LABORATORY NOTEBOOK

Mechanics

"All he thinks about is that stupid ball."

Luc Tremblay

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MECHANICS

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Lab 1

Kinematics

Goal

To check whether the acceleration of an object sliding on an inclined surface is constant and whether the magnitude of the acceleration is equal to the acceleration predicted by the theory.

Theory

In kinematics, the position of an object that performs a uniformly accelerated rectilinear motion is given by

$$x = v_0 t + \frac{1}{2} a t^2 \quad \textbf{(1)}$$

if the initial position is at $x = 0$. For an object sliding along a surface inclined at the angle α and experiencing no friction, the acceleration is given by

$$a = g \sin \alpha \quad \textbf{(2)}$$

Method Used

To verify this law, we will simply measure the position of an object as a function of time on an inclined plane. To perform the measurements of the positions, we will use an air cushion table. On this table, metal pucks are sliding. Friction is greatly reduced by using a compressor to push air under the pucks. Thus, the puck floats on an “air cushion” and there is practically no friction. To mark the position of the puck, we will use a spark generator. This generator produces a spark at regular intervals (50 ms in this experiment) and it is connected to the puck so that the spark occurs under the puck. Thus, the sparks will leave a mark on a paper that we have previously placed on the air cushion table.

We will tilt the table and let the puck slide under the effect of gravity. In this way, the puck will accelerate uniformly. With the spark marks, we can measure the position of the puck at different times.

It will not be very useful to plot the graph of the position as a function of time for this uniformly accelerated motion since we would then obtain a parabola. Since it is difficult to verify whether a curve is indeed a parabola, it would be difficult to verify equation (1) in this way.

To check the equation, the average speed will be used. This speed is

$$\bar{v} = \frac{x}{t}$$

Since

$$x = v_0 t + \frac{1}{2} a t^2$$

the average speed formula becomes

$$\bar{v} = \frac{v_0 t + \frac{1}{2} a t^2}{t}$$

$$\bar{v} = v_0 + \frac{1}{2} a t$$

This is the equation of a straight line. The slope of this line is

$$\text{slope} = \frac{1}{2} a$$

and the intercept is

$$\text{intercept} = v_0$$

By plotting the graph of $\bar{v}$ as a function of time, it will be easy to check whether we have a linear relation or not. If the relation is linear, then the acceleration is constant. With the slope of the graph, it will even be possible to find the acceleration and check whether it agrees with the predicted acceleration or not.

We will then check if the experimental acceleration (obtained with the slope of the graph) agrees with the theoretical acceleration (obtained with $g \sin \alpha$).

Equipment

- Air cushion table
- Compressor
- Spark generator
  Uncertainty of the period: ± 0.5%
  Uncertainty of the position of sparks: ± 1 mm
  (Does not include the uncertainty of the ruler)
- Puck
- Paper
- Ruler
- Electronic level
  Uncertainty of the angle: 0.05°

Procedure

- Select the 50 ms period on the spark generator.
- Tilt the table by placing an object under the back leg.
- For sparks to occur, the two pucks must be on the table. You can block the motion of the unused puck by placing it on a folded corner of the paper at the bottom of the table.
- Hold the other puck at the top of the table, start the spark generator and then let it go. Be careful not to push the puck in any direction as you let it go. You can prevent this unwanted movement by holding the puck at the edge of the table with a rope. To let the puck go, just release the rope. In this way, there will be no sideways motion.
- Measure the tilting angle of the table.

Maximum tilting angle:___________±_________
Minimum tilting angle:___________±_________

Measurements

In the lab report, give the following values:

- The maximum and minimum values of the tilting angle.
- The position x versus time t in a table.

Calculations

- Calculate the values of $\bar{v}$ (and their uncertainties) using the equation

  $$\bar{v} = \frac{x}{t}$$

  Present the results in a table.

- Plot the graph of $\bar{v}$ as a function of time.
- Calculate the value of the acceleration from the slope on the graph using the formula

  $$\text{slope} = \frac{1}{2}a$$

- Calculate the value of the tilting angle from the maximum and minimum values of the angle.
- Calculate the value of the theoretical acceleration with $a = g \sin \alpha$. (α is the tilting angle of the table.) Use $g = 9.81$ m/s² ± 0.01 m/s².

Analysis

- Is the acceleration constant? (Do you have a linear relation for $\bar{v}$ as a function of time as expected?)
- Do your two acceleration values agree?

Attach the large lab sheet to the lab report.

Lab 2

Projectile Motion

Goal

Check the equations giving the flight time, the range and the maximum height for the motion of a projectile.

