Forces, momentum and circular motion: practice worksheet

IB Physics HL · A.2 · 47 minutes · 39 marks

Question 1

A packing block rests on a rough horizontal table. A worker applies a horizontal force to the right, but the block remains stationary.

(a) Sketch a free-body diagram for the block. Label every force with its correct name and direction. [2]

(b) Identify the Newton's-third-law partner of the normal reaction acting on the block. [1]

Question 2

A trolley of mass 0.400 kg initially moves east at 3.00 $\mathrm{m\,s^{-1}}$. Take east as positive. A horizontal force acts for 0.300 s. On a force–time graph, straight lines join the points $(0\ \mathrm{s}, 0\ \mathrm{N})$, $(0.100\ \mathrm{s}, -12.0\ \mathrm{N})$ and $(0.300\ \mathrm{s}, 0\ \mathrm{N})$. All other horizontal forces are negligible.

(a) Determine the impulse exerted on the trolley. [2]

(b) Hence determine the final velocity of the trolley. [1]

Question 3

A block on a rough slope is attached to a light spring that pulls parallel to the slope, upwards. The upper end of the spring can be moved to change its extension. The block is initially stationary with spring extension 0.0800 m. Data: block mass $m = 2.00$ kg; slope angle $\theta = 30.0^\circ$ to the horizontal; spring constant $k = 160\ \mathrm{N\,m^{-1}}$; coefficient of static friction $\mu_s = 0.300$; coefficient of dynamic friction $\mu_d = 0.200$. The spring obeys Hooke's law. Take $g = 9.81\ \mathrm{m\,s^{-2}}$.

(a) Determine the normal reaction acting on the block. [1]

(b) The spring extension is increased slowly. Show that the block is about to move upwards when the extension is approximately 0.0932 m. [2]

(c) At a later instant, the block is sliding upwards and the spring extension is 0.120 m. Calculate the acceleration of the block at this instant. [3]

Question 4

Two instrument carriers collide on a straight horizontal rail and lock together. Data: carrier A has mass 0.650 kg and initial velocity 4.80 $\mathrm{m\,s^{-1}}$ east; carrier B has mass 0.950 kg and initial velocity 1.20 $\mathrm{m\,s^{-1}}$ west. Take east as positive.

(a) State the condition required for the total momentum of the two carriers to be conserved during the collision. [1]

(b) Assume this condition is satisfied. Show that the carriers move together at approximately 1.24 $\mathrm{m\,s^{-1}}$ east. [2]

(c) Calculate the kinetic energy lost during the collision. [3]

(d) Determine the impulse exerted on carrier A during the collision. [1]

Question 5

A test capsule of mass 0.800 kg travels at constant speed 14.0 $\mathrm{m\,s^{-1}}$ around a banked horizontal circular track of radius 20.0 m. The track surface is inclined at angle θ to the horizontal and rises away from the centre of the circle. Friction and air resistance are negligible. Later, the capsule travels on the inside surface of a smooth vertical circular loop of radius 8.00 m. Its speed at the top of this loop is 14.0 $\mathrm{m\,s^{-1}}$. Take $g = 9.81\ \mathrm{m\,s^{-2}}$.

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(a) Sketch a labelled free-body diagram for the capsule on the banked horizontal track. [2]

(b) Determine the banking angle θ. [2]

(c) Explain which forces provide the centripetal force at the top of the vertical loop. [1]

(d) Calculate the normal reaction on the capsule at the top of the vertical loop. [2]

(e) Determine the frequency of the capsule's motion around the banked horizontal track. [1]

Question 6

A device moves east across a smooth horizontal surface and separates into two fragments when an internal mechanism releases stored energy. This question links momentum conservation to kinetic energy and energy transfer. Data: initial device mass 0.900 kg; initial speed 6.00 $\mathrm{m\,s^{-1}}$; fragment A mass 0.300 kg; fragment B mass 0.600 kg. Immediately after separation, A has velocity components 2.00 $\mathrm{m\,s^{-1}}$ east and 8.00 $\mathrm{m\,s^{-1}}$ north. Air resistance is negligible. All released internal energy becomes additional kinetic energy. Subsequently, B enters a smooth circular guide in a vertical plane. At the top, B is on the inside surface of the guide and its speed equals its speed immediately after separation. The guide radius is 2.00 m. Take $g = 9.81\ \mathrm{m\,s^{-2}}$.

(a) State the condition that allows total horizontal momentum to be conserved during separation. [1]

(b) Assume this condition is satisfied. Determine the eastward and northward components of the velocity of fragment B immediately after separation. [3]

(c) Show that the speed of B is approximately 8.94 $\mathrm{m\,s^{-1}}$ and determine its direction relative to east. [2]

(d) Calculate the internal energy released during separation. [3]

(e) At the top of the circular guide, explain how the centripetal force is provided and determine the normal reaction on fragment B. [3]

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Markscheme

Question 1

(a)

Weight vertically downwards and normal reaction vertically upwards, both correctly labelled. **1**

Applied force to the right and static friction to the left, both correctly labelled. **1**

Arrows must represent forces acting on the block. Accept equivalent force names.

(b)

The block exerts an equal downward contact force on the table. OWTTE. **1**

The weight of the block is not the third-law partner.

Question 2

(a)

Uses the signed triangular area: $J = -\frac{1}{2}(0.300)(12.0)$. **1**

$J = -1.80\ \text{N s}$. **1**

Accept an equivalent calculation using two triangular areas.

