AQA A-LEVEL PHYSICS · 7408

# PHYSICS



EXAM QUESTION PACK

## 3.11.1 ROTATIONAL DYNAMICS

| SCORE | PERCENTAGE |
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## Q1.

(a) State the law of conservation of angular momentum.

_____

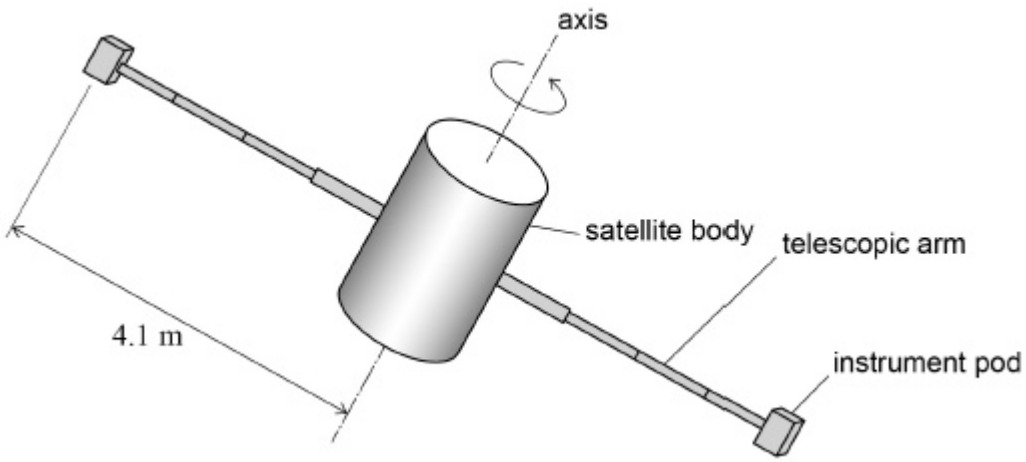
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**(1)**

(b) The diagram 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.




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 m2

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)**

(c) 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.



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

**(3)**

(d) 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)**
**(Total 9 marks)**

## Q2.

(a) State **one** function of a flywheel.

**(1)**

(b) 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



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circumference of the flywheel on a horizontal line through the axis of rotation as shown in **Figure 1a**. 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 1b**.

**Figure 1a**

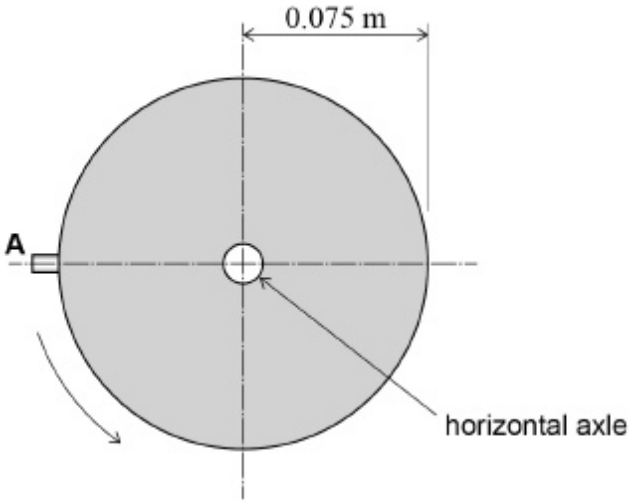
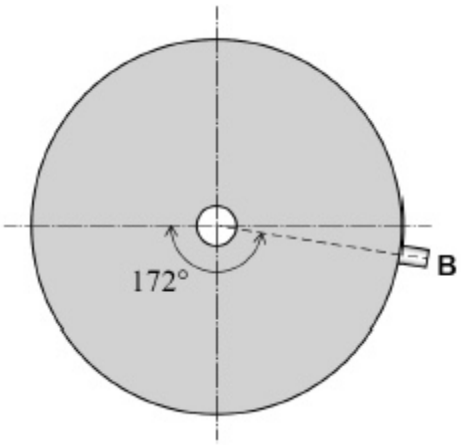



**Figure 1b**




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 $7 \times 10^{-4}$ N m

**(3)**

(c) 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 (b).

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



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moment of inertia = _____ kg $m^2$

**(3)**

**(Total 7 marks)**

## Q3.

(a) There is an analogy between quantities in rotational and translational dynamics.

