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Centre number

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Candidate number

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A-level PHYSICS

Paper 3

Section B Engineering physics

Thursday 14 June 2018

Morning

Time allowed: The total time for both sections of this paper is 2 hours. You are advised to spend approximately 50 minutes on this section.

Materials

For this paper you must have:

- a pencil and a ruler
- a scientific calculator
- a Data and Formulae Booklet.

Instructions

- Use black ink or black ball-point pen.
- Fill in the boxes at the top of this page.
- Answer **all** questions.
- You must answer the questions in the spaces provided. Do not write outside the box around each page or on blank pages.
- Do **all** rough work in this book. Cross through any work you do not want to be marked.
- Show **all** your working.

Information

- The marks for questions are shown in brackets.
- The maximum mark for this paper is 35.
- You are expected to use a scientific calculator where appropriate.
- A Data and Formulae Booklet is provided as a loose insert.

For Examiner's Use	
Question	Mark
1	
2	
3	
4	
TOTAL	



J U N 1 8 7 4 0 8 3 B C 0 1

Section BAnswer **all** questions in this section.

0	1	.	1
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State the law of conservation of angular momentum.

[1 mark]

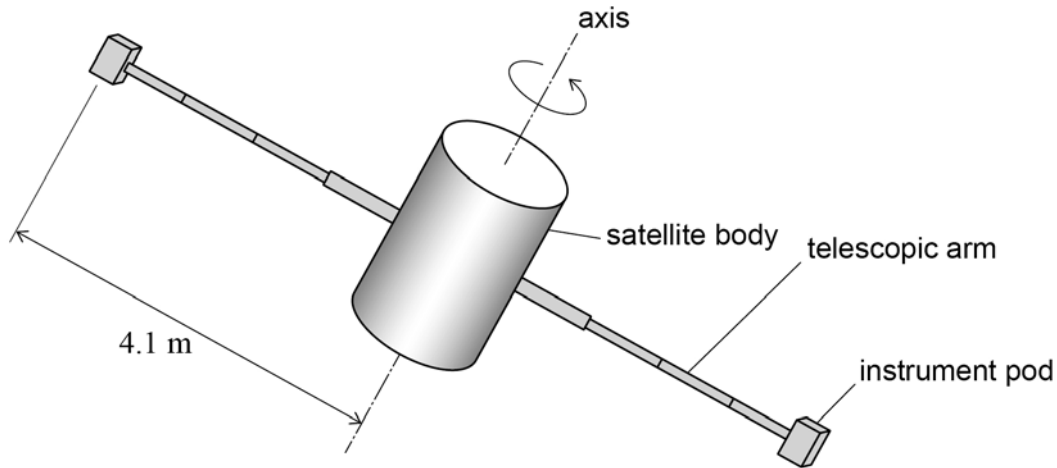
The total angular momentum of a system remains constant (is conserved) provided no external torque acts on the system.



0 1 . 2

Figure 1 shows an orbiting satellite fitted with two small instrument pods attached to the ends of telescopic arms. The arms can be extended or retracted by a motor in the body of the satellite.

Figure 1



With the telescopic arms fully extended, the centre of mass of each instrument pod is at a radius of 4.1 m from the axis of rotation.

moment of inertia of satellite body about axis = 71 kg m^2

mass of each instrument pod = 5.0 kg

The mass of the telescopic arms is negligible.

Show that the total moment of inertia of the satellite with the arms fully extended is 240 kg m^2

[2 marks]

$$I = I_{\text{body}} + 2 \times mr^2$$

$$I = 71 + 2 \times 5.0 \times 4.1^2$$

$$I = 71 + 168.1$$

$$I = 239 \text{ kg m}^2 \approx 240 \text{ kg m}^2$$

Question 1 continues on the next page

Turn over ►



0 1 . 3

The satellite is initially rotating slowly about its axis with the arms fully extended. The arms are slowly retracted so that the instrument pods move closer to the body of the satellite.

State and explain the change in the angular speed of the satellite as the arms are retracted.

[3 marks]

The moment of inertia of the satellite decreases.

This is because the mass of the pods is moved closer to the axis, and $I = \Sigma mr^2$, so with r smaller, I is smaller.

No external torque acts, so the angular momentum $I\omega$ remains constant (is conserved).

So as I decreases, the angular speed ω must increase.

0 1 . 4

The satellite is initially rotating at 1.3 rad s^{-1} with the telescopic arms fully extended. When fully retracted the instrument pods are at a radius of 0.74 m from the axis. The satellite contains sensitive equipment that may be damaged if the rotational speed exceeds 4.2 rad s^{-1}

Deduce whether the arms can be retracted fully without the satellite exceeding its maximum permitted angular speed.