(b)

$v = 3.00 + \frac{-1.80}{0.400} = -1.50\ \text{m s}^{-1}$. **1**

ECF from part (a), with consistent signs.

Question 3

(a)

$F_N = (2.00)(9.81)\cos 30.0^\circ = 17.0\ \text{N}$. **1**

The spring has no component perpendicular to the slope.

(b)

At impending upward motion, friction acts down the slope: $kx = mg\sin 30.0^\circ + \mu_s F_N$. **1**

$x = \frac{9.81 + 0.300(16.9914)}{160} = 0.0932\ \text{m}$. **1**

Accept equivalent forms. Substitution into a correct limiting-equilibrium equation is required.

(c)

Dynamic friction acts down the slope with magnitude $F_f = \mu_d F_N = 3.40\ \text{N}$. **1**

Applies Newton's second law up the slope: $160(0.120) - 2.00(9.81)\sin 30.0^\circ - F_f = 2.00a$. **1**

$a = 3.00\ \text{m s}^{-2}$ up the slope. **1**

ECF from part (a). Accept a consistent alternative sign convention.

Question 4

(a)

The resultant external impulse during the collision is zero or negligible. OWTTE. **1**

Accept negligible resultant external force over the collision interval.

(b)

Conservation of momentum gives $0.650(4.80) + 0.950(-1.20) = (0.650 + 0.950)v$. **1**

$v = 1.2375\ \text{m s}^{-1} \approx 1.24\ \text{m s}^{-1}$ east. **1**

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A correct momentum equation with opposing initial signs is required.

(c)

Initial kinetic energy is $E_{k,i} = \frac{1}{2}(0.650)(4.80)^2 + \frac{1}{2}(0.950)(1.20)^2 = 8.172$ J. **1**
Final kinetic energy is $E_{k,f} = \frac{1}{2}(1.60)(1.2375)^2 = 1.225125$ J. **1**
Kinetic energy lost is $E_{k,i} - E_{k,f} = 6.95$ J. **1**

ECF from part (b). Accept 6.94 J *when the shown speed* 1.24 m s^{-1} *is used.*

(d)

$J_A = 0.650(1.2375 - 4.80) = -2.32$ N s. **1**

ECF from part (b). Accept 2.31 N s *west when the shown speed is used.*

Question 5

(a)

Weight is correctly labelled and directed vertically downwards. **1**
Normal reaction is correctly labelled and directed perpendicular to the surface, upwards and towards the centre. **1**

Only the two real forces act. Do not award full marks if an additional centripetal or centrifugal force is drawn.

(b)

Resolves the normal reaction: $F_N \cos\theta = mg$ and $F_N \sin\theta = mv^2/r$. **1**
$\tan\theta = v^2/(rg)$ gives $\theta = 45.0°$. **1**

Accept equivalent forms.

(c)

The resultant of weight and normal reaction, both directed downwards towards the centre, provides the centripetal force. OWTTE. **1**

The explanation must identify the resultant of the real forces.

(d)

At the top, $F_N + mg = mv^2/r$. **1**
$F_N = 0.800\left(\frac{14.0^2}{8.00} - 9.81\right) = 11.8$ N downwards. **1**

Accept a consistent alternative sign convention.

(e)

$f = v/(2\pi r) = 0.111$ Hz. **1**

Use the horizontal-track radius.

Question 6

(a)

The resultant external impulse in the horizontal plane is zero or negligible. OWTTE. **1**

The condition applies to the complete two-fragment system during separation.

(b)

Eastward momentum: $0.900(6.00) = 0.300(2.00) + 0.600v_{Bx}$. **1**
Northward momentum: $0 = 0.300(8.00) + 0.600v_{By}$. **1**
$v_{Bx} = 8.00$ m s^{-1} and $v_{By} = -4.00$ m s^{-1}. **1**

Accept consistent alternative coordinate conventions.

(c)

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$v_B = \sqrt{8.00^2 + (-4.00)^2} = \sqrt{80}\,\text{m s}^{-1} \approx 8.94\,\text{m s}^{-1}$. **1**
$\alpha = \tan^{-1}(4.00/8.00) = 26.6°$ south of east. **1**

ECF for the direction from part (b). The direction must specify the correct quadrant.

(d)

Initial kinetic energy is $E_{k,i} = \frac{1}{2}(0.900)(6.00)^2 = 16.2\,\text{J}$. **1**
Final total kinetic energy is $E_{k,f} = \frac{1}{2}(0.300)(2.00^2 + 8.00^2) + \frac{1}{2}(0.600)(80) = 34.2\,\text{J}$. **1**
Released internal energy equals the kinetic-energy increase: $E_{\text{released}} = 34.2 - 16.2 = 18.0\,\text{J}$. **1**

ECF from parts (b) and (c). Both perpendicular velocity components must contribute to each fragment's kinetic energy.

(e)

Weight and normal reaction both act towards the centre, and their resultant provides the centripetal force. OWTTE. **1**
Applies the radial force equation $F_N + m_B g = m_B v_B^2/r$. **1**
$F_N = 0.600\left(\frac{80}{2.00} - 9.81\right) = 18.1\,\text{N}$ downwards. **1**

ECF from part (c). Accept use of the shown speed $8.94\,\text{m s}^{-1}$.

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