Theory

When a projectile is launched and falls back at the same height as it was launched, the flight time is

$$t = \frac{2v_0 \sin\theta}{a}$$

The range of the projectile is

$$R = \frac{v_0^2 \sin 2\theta}{a}$$

The maximum height reached by the projectile is

$$h = \frac{v_0^2 \sin^2\theta}{2a}$$

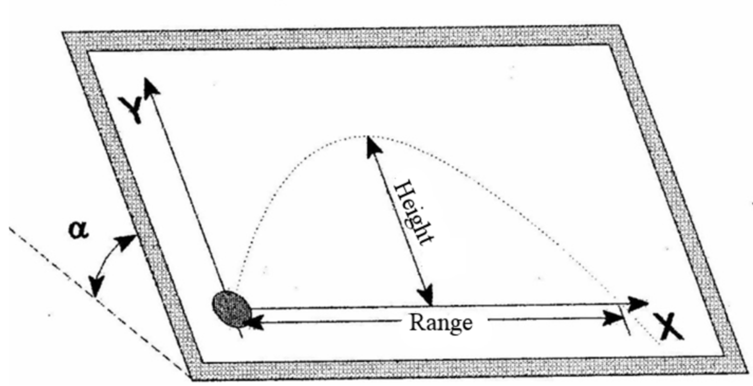
The acceleration is obviously g for a projectile launched in the air. However, if the motion occurs on a tilted table, the acceleration a is

$$a = g \sin\alpha$$

where α is the tilting angle of incline of the table and $g = 9.81$ m/s² $\pm$ 0.01 m/s².

Method Used

The position of an object that performs a projectile motion in two dimensions must be recorded. To do this, a tilted air cushion table is used. Giving a slight push to the puck at the start, we obtain a projectile motion as shown in the figure. Starting the spark generator shortly before launch, the position at regular intervals is recorded. Then, we can measure the flight time, the range and the maximum height attained by the projectile. Knowing the time between the sparks, the initial speed can also be calculated.



Equipment

- Air cushion table
- Compressor
- Spark generator
  Uncertainty of the period: ± 0.5%
  Uncertainty of the position of sparks: ± 1 mm
  (Does not include the uncertainty of the ruler)
- Puck
- Paper
- Ruler
- Electronic level
  Uncertainty of the angle: 0.05°

Procedure

- Place an object under the back leg of the table to tilt the table.

- Measure the tilting angle of the table.

Tilting angle (α) = ______________ ± __________

- Select the 10 ms period on the spark generator.

- To get the best projectile motion, the puck must be launched so that it passes as close as possible to the top of the recording sheet and arrives at the other corner of the table (see figure 1). Practice a few times before making the recording.

- Let a puck fall from the top of the table without pushing it while recording its motion. The trajectory of this puck will be your y-axis. To make sure that it falls exactly in the direction of the acceleration, you can hold your puck with a rope and let go of the rope so that there is no sideways motion.

Measurements

- Choose a starting point for your projectile motion. This point is not necessarily at the beginning of the path; it can be anywhere on the ascending part of the trajectory, provided that this position corresponds to a place where the puck is not being pushed.

- From this starting point, draw a horizontal and a vertical axis. Your vertical axis must be absolutely parallel to the path of the falling puck obtained in the last stage of manipulation.

- Count the number of points recorded between the starting point and the final point of your projectile motion. Do not count the starting point.

Number of points (N) = ______________ ± __________

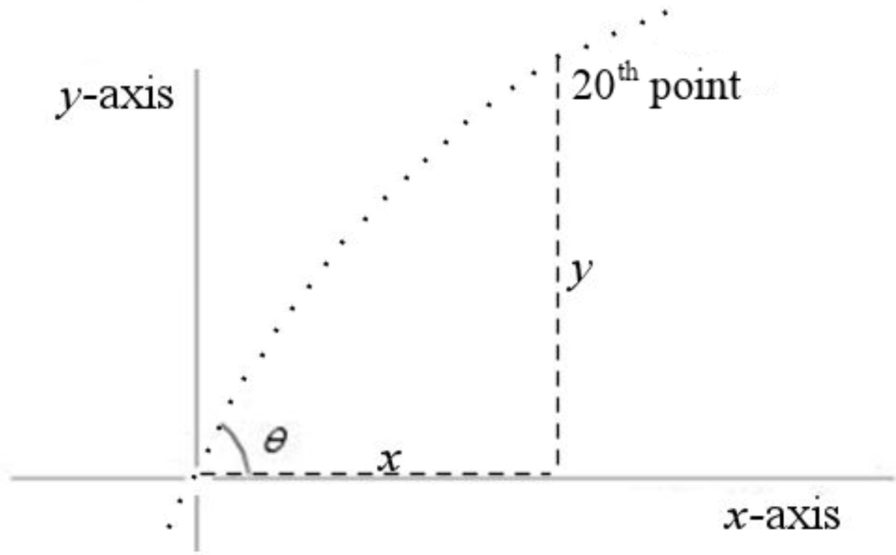
- Measure the range (R) of your projectile.