[3 marks]

Conservation of angular momentum: $I_1\omega_1 = I_2\omega_2$

$$I_1\omega_1 = 240 \times 1.3 = 312 \text{ N m s}$$

$$\text{Retracted: } I_2 = 71 + 2 \times 5.0 \times 0.74^2 = 76.5 \text{ kg m}^2$$

$$312 = 76.5 \times \omega_2$$

$$\omega_2 = 312 \div 76.5 = 4.08 \text{ rad s}^{-1}$$

4.08 rad s^{-1} is less than 4.2 rad s^{-1} , so the maximum speed is not reached: the arms can be retracted fully safely.



0 2 . 1

State **one** function of a flywheel.**[1 mark]**

To store rotational kinetic energy, so that it smooths out fluctuations in the rotational speed.

Question 2 continues on the next page

Turn over ►

0 2 . 2

A student does an experiment to determine the frictional torque acting at the bearings of a steel flywheel. The flywheel has a radius of 0.075 m and is perfectly balanced.

The student places a small magnet of mass 0.020 kg at point **A** on the circumference of the flywheel on a horizontal line through the axis of rotation as shown in **Figure 2a**. The student releases the flywheel. The flywheel first comes to rest when it has moved through an angle of 3.00 rad (172°), with the magnet now in position **B** as shown in **Figure 2b**.

Figure 2a

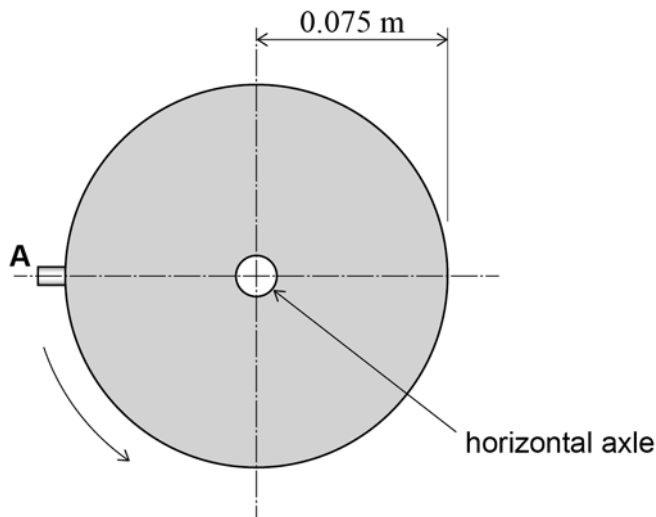
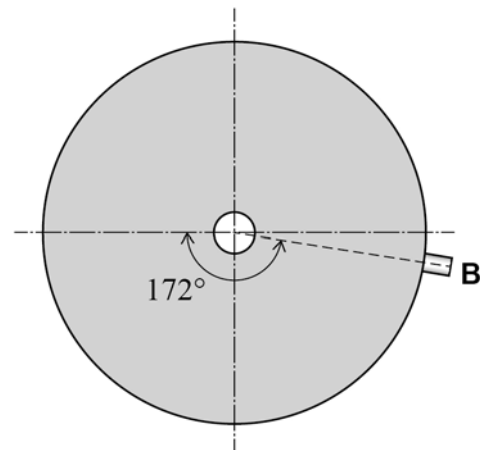


Figure 2b



The loss in gravitational potential energy of the magnet equals the work done against the frictional torque acting at the bearings.

Show that the frictional torque is about 7×10^{-4} N m

[3 marks]

Magnet falls through 3.00 rad = 172° , ending $180^\circ - 172^\circ = 8^\circ$ below the horizontal, so $h = 0.075 \sin 8^\circ = 1.04 \times 10^{-2}$ m

$$\begin{aligned} \text{Loss in GPE} &= mgh = 0.020 \times 9.81 \times 1.04 \times 10^{-2} \\ &= 2.04 \times 10^{-3} \text{ J} \end{aligned}$$

Work done against friction = $T\theta$, so $T \times 3.00 = 2.04 \times 10^{-3}$

$$T = 2.04 \times 10^{-3} \div 3.00 = 6.80 \times 10^{-4} \text{ N m}$$

(about 7×10^{-4} N m)



0 2 . 3

The student goes on to determine the moment of inertia of the flywheel.

The magnet is removed and the flywheel is made to spin. Measurements show that the flywheel makes 573 rotations as its angular speed reduces uniformly from 25.0 rad s^{-1} to zero. Assume the frictional torque at the bearings is constant and the same as in question 02.2.

Determine the moment of inertia of the flywheel about its axis of rotation.