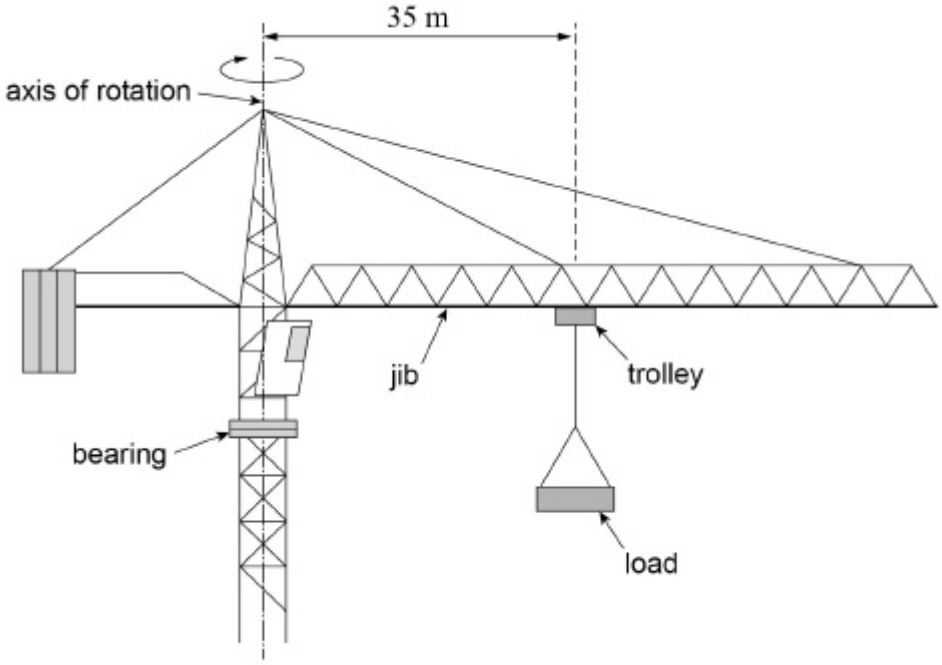
Complete the table, stating in words the quantities in rotational dynamics that are analogous to force and mass in translational dynamics.

| Translational dynamics | Rotational dynamics |
|---|---|
| force | |
| mass | |

**(2)**

**Figure 1** shows a side view of the jib of a tower crane. The load is supported by a trolley which can move along the jib. The jib consists of all the parts of the crane above the bearing, but excluding the trolley and load.

**Figure 1**




The moment of inertia of the jib about the axis of rotation = $2.6 \times 10^7$ kg $m^2$

Mass of trolley and load = $2.2 \times 10^3$ kg

(b) The load is at a distance of 35 m from the axis of rotation.

Show that the total moment of inertia of the jib, and the trolley and load, about the axis of rotation is about $3 \times 10^7$ kg $m^2$.

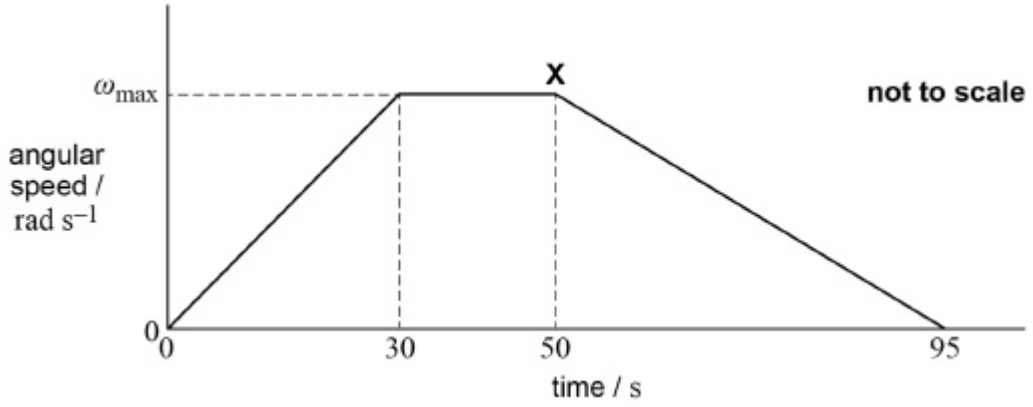


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**(1)**

(c) **Figure 2** shows the variation of angular speed of the jib as it turns through an angle of 4.7 rad (270°) in a total time of 95 s. The trolley and load remain at a distance of 35 m from the axis.

**Figure 2**




Calculate the maximum angular speed $\omega_{max}$ of the jib.

maximum angular speed = _____ rad s$^{-1}$

**(2)**

(d) At time **X** in **Figure 2** the motor that is driving the jib is disengaged. A constant braking torque is then applied to bring the jib to a standstill from its maximum angular speed.

The crane driver repeats the movement of the jib with the same load at 35 m from the axis of rotation. Up to time **X** the motion is the same as before. From time **X** the trolley is driven at a steady speed away from the axis as the jib continues to rotate until the jib comes to a standstill.

Assume the braking torque remains the same as before.

Discuss how the motion of the trolley affects the time taken for the jib to come to a standstill.

