaging are produced using a **piezoelectric transducer**. When a direct potential difference is applied to the transducer plate it either compresses or expands, reverse the process and the opposite happens. When the crystal expands it produces a compression (region of high pressure) followed by a rarefaction (region of low pressure) which moves through the air. This is the ultrasound wave. A single, sudden change of p.d. across the plate will set the transducer oscillating in the same manner as striking the edge of a wine glass. Like the wine glass, the transducer will oscillate at its resonant frequency. This frequency depends on the width of the transducer crystal: a standing wave will be formed in the crystal of wavelength equal to twice the width of the crystal. The crystal will oscillate at the frequency of the standing wave, producing a pulse of sound at the same frequency.

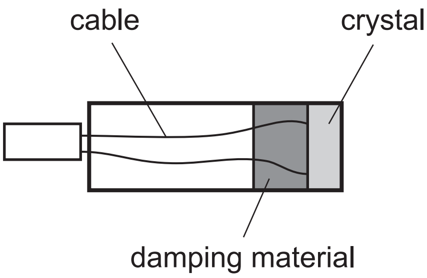

Fig. 4 Simplified diagram of single-element piezoelectric transducer (not to scale)

Sound waves travel in tissue at about $1540\,\mathrm{m\,s^{-1}}$, but this depends on the type of tissue. For example, the velocity of sound in body fat is about $1450\,\mathrm{m\,s^{-1}}$ and in muscle it is around $1585\,\mathrm{m\,s^{-1}}$.

As the ultrasound pulse produced by the transducer travels through tissue it will reflect from interfaces where the velocity of sound changes. The reflections are detected by the transducer and produce a change in potential difference. The potential difference changes of the transducer are digitised and displayed as the ultrasound image.

The time interval between the outgoing and return pulses allows distance between the transducer and the reflecting surface to be found, this is **longitudinal imaging**. The image shown in **Fig. 3** is taken by scanning *across* the object and detecting return pulses from a constant depth. This is **latitudinal imaging**.

Resolution of medical ultrasound

It is important for an ultrasound imaging system to have good depth resolution (longitudinal) and good latitudinal resolution.

As with bats, obtaining good longitudinal resolution requires short spatial pulse lengths, where spatial pulse length = wavelength of pulse × number of cycles of pulse. A lightly damped crystal will vibrate for a number of cycles as shown in **Fig. 5 a**, which oscillates for seven and a half cycles.

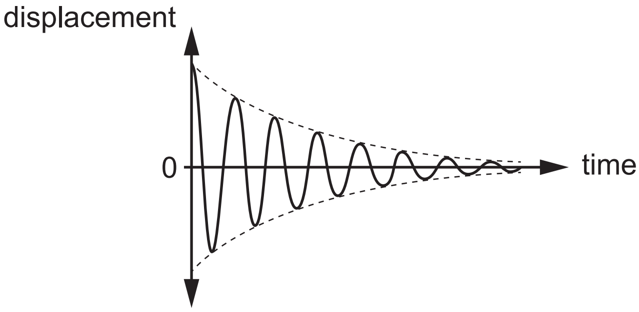

Fig. 5 a

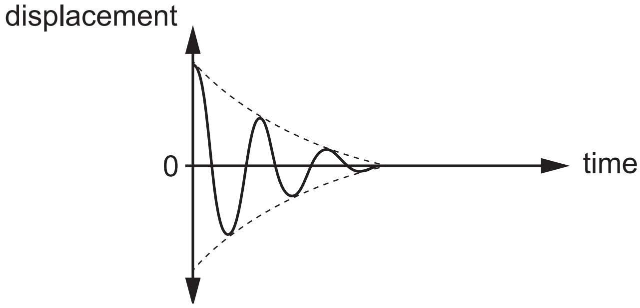

Fig. 5 b

Placing a damping block behind the crystal reduces the number of oscillations and reduces the pulse time. This is equivalent to placing a hand on a ringing wine glass. A heavily damped oscillation is shown in **Fig. 5 b**.

The longitudinal resolution of an ultrasound scan is equal to half the spatial pulse length of the pulse. An ultrasound pulse of 1 μs corresponds to about 3 cycles for a typical ultrasound frequency used in medical imaging. This produces a longitudinal resolution of less than 1 mm.

Latitudinal resolution depends on the width of the beam. The narrower the beam the better the resolution. One way of achieving a narrow beam where required is to electronically focus the beam at a given depth in the tissue. Consider the set of transducers labelled A to D in **Fig. 6**. When activated each transducer will emit an ultrasound pulse in the manner described above. Applying the principle of superposition, the ultrasound beam can be seen to have the greatest power at point X if the pulse from the pair of transducers labelled D is emitted slightly earlier than the pulse from pair C, which is emitted slightly earlier than pair B. The final pulse comes from transducer A. Changing the time delay between pulses from different transducers allows the beam to be focused at different depths.

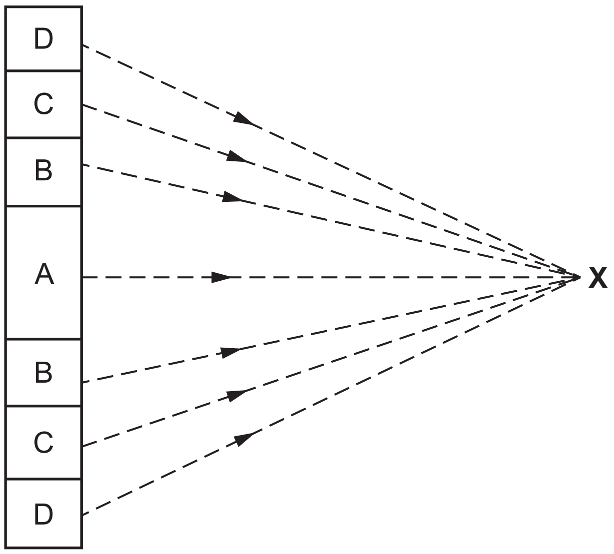

Fig. 6

This highly technical focusing system uses similar principles to those species of bats which strengthen the power of their pulses through using two sources of sound. Scientists and technologists are developing ways of seeing with sound similar to those which evolution produced in bats millions of years ago.