[3 marks]

$$\theta = 573 \times 2\pi = 3600 \text{ rad}$$

$$\text{Uniform deceleration: } 0 = \omega_f^2 - 2\alpha\theta$$

$$\alpha = \omega_f^2 \div 2\theta = 25.0^2 \div (2 \times 3600)$$

$$\alpha = 0.0868 \text{ rad s}^{-2}$$

$$T = I\alpha, \text{ so } I = T \div \alpha$$

$$I = 6.80 \times 10^{-4} \div 0.0868$$

$$I = 7.83 \times 10^{-3} \text{ kg m}^2$$

moment of inertia = 7.83×10^{-3} kg m²

7

Turn over for the next question

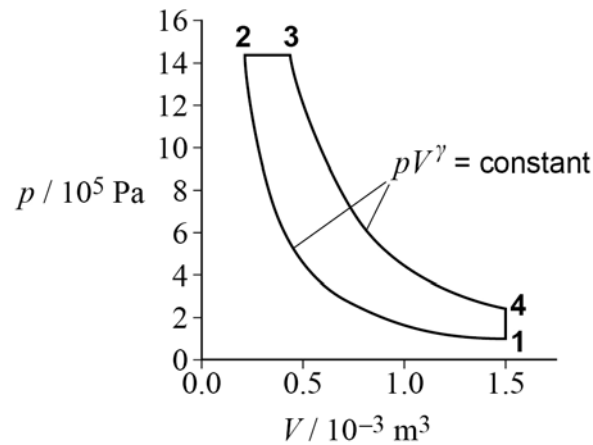
Turn over ►



0 3

Figure 3 shows the p - V diagram for an idealised diesel engine cycle. In this cycle a fixed mass of air is taken through four processes $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 1$.

Figure 3



0 3

1

Which statement about this cycle is true?

Tick (✓) the correct answer.

[1 mark]

Work is done by the air in process $4 \rightarrow 1$.

☐

Energy is supplied to the air by heating only in process $2 \rightarrow 3$.

☒

The temperature of the air rises in process $3 \rightarrow 4$.

☐

The area enclosed by the loop $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 1$ is the power output of the cycle.

☐

0 3

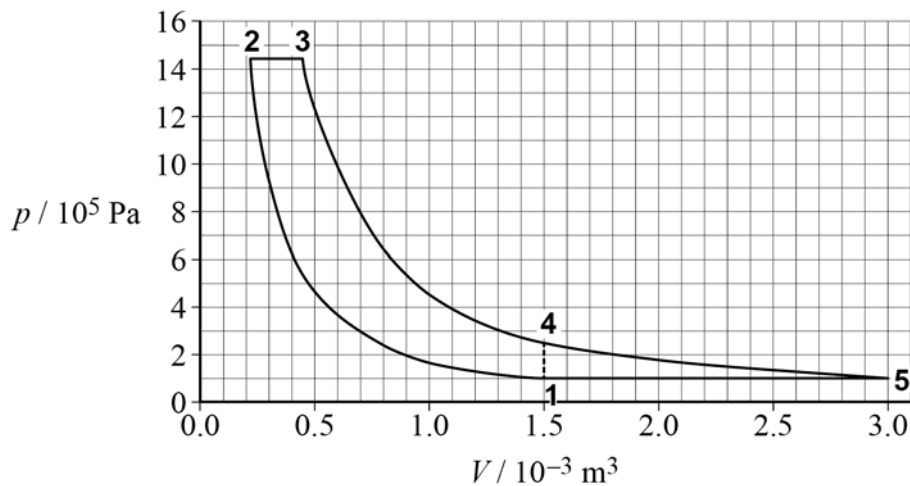
2

The cycle in **Figure 3** may be modified by allowing the air to continue to expand adiabatically from state **4** until it is at atmospheric pressure at state **5**.

Figure 4 shows the modified cycle.



Figure 4



The expansion stroke $3 \rightarrow 5$ is now longer than the compression stroke $1 \rightarrow 2$. Process $5 \rightarrow 1$ takes place at constant pressure.

It has been claimed that, compared to the cycle in **Figure 3**, the modified cycle of **Figure 4** gives

- A** an increase in work done per cycle of 130 J
- B** an increase in efficiency of more than 15%

Deduce whether these claims are true.

[5 marks]

Claim **A**

$$\text{Each small square} = 0.1 \times 10^{-3} \text{ m}^3 \times 1 \times 10^5 \text{ Pa} = 10 \text{ J}$$

$$\text{Extra area, loop } 4 \rightarrow 5 \rightarrow 1 \rightarrow 4 = 9 \text{ squares}$$

$$\text{Increase in work done per cycle} = 9 \times 10 = 90 \text{ J}$$

90 J is less than 130 J, so claim A is not true.

Claim **B**

$$\text{Area enclosed by loop } 1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 1 = 55 \text{ squares} = 550 \text{ J}$$

For the same heat input, efficiency $\propto$ work done per cycle, so

$$\begin{aligned} \text{increase in efficiency} &= 90 \text{ J} \div 550 \text{ J} = 9 \text{ squares} \div 55 \text{ squares} \\ &= 0.16 = 16\% \end{aligned}$$

16% is more than 15%, so the efficiency is better than claimed:

claim B is true.