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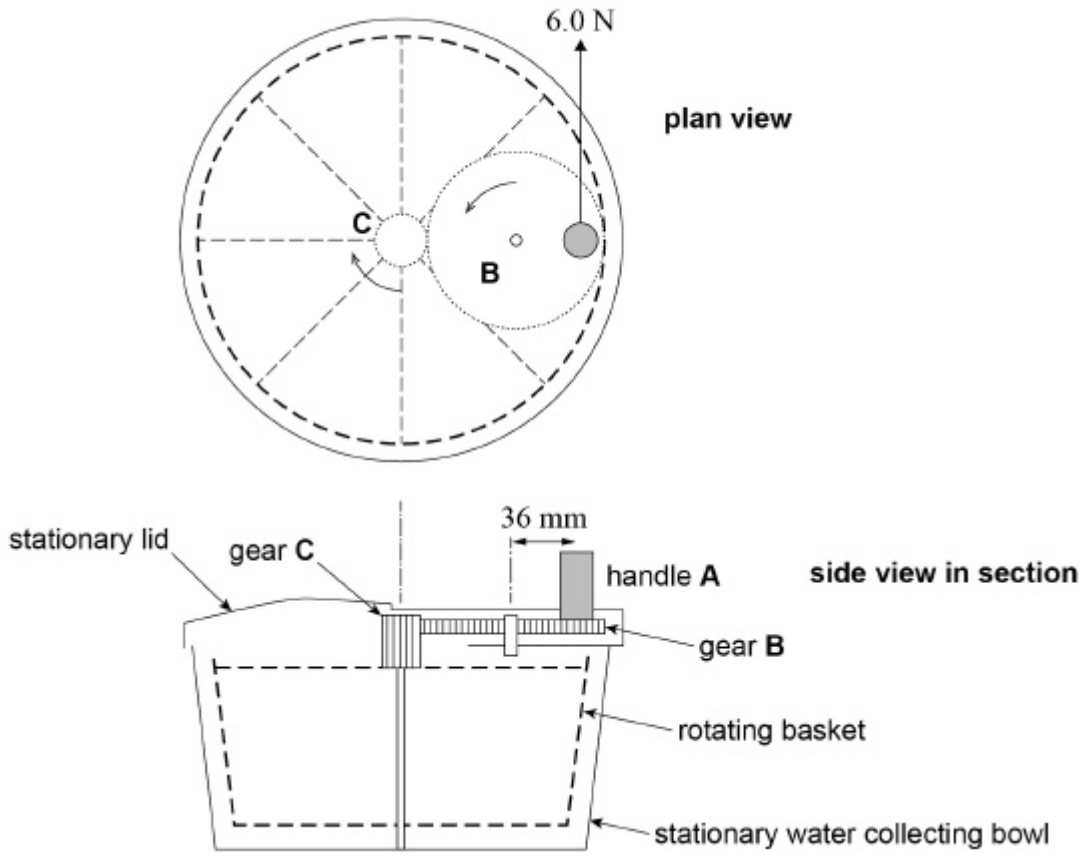
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**(3)**

**(Total 8 marks)**

## Q4.

The diagram shows the basic principle of operation of a hand-operated salad spinner used to dry washed salads.




The salad is placed in the basket and the lid is attached.

When handle **A** is turned the basket and its contents spin rapidly. Water on the salad is driven through holes in the basket into the stationary water collecting bowl. The pivot for gear **B** is fixed to the lid. This pivot and the lid do not move. When gear **B** rotates, gear **C** also rotates but at a greater angular speed. Gear **C** is fixed to the basket and rotates it.

A force of 6.0 N is applied to handle **A** as shown. Handle **A** is at a radius of 36 mm from its centre of rotation.

(a) Calculate the input torque.



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torque = _____ N m

**(1)**

(b) Gear **C** rotates four times for every one revolution of gear **B**.

Deduce whether it is possible for the torque on gear **C** to be greater than one quarter of the input torque.

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**(2)**

(c) It takes 2.1 s for the empty basket to reach an angular speed of 76 rad $s^{-1}$. The torque on gear **C** is a constant 0.054 N m during this time. Frictional losses are negligible.

Calculate the moment of inertia of the basket about its axis of rotation.

moment of inertia = _____ kg $m^2$

**(2)**

(d) The gears are made from polymer (plastic). An early version of this salad spinner suffered from damaged gear teeth.

Explain with reference to angular impulse why a great force is put on the gear teeth if the user tries to stop the loaded basket too quickly using the handle.

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**(3)**

**(Total 8 marks)**



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**Q5.**

(a) A metal flywheel is rotating on frictionless bearings. The temperature is increased so that the flywheel expands.

Consider **each** of the following statements and indicate with a tick (✓) if it is correct.

| | ✓ **if correct** |
|---|---|
| The moment of inertia will decrease. | |
| The angular velocity will decrease. | |
| The angular momentum will be unaltered. | |

**(1)**

An electric motor drives a machine which stamps out shapes from sheet steel. The machine is fitted with a flywheel of moment of inertia 25 kg $m^2$ which is accelerated uniformly until it is rotating at 640 rev $min^{-1}$. The machine then starts a stamping operation which reduces the flywheel's angular speed to 360 rev $min^{-1}$.

