

## Two Problems in Mechanics (10 points)

Please read the general instructions provided in the separate envelope before you start this problem.

### Part A. The Hidden Disk (3.5 points)

We consider a solid wooden cylinder of radius  $r_1$  and thickness  $h_1$ . Somewhere inside the wooden cylinder, the wood has been replaced by a metal disk of radius  $r_2$  and thickness  $h_2$ . The metal disk is placed in such a way that its symmetry axis  $B$  is parallel to the symmetry axis  $S$  of the wooden cylinder, and is placed at the same distance from the top and bottom faces of the wooden cylinder. We denote the distance between  $S$  and  $B$  by  $d$ . The density of wood is  $\rho_1$ , the density of the metal is  $\rho_2 > \rho_1$ . The total mass of the wooden cylinder and the metal disk inside is  $M$ .

In this task, we place the wooden cylinder on the ground so that it can freely roll to the left and right. See Fig. 1 for a side view and a view from above the setup.

The goal of this task is to determine the size and the position of the metal disk.

In what follows, when asked to express the result in terms of known quantities, you may always assume that the following are known:

$$r_1, h_1, \rho_1, \rho_2, M. \quad (1)$$

The goal is to determine  $r_2, h_2$  and  $d$ , through indirect measurements.

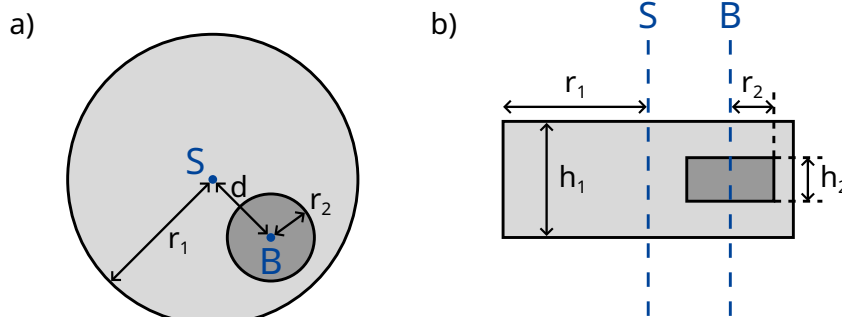


Figure 1: a) side view b) view from above

We denote  $b$  as the distance between the centre of mass  $C$  of the whole system and the symmetry axis  $S$  of the wooden cylinder. In order to determine this distance, we design the following experiment: We place the wooden cylinder on a horizontal base in such a way that it is in stable equilibrium. Let us now slowly incline the base by an angle  $\Theta$  (see Fig. 2). As a result of the static friction, the wooden cylinder can roll freely without sliding. It will roll down the incline a little bit, but then come to rest in stable equilibrium after rotating by an angle  $\phi$  which we measure.

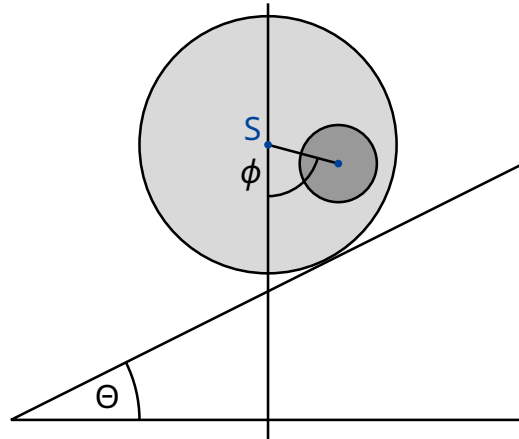


Figure 2: Cylinder on an inclined base.

- A.1** Find an expression for  $b$  as a function of the quantities given in (1), the angle  $\phi$  and the tilting angle  $\Theta$  of the base. 0.8pt

From now on, we can assume that the value of  $b$  is known.

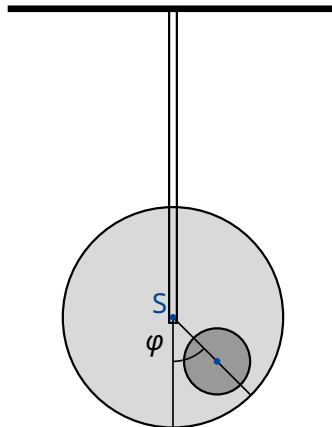


Figure 3: Suspended system.