Range (R) = ______________ ± __________

- Measure the maximum height (h) of your projectile.

Height (h) = ____________ ± ____________

- To determine the initial speed of the puck, the x-position of a point a little after the starting point must be measured. For example, the position of the 20th point is measured in the figure.



x = ____________ ± ____________

Time at the point used (t_v) = ____________ ± ____________

- Measure the launch angle (θ) of your projectile.

Launch angle (θ) = ________ ± ______

In the lab report, give the following values:

- The tilting angle α
- The number of point N
- The range R
- The maximal height h
- The x position of the point used to find the initial speed
- The time t_v at the point used to find the initial speed
- The launch angle θ

Calculations

- Calculate the time of flight of the projectile with

$$t = N \cdot 0,01s$$

- Calculate the acceleration of the projectile with

$$a = g\sin\alpha$$

where g = 9.81 m/s² ± 0.01 m/s² and α is the tilting angle of the table (not to be confused with the launch angle of the projectile θ).

- Since the x-position of the 20th point is $x = v_{0x}t_v$, the x-component of the initial velocity can be calculated with

$$v_{0x} = \frac{x}{t_v}$$

- Calculate the initial speed of the projectile with

$$v_{0x} = v_0\cos\theta$$

- Calculate the theoretical flight time of the projectile with

$$t = \frac{2v_0\sin\theta}{a}$$

- Calculate the theoretical range with

$$R = \frac{v_0^2\sin 2\theta}{a}$$

- Calculate the theoretical maximal height with

$$h = \frac{v_0^2\sin^2\theta}{2a}$$

Data analysis

- Compare your theoretical flight time and the measured flight time.
- Compare your theoretical range and the measured range.
- Compare your theoretical height and the measured height.

Attach the large lab sheet to the lab report.

Lab 3

Newton's Laws and the Gravitational Force

Goal

Check that the value of the acceleration of a system on which the gravitational force acts is given by Newton's laws and by $F = mg$.

Theory

When a non-zero net force acts on an object, there is an acceleration in the direction of the net force. According to Newton's second law, the acceleration is given by

$$\sum \vec{F} = m\vec{a} \qquad \textbf{(1)}$$

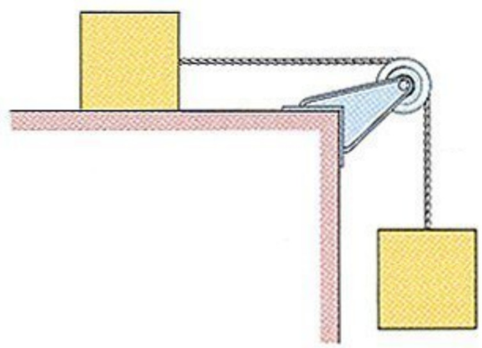
To use this law, the force must be known. A well-known force is the force of gravity. On the surface of the Earth, the gravitational force exerted on a mass is given by

$$F = mg \quad \text{downwards} \qquad \textbf{(2)}$$

where g is 9.81 m/s² ± 0.01 m/s² in Quebec City.

Method used

We will simply tie a suspended object to a puck on a horizontal surface with a string. The gravitational force exerted on the suspended object will then accelerate the two masses. We will use the air cushion table to eliminate any friction and mark the position of the puck at regular intervals. With these position marks, we will be able to calculate the acceleration and check whether it is consistent with the acceleration given by the formulas 1 and 2.



Equipment

- Air cushion table
- Compressor
- Spark generator
  Uncertainty of the period: ± 0.5%
  Uncertainty of the position of spark: ± 1 mm
  (Does not include the uncertainty of the ruler)
- Puck
- Paper
- 100 g mass (suspended object)
- Rope
- Scale
  Uncertainty ± 0.1 g
- Ruler

Procedure

- Measure the masses of the suspended object and the puck

Mass of the suspended object $m =$ ______________ $\pm$ ________

Mass of the puck $M =$ ______________ $\pm$ ________

- Level the table.
- Connect the puck and the 100 g mass with a rope.
- Select the 50 ms period on the spark generator.
- Record the accelerated motion of the puck.

Measurements

In the lab report, give the following values:

- the masses m and M.
- the position of the puck as a function of time (present these results in a table).