(b) Explain why a flywheel is fitted between the motor and the stamping machine.

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**(2)**

(c) Calculate the energy needed for the stamping operation.

energy _____ J

**(2)**

(d) Immediately after the stamping operation the flywheel is accelerated to its initial speed of 640 rev $min^{-1}$ in a time of 5.0 s. The next stamping operation then begins.

Calculate the constant torque provided by the motor during this 5.0 s. Assume that the bearing frictional torque is negligible.



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torque = _____ N m

**(2)**

(e) Calculate the minimum power output of the electric motor required.

power _____ W

**(2)**

(f) The flywheel is a solid disc. It is to be replaced with a flywheel which gives a smaller angular speed change for each stamping operation.

Two replacement flywheels, **A** and **B**, are available and information about them and the original flywheel is given in the table below.

| flywheel | density of material / kg $m^{-3}$ | thickness of disc / m | outer radius / m |
|---|---|---|---|
| **original** | 7800 | 0.10 | 0.38 |
| **A** | 8800 | 0.20 | 0.30 |
| **B** | 2900 | 0.10 | 0.50 |

Deduce which flywheel, **A** or **B**, would be more suitable. Explain your choice.

The moment of inertia $I$ of a solid disc of mass $m$ and outer radius $r$ about an axis through the centre is given by

$$I = \frac{1}{2} m r^2$$

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**(3)**

**(Total 12 marks)**

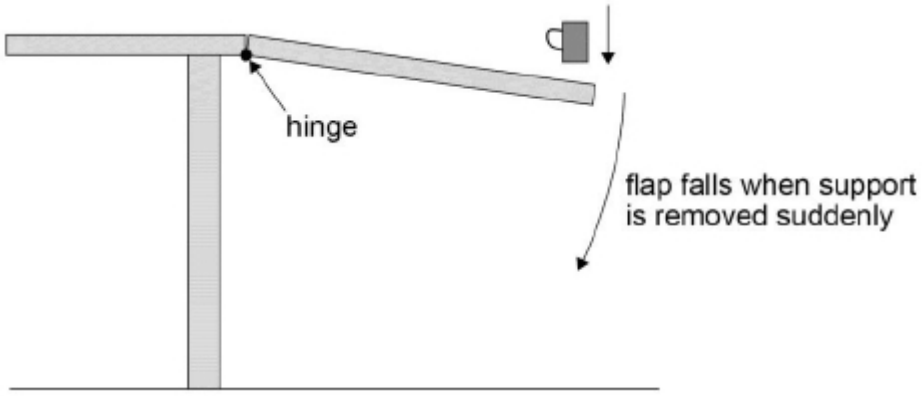


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## Q6.

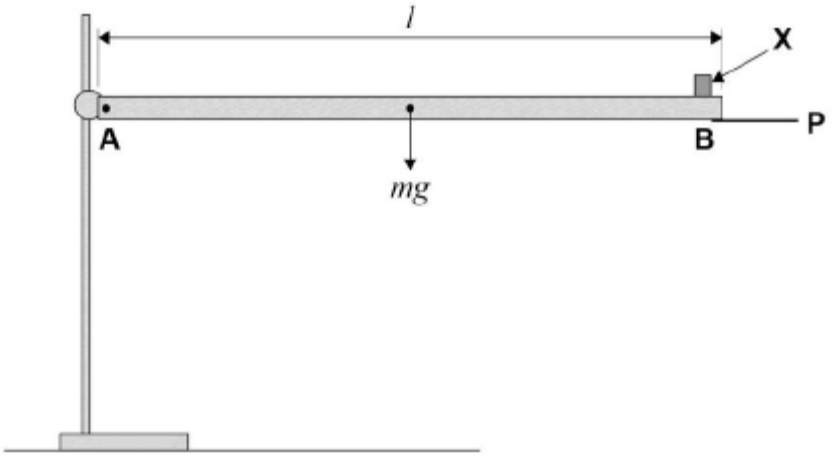
A student is told that if a small cup of coffee is placed near the edge of a table flap, the cup and the flap will lose contact if the flap support is suddenly removed. This is shown in **Figure 1**.

**Figure 1**




The student does not believe this to be true so decides to model the arrangement using a metre ruler free to pivot about one end **A**, with a small mass **X** resting on the ruler at the other end **B**. The arrangement is shown in **Figure 2**. The mass of **X** is negligible compared to the mass of the ruler. The metre ruler is held in the horizontal position by a support **P** which is quickly removed. A video is taken of the subsequent motion of the ruler and mass.