Next we want to measure the moment of inertia  $I_S$  of the system with respect to the symmetry axis  $S$ . To this end, we suspend the wooden cylinder at its symmetry axis using a rigid rod. We then turn it away from its equilibrium position by a small angle  $\varphi$ , and let it go. See Figure 3 for the setup. We find that  $\varphi$  describes a periodic motion with period  $T$ .

- A.2** Write down the equation of motion for  $\varphi$ . Express the moment of inertia  $I_S$  of the system around its symmetry axis  $S$  in terms of  $T$ ,  $b$  and the known quantities given in (1). You may assume that we are only disturbing the equilibrium position by a small amount so that  $\varphi$  is always very small. 0.5pt

From the measurements in questions **A.1** and **A.2**, we now want to determine the geometry and the position of the metal disk inside the wooden cylinder.

- A.3** Find an expression for the distance  $d$  as a function of  $b$  and the quantities given in (1). You may also include  $r_2$  and  $h_2$  as variables in your expression, as they will be calculated in subtask **A.5**. 0.4pt

- A.4** Find an expression for the moment of inertia  $I_S$  in terms of  $b$  and the known quantities given in (1). You may also include  $r_2$  and  $h_2$  as variables in your expression, as they will be calculated in subtask **A.5**. 0.7pt

- A.5** Using all the above results, write down an expression for  $h_2$  and  $r_2$  in terms of  $b$ ,  $T$  and the known quantities given in (1). You may express  $h_2$  as a function of  $r_2$ . 1.1pt

## Part B. Rotating Space Station (6.5 points)

Alice is an astronaut living on a space station. The space station is a gigantic wheel of radius  $R$  rotating around its axis, thereby providing artificial gravity for the astronauts. The astronauts live on the inner side of the rim of the wheel as shown in Figure 4. The gravitational attraction of the space station and the curvature of the floor can be ignored.

- B.1** At what angular frequency  $\omega_{ss}$  does the space station rotate so that the astronauts experience the same gravitational field strength  $g_E$  as on the Earth's surface? 0.5pt

Alice and her astronaut friend Bob have an argument. Bob does not believe that they are in fact living in a space station and claims that they are on Earth. Alice wants to prove to Bob that they are living on a rotating space station by using physics. To this end, she attaches a mass  $m$  to a spring with spring constant  $k$  and lets it oscillate. The mass oscillates only in the vertical direction, and cannot move in the horizontal direction.

- B.2** If they did this on Earth, what would be the angular oscillation frequency  $\omega_E$  that they would measure? Assume that on Earth gravity is constant with acceleration  $g_E$ . 0.2pt

- B.3** What angular oscillation frequency  $\omega$  does Alice measure on the space station? 0.6pt

Alice is convinced that her experiment proves that they are on a rotating space station. Bob remains skeptical. He claims that when taking into account the change in gravity above the surface of the Earth, one finds a similar effect. In the following tasks we investigate whether Bob is right.

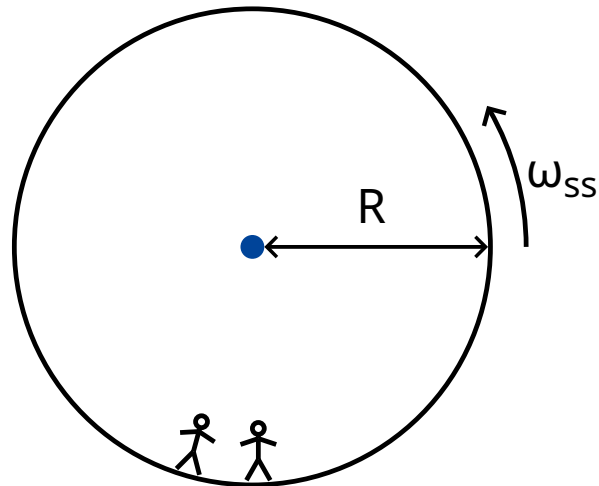


Figure 4: Space station

- B.4** Derive an expression of the gravitational field strength  $g_E(h)$  for small heights  $h$  above the surface of the Earth and compute the oscillation frequency  $\tilde{\omega}_E$  of the oscillating mass (linear approximation is enough). Denote the radius of the Earth by  $R_E$ . Neglect the rotation of Earth. 0.8pt

Indeed, for this space station, Alice finds that the spring pendulum oscillates with the frequency that Bob predicted.