Calculations

The acceleration will be found with a graph. As this is theoretically a uniformly accelerated motion, the method is identical to the method used in lab 1. Therefore, these steps must be followed:

- Calculate the values of $\bar{v}$ (with their uncertainties) with the following equation.

$$\bar{v} = \frac{x}{t}$$

Present your results in a table form.

- Plot the graph of $\bar{v}$ as a function of time.

- Calculate the value of the acceleration from the slope of the graph using the formula

$$\text{slope} = \frac{1}{2}a$$

  This is your experimental acceleration.

- Calculate the theoretical acceleration of the system from Newton's laws. Remember that g = 9.81 m/s² ± 0.01 m/s².

Data Analysis

- Compare the experimental acceleration and the theoretical acceleration.

Attach the large lab sheet to the lab report.

LAB 4

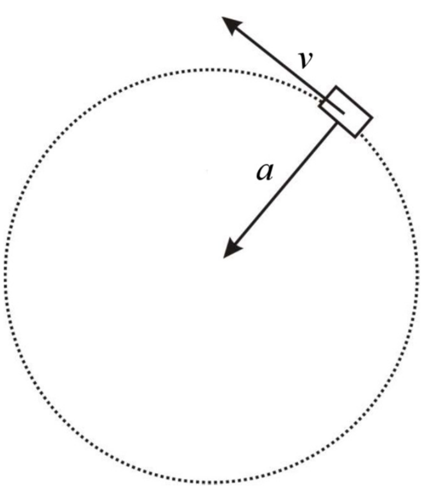
CENTRIPETAL FORCE

Goal

Check the formula for the centripetal force.

$$F = \frac{4\pi^2 mr}{T^2}$$

Theory



When an object makes a uniform circular motion, the centripetal acceleration of the object is given by

$$a = \frac{v^2}{r} \tag{1}$$

where v is the speed of the object and r is the radius of the path.

If the mass of the object is m, the centripetal force is

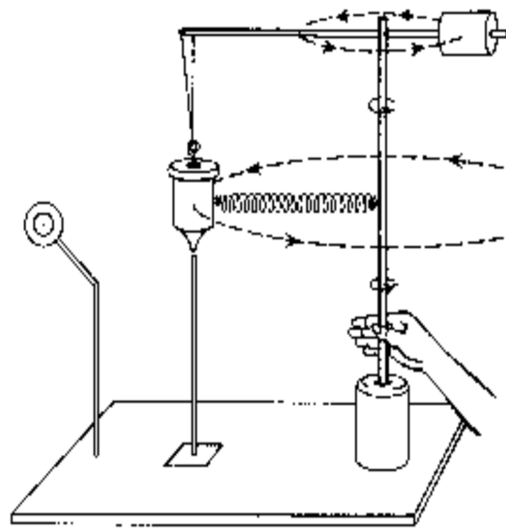
$$F = \frac{mv^2}{r} \tag{2}$$

towards the centre. Since $v = 2\pi r / T$ (where T is the period), the equation becomes

$$F = \frac{4\pi^2 mr}{T^2} \tag{3}$$

Method used

The setup shown in the figure will be used



The mass M hangs from a horizontal rod that can rotate around a vertical axis. You can adjust the distance of the mass from the axis of rotation (r). A spring connects the axis to the mass. This spring will exert the centripetal force. On the base of the setup, an adjustable vertical rod is installed. Place the rod at the same distance from the axis that the mass.

The mass M of the rotating object and the radius r of the circular path will be measured.

The mass will then be rotated at a constant speed, and the period of revolution will be measured. Then we will be able to calculate the centripetal force with the equation 3.

This centripetal force is exerted by the spring that goes from the vertical axis to the mass M. As we are familiar with springs, it is easy to determine the force exerted by the spring. This force should be the same as the force calculated with equation 3.

Material

- Centripetal force apparatus
- Stopwatch
- Ruler
- Slotted masses and weight hanger
- Scale
  Uncertainty ± 0,1 g

Procedure

- Measure the mass M of the rotating object.

M = ______________ ± _________

- Hang the mass M to the horizontal rod, but not to the spring.

- Adjust the position of the adjustable vertical rod so it is positioned exactly below the pointed end of the mass.

- Measure the distance from the mass to the axis. Attention, the radius r is measured from the centre of both rods.

r = ______________ ± _________

- Attach the spring to the mass M. Pass the string attached to the mass M over the pulley and tie the end of the string to the weight hanger. Gradually add masses on this weight hanger until the pointed end of the mass M is exactly over the adjustable vertical rod. Measure the masses of the suspended weight (m).

m max = ______________ ± _________
min = ______________ ± _________

We know then the force exerted by the spring when the mass M is directly above the adjustable rod since the spring force is exactly offset by the weight of the suspended mass m. Therefore, $F_{\text{spring}} = mg$.