**Figure 2**




Assume the ruler is a thin uniform beam of mass $m$ and length $l$.

(a) Derive an expression for the torque $T$ acting on the ruler at the moment of release.

_____

_____

**(1)**

(b) The moment of inertia $I$ of the metre ruler about the axis through **A** is given by



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$$I = \frac{m}{3} l^2$$

Show that the angular acceleration $\alpha$ of the ruler at the moment of release is given by

$$\alpha = \frac{3g}{2l}$$

**(2)**

(c) The linear acceleration $a$ of a point on a rotating rigid body at a distance $r$ from the axis of rotation is related to the angular acceleration $\alpha$ by

$$a = r \times \alpha$$

Explain why this causes the small mass to lose contact with the metre ruler as soon as the ruler is released.

**(2)**

(d) Estimate how far from **A** the small mass must be placed to ensure it just maintains contact with the ruler when the ruler is released.

**(1)**

**(Total 6 marks)**

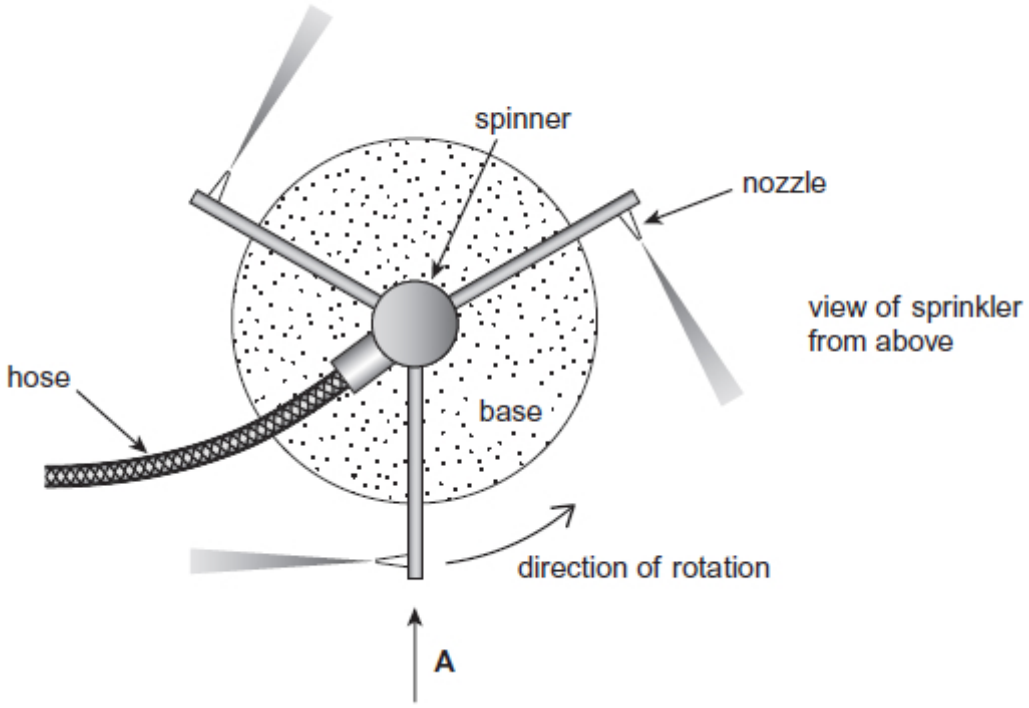
## Q9.

A garden sprinkler consists of a fixed base and a rotating spinner having three arms as shown in **Figure 1**.



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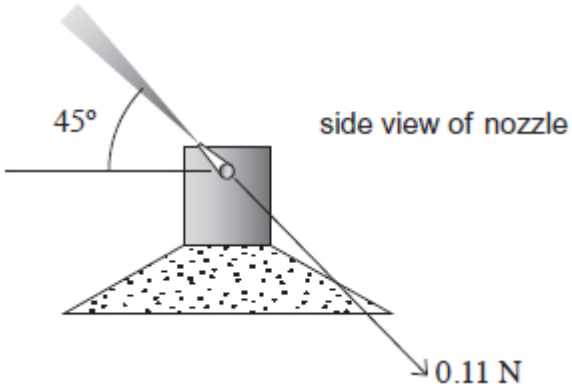
Figure 1




At the end of each arm is a nozzle at 90° to the arm and inclined at 45° to the horizontal. Water flows in jets at a constant rate from these nozzles when the hose water tap is turned on.

**Figure 2** shows a side view of one of the nozzles viewed in the direction of arrow **A** in **Figure 1**.

Figure 2




The water jets produce reaction forces that act on the arms which cause the spinner to rotate. The base remains fixed in position. In operation, the spinner rotates at a constant rate of 240 rev $min^{-1}$. The nozzles rotate in a horizontal circle of radius 120 mm.