Question 3 continues on the next page

Turn over ►



0 3 . 3

The first law of thermodynamics can be written as

$$Q = \Delta U + W$$

State the meaning of the terms Q and ΔU in this equation.

[2 marks]

Q energy supplied (transferred) to the gas by heating; negative if energy is lost by cooling.

ΔU the increase (change) in the internal energy of the gas; negative if it decreases.

0 3 . 4

For the air in process $5 \rightarrow 1$ in **Figure 4**, $\Delta U = -374 \text{ J}$ Calculate the energy that must be removed by cooling for process $5 \rightarrow 1$.

[2 marks]

Work done by the gas at constant pressure:

$$W = p\Delta V = 1.0 \times 10^5 \times (1.50 - 3.00) \times 10^{-3} = -150 \text{ J}$$

$$Q = \Delta U + W = -374 + (-150)$$

$$Q = -524 \text{ J, so } 524 \text{ J must be removed by cooling}$$

energy removed by cooling = 524 J



0 3 . 5 0.060 mol of air is taken through the cycle.

Determine the maximum temperature in the cycle.

[3 marks]

Maximum temperature is at point 3 (largest pV in the cycle).

At point 3: $p = 14.3 \times 10^5 \text{ Pa}$, $V = 0.46 \times 10^{-3} \text{ m}^3$

$pV = nRT$, so $T = pV \div nR$

$T = (14.3 \times 10^5 \times 0.46 \times 10^{-3}) \div (0.060 \times 8.31)$

$T = 658 \div 0.499 = 1320 \text{ K}$

maximum temperature = 1.32×10^3 K

13

Turn over for the next question

Turn over ►



0 4

The National Grid is supplied mainly from power stations which have overall efficiencies of up to about 40%

Table 1 shows the average power requirements of a large paper-manufacturing business (a paper mill).

Table 1

Requirement	Average power / MW
for driving electric motors for wood grinders, pumps, fans, etc.	49
for heating, ie boiling and drying in the paper-making process and for heating the paper mill	141
for running electrical office equipment, lighting, etc.	8

The paper mill can either

- take all of its energy from the National Grid, or
- install an electrical generator of output 60 MW driven by a gas turbine of efficiency 36% as part of a combined heat and power (CHP) scheme. The hot exhaust gases from the turbine are used to produce steam at high temperature and pressure for heating.

The owners of the paper mill are considering the CHP option.

Explain, with reference to the data above and any other factors, the advice you would give them.

In your answer you should

- explain why the maximum theoretical efficiency of a heat engine is much less than 100%
- use the information above, including the numerical data, to compare the two options.

[6 marks]

No heat engine can be 100% efficient because of the second law of thermodynamics: it must reject some energy as heat to a cold sink (the surroundings at a low temperature).

The maximum theoretical efficiency depends only on the source and sink temperatures: $\text{efficiency} = (T_H - T_C) \div T_H$. For 100% efficiency T_C would have to be 0 K, which is impossible, and in practice the



difference between T_H and T_C is limited, so the maximum efficiency is well below 100%.

Real engines are less efficient still because of the nature of the working cycle, friction and incomplete combustion.

The mill needs $49 + 8 = 57$ MW of electrical power and 141 MW for heating, a total of 198 MW.

CHP option: the 60 MW generator covers the 57 MW electrical need, but with only 3 MW spare there is not much margin for expansion. Input power to the turbine = $57 \div 0.36 = 158$ MW (or $60 \div 0.36 = 167$ MW at full output).

The heat available from the exhaust gases is at most $158 - 57 = 101$ MW (or $167 - 60 = 107$ MW at 60 MW output), and in practice less than this. This is not enough for the 141 MW heating requirement, so at least 34 MW ($141 - 107$) will still have to come from the National Grid or other heating.

National Grid only: with power stations of about 40% efficiency, the input power needed to supply 198 MW to the mill is $198 \div 0.40 = 495$ MW, and most of the waste heat at the power station is lost. With CHP, energy that would otherwise be wasted is used for heating, so far less fuel is burned overall and the carbon footprint is lower.

Other factors: CHP makes the mill independent of grid supply problems and power cuts, and excess electricity can be sold to the grid. However it needs a large capital cost, space for the plant, and has maintenance and depreciation costs, and production spikes may need more than 60 MW. The grid needs no capital outlay and gives a highly reliable supply, but its cost per kWh includes the waste heat at the power station and

Question 4 continues on the next page



the transmission costs.

Advice: choose the CHP scheme, keeping a National Grid connection for the extra heating and electrical needs and as a backup, because it uses much less fuel overall and should save money in the long term.

END OF QUESTIONS



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