- B.5** For what radius  $R$  of the space station does the oscillation frequency  $\omega$  match the oscillation frequency  $\tilde{\omega}_E$ ? Express your answer in terms of  $R_E$ . 0.3pt

Exasperated with Bob's stubbornness, Alice comes up with another experiment to prove her point. To this end, she climbs on a tower of height  $H$  over the floor of the space station and drops a mass. This experiment can be understood in the rotating reference frame as well as in an inertial reference frame.

In a uniformly rotating reference frame, the astronauts perceive a fictitious force  $\vec{F}_C$  called the Coriolis force. The force  $\vec{F}_C$  acting on an object of mass  $m$  moving at velocity  $\vec{v}$  in a rotating frame with constant angular frequency  $\vec{\omega}_{ss}$  is given by

$$\vec{F}_C = 2m\vec{v} \times \vec{\omega}_{ss} . \quad (2)$$

In terms of the scalar quantities you may use

$$F_C = 2mv\omega_{ss} \sin \phi , \quad (3)$$

where  $\phi$  is the angle between the velocity and the axis of rotation. The force is perpendicular to both the velocity  $v$  and the axis of rotation. The sign of the force can be determined from the right-hand rule, but in what follows you may choose it freely.

- B.6** Calculate the horizontal velocity  $v_x$  and the horizontal displacement  $d_x$  (relative to the base of the tower, in the direction perpendicular to the tower) of the mass at the moment it hits the floor. You may assume that the height  $H$  of the tower is small, so that the acceleration as measured by the astronauts is constant during the fall. Also, you may assume that  $d_x \ll H$ . 1.1pt

To get a good result, Alice decides to conduct this experiment from a much taller tower than before. To her surprise, the mass hits the floor at the base of the tower, so that  $d_x = 0$ .

- B.7** Find a lower bound for the height of the tower for which it can happen that  $d_x = 0$ . 1.3pt

Alice is willing to make one last attempt at convincing Bob. She wants to use her spring oscillator to show the effect of the Coriolis force. To this end, she changes the original setup: she attaches her spring to a ring which can slide freely on a horizontal rod in the  $x$  direction without any friction. The spring itself oscillates in the  $y$  direction. The rod is parallel to the floor and perpendicular to the axis of rotation of the space station. The  $xy$  plane is thus perpendicular to the axis of rotation, with the  $y$  direction pointing straight towards the center of rotation of the station.

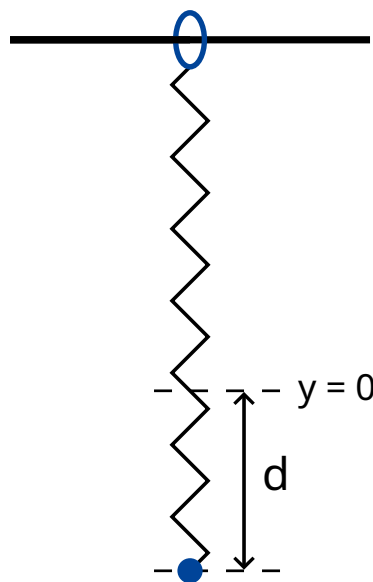


Figure 5: Setup.

- B.8** Alice pulls the mass a distance  $d$  downwards from the equilibrium point  $x = 0$ ,  $y = 0$ , and then lets it go (see Figure 5). 1.7pt
- Give an algebraic expression of  $x(t)$  and  $y(t)$ . You may assume that  $\omega_{ss}d$  is small, and neglect the Coriolis force affecting the motion along the  $y$ -axis.
  - Sketch the trajectory  $(x(t), y(t))$ , marking all important features such as amplitude.

Alice and Bob continue to argue.