(a) Each water jet exerts a constant force of 0.11 N on its arm at 45° to the horizontal.

Show that the torque exerted on the spinner by the jets of water is about $3 \times 10^{-2}$ N m.



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**(2)**

(b) (i) Explain why, when the water tap is turned on, the spinner accelerates initially but then reaches a constant angular speed.
Assume that, when the tap is turned on, the flow-rate of the water from the jets is constant.

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**(2)**

(ii) Calculate the power dissipated by the frictional torque acting between the spinner and the fixed base when the sprinkler is rotating at 240 rev $min^{-1}$.

power = _____ W

**(2)**

(c) When the water is suddenly turned off all the kinetic energy of the spinner and arms is dissipated as heat due to work done by the frictional torque and the spinner makes a further 13 rotations before coming to rest. Assume uniform deceleration.

(i) Calculate the time taken for the spinner to come to rest.

time = _____ s

**(2)**

(ii) Show that the kinetic energy of the spinner when rotating at its operating speed is about 2 J.

**(1)**

(iii) Determine the moment of inertia of the spinner about its axis of rotation.



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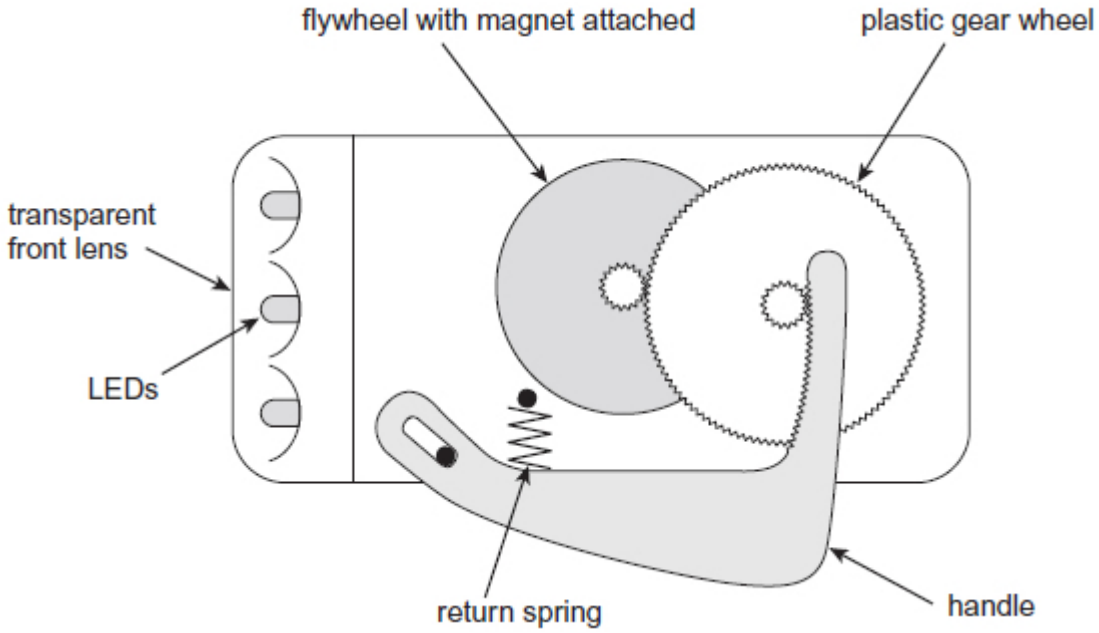
moment of inertia = _____ kg $m^2$

**(1)**

**(Total 10 marks)**

## Q10.

The diagram shows the mechanism of a dynamo torch for providing light without the use of batteries. When the handle is squeezed the gears rotate the flywheel increasing the kinetic energy stored in the flywheel. On the same axle as the flywheel is a magnet which generates an emf in surrounding coils as it rotates. The magnet, coils and electrical connections are not shown.




When the handle is released the mechanism disengages and a spring returns the handle to its original position. During this time the gears continue to turn. The energy of the flywheel enables it to continue to rotate for several seconds.

A designer wishes to enable the flywheel to store more energy and thus rotate for longer after the handle has been released.
The radius of the flywheel is limited by the overall size of the torch and cannot be increased.

Describe and explain other changes that can be made to the mechanism and flywheel to store more energy. Your answer should include consideration of:

- the flywheel's shape
- the material from which it is made
- changes to the mechanism.

The quality of your written communication will be assessed in your answer.

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**(Total 6 marks)**

## Q11.

A roundabout in a fairground requires an input power of 2.5 kW when operating at a constant angular velocity of 0.47 rad $s^{-1}$.

(a) Show that the frictional torque in the system is about 5 kN m.

**(3)**

(b) When the power is switched off, the roundabout decelerates uniformly because the frictional torque remains constant. The roundabout takes a time of 34 s to come to rest.

(i) Calculate the moment of inertia of the roundabout.
Give an appropriate unit for your answer.

moment of inertia _____ unit _____

**(3)**

(ii) Calculate the number of revolutions that are made before the roundabout comes to rest.

number of revolutions _____

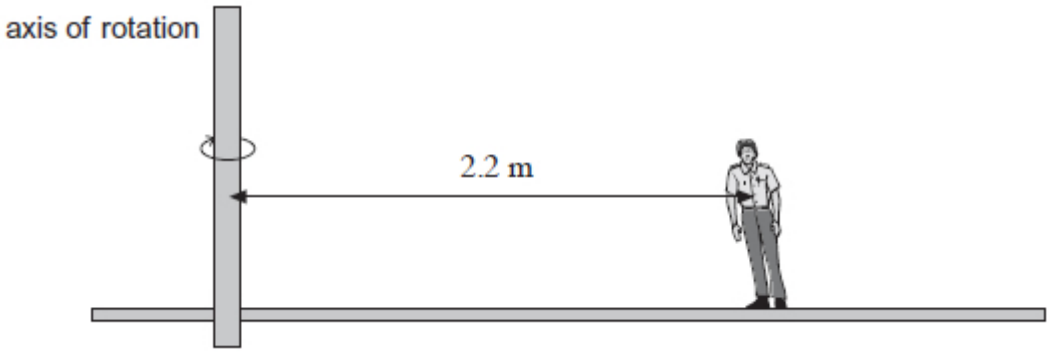
**(3)**

(c) An operator of mass 65 kg is standing on the roundabout when the roundabout is rotating at an angular velocity of 0.47 rad $s^{-1}$. His centre of mass is 2.2 m from the axis of rotation. The diagram shows that his body leans towards the centre of the



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path.




(i) Calculate the centripetal force needed for the operator to remain at this radius on the roundabout.

centripetal force _____ N

**(2)**

(ii) State the origin of this centripetal force and suggest why the operator has to incline his body towards the centre of rotation to avoid falling over.

You may draw the forces that act on the operator in the diagram to help your answer.

_____

_____

_____

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_____

**(2)**

(iii) While the roundabout is moving, the operator drops a coin.

Which statement correctly describes and explains what happens to the coin? Tick (✓) the correct answer in the right-hand column.

| | Tick (✓) |
|---|---|
| There is no longer a centripetal force acting, so the coin falls vertically downwards and lands on the roundabout directly below the point at which it was dropped. | |
| The centripetal force causes the coin to have a horizontal component of velocity towards the centre of the roundabout, so that it follows a trajectory towards | |



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| | |
|---|---|
| the centre of the roundabout. | |
| There is no longer a centripetal force acting, so there is a horizontal component of the coin's velocity directed away from the centre of the roundabout and it follows a trajectory directly away from the centre. | |
| There is no longer a centripetal force acting, so the coin has a horizontal component of its velocity tangential to its original path on the roundabout and it follows a trajectory along this tangent. | |

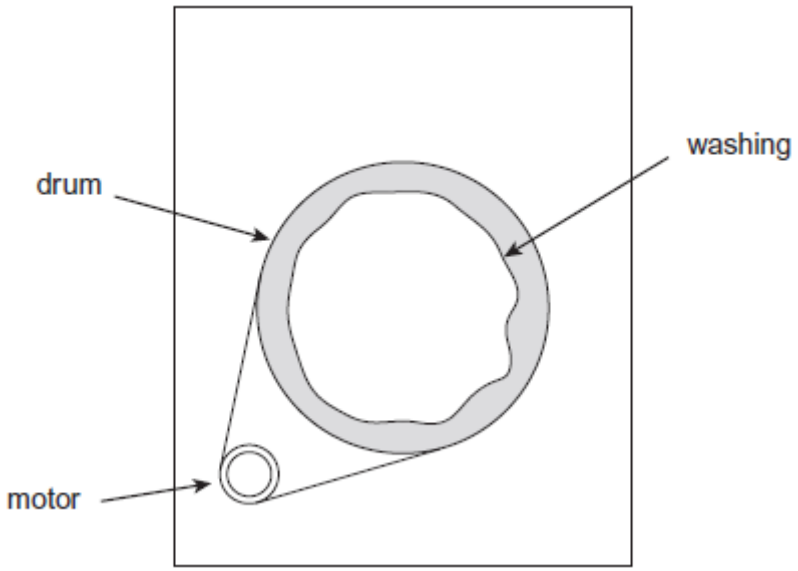
**(1)**

**(Total 14 marks)**

## Q12.

During the spin part of a washing machine programme the maximum rotational speed is 126 rad $s^{-1}$ (1200 rev $min^{-1}$). The moment of inertia of the drum and washing at the start of the spin part of the cycle is 0.565 kg $m^2$. Assume that the wet washing is evenly distributed around the drum as shown in **Figure 1**.

**Figure 1**

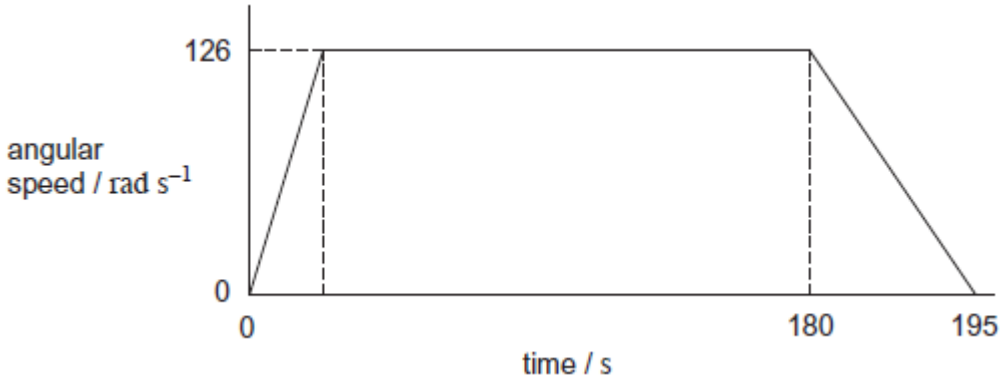



(a) **Figure 2** shows the variation of angular speed with time for the spin part of the cycle. The graph is not drawn to scale.

**Figure 2**



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The motor provides a torque of 8.80 N m to accelerate the drum to 126 rad s$^{-1}$. The drum rotates at 126 rad s$^{-1}$ until near the end of the spin cycle, when the drum decelerates uniformly to zero angular speed in 15 seconds. Friction at the bearings may be neglected. Assume that during acceleration the moment of inertia of the drum and washing remains constant.

(i) Show that the drum accelerates for about 8 s.

**(2)**

(ii) Calculate the total number of revolutions made by the drum during the 195 s shown in **Figure 2**.

number of revolutions = _____

**(3)**

(b) (i) In practice, at the start of the cycle the acceleration will not remain constant. Draw on **Figure 2** a line to show how the initial part of the graph will change.

**(1)**

(ii) Explain your reasons for the line you have drawn.



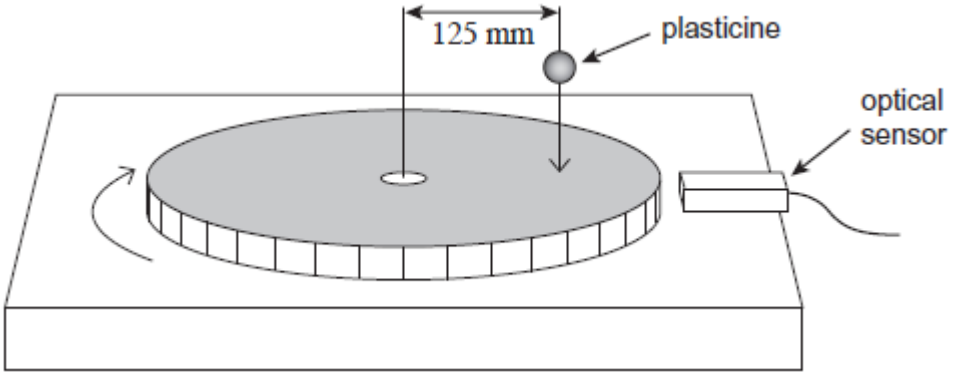
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**(2)**

**(Total 8 marks)**

## Q13.

A student carries out an experiment to determine the moment of inertia of a turntable. The diagram shows the turntable with a small lump of plasticine held above it. An optical sensor connected to a data recorder measures the angular speed of the turntable.




The turntable is made to rotate and then it rotates freely. The lump of plasticine is dropped from a small height above the turntable and sticks to it. Results from the experiment are as follows.

mass of plasticine = 16.0 g
radius at which plasticine sticks to the turntable = 125 mm
angular speed of turntable immediately before plasticine is dropped = 3.46 rad $s^{-1}$
angular speed of turntable immediately after plasticine is dropped = 3.31 rad $s^{-1}$

The student treats the plasticine as a point mass.

(a) Explain why the turntable speed decreases when the plasticine sticks to it.

**(3)**



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(b) Use the results of the experiment to determine the moment of inertia of the turntable.

Give your answer to an appropriate number of significant figures.

moment of inertia _____ kg $m^2$

**(3)**

(c) (i) Calculate the change in rotational kinetic energy of the turntable and plasticine from the instant before the plasticine is dropped until immediately after it sticks to the turntable.

change in kinetic energy _____ J

**(2)**

(ii) Explain the change in rotational kinetic energy.

_____

_____

**(1)**

**(Total 9 marks)**



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