Caution: the spring and the string that goes from the mass M to the pulley must be horizontal. If not, we cannot say that mg is equal to the spring force because the force of gravity exerted on M will come into play.

- Remove the slotted masses as well as the weight hanger. Acting on the vertical axis, rotate the apparatus with your hand. Adjust the speed so that the pointed end of the mass M passes right over the adjustable vertical rod. Keep a constant rotational speed and measure, using a stopwatch, the duration of 20 complete rotations.

t = ______________ ± _________

Measurements

In the lab report, give the following values:

- The mass of the turning object (M)
- The radius of the circular path (r)
- The maximum and minimum value suspended mass (m)
- The suspended mass (m) (found from the maximum and minimum values)
- The time required to do 20 rotations (t)

Calculations

- Calculate the period of rotation.

- Calculate the centripetal force (equation 3).

- Calculate the force exerted by the spring ($F = mg$).

Data Analysis

- Compare the two values of the force.

Lab 5

Energy Conservation

Goal

Check the law of conservation of mechanical energy.

Theory

For an isolated system involving only conservative forces, the total mechanical energy is conserved.

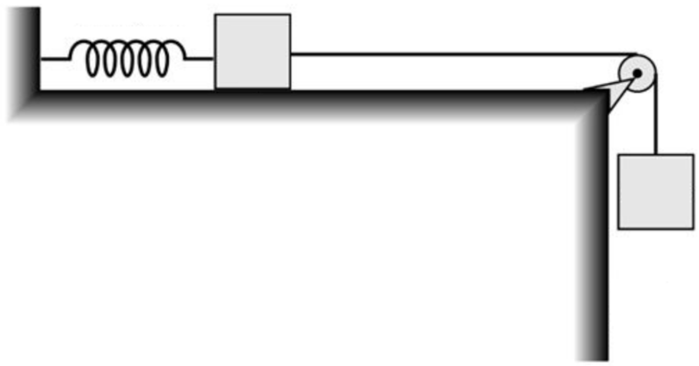
In our experiment, a system consisting of two masses and a spring will be used. Thus, the law of conservation of mechanical energy becomes

$$E = \frac{1}{2}M_1 v^2 + M_1 g y_1 + \frac{1}{2}M_2 v^2 + M_2 g y_2 + \frac{1}{2}kx^2 = \text{constant}$$

where g = 9.81 m/s² ± 0.01 m/s² in Quebec City.

Method Used

To check the mechanical energy conservation, the following setup will be used.



When the suspended mass falls, its gravitational energy decreases. The energy then becomes kinetic energy of the system and spring energy. However, the mechanical energy is only conserved if there is no friction. The air cushion table is therefore used to eliminate the friction between the puck and the table.

Using the spark generator to mark the position of the puck, we will be able to measure the fall distance of the suspended mass, the speed of the system and the stretching of the spring. With these data, we will be able to calculate the initial and final mechanical energies and verify whether there is conservation or not.

Equipment

- Air cushion table
- Compressor
- Spark generator
  Uncertainty of the period: ± 0.5%
  Uncertainty of the position of sparks: ± 1 mm
  (Does not include the uncertainty of the ruler)
- Puck
- Paper
- A 200 g mass (suspended object) and a 100 g mass
- Rope
- Spring

- Scale
  Uncertainty ± 0.1 g

- Stopwatch

- Ruler

Procedure

- Level the table.

Spring Constant Measurement

The spring constant must first be measured. To achieve this, we use the fact that the period of oscillation of a spring-mass system depends on the spring constant according to

$$k = \frac{4\pi^2 m}{T^2}$$

where m is the mass of the object attached to the spring.

- Hang a mass of 100 g to the spring.

$m =$ ______________ ± __________

- Give the mass an oscillation motion with an amplitude of about 5 cm.

- Using a stopwatch, measure the period of 50 oscillations

Time = ______________ ± __________

Energy Conservation

- Measure the mass of the puck.

$M_1 =$ ______________ ± __________

- Measured the mass of the suspended mass

$$M_2 = \underline{\qquad\qquad\qquad \pm \qquad\qquad}$$

- Attach your suspended mass to the puck.

- Attach the spring to the puck and to the table.

- Select the 10 ms period on the spark generator.

- Record the motion when the system is released. Make sure that the spring is not stretched at the beginning so that there is no spring energy.

Measurements

For the end point of the motion, we will take the penultimate point. We make this choice because the speed of the puck at the final position must be found and, in order to do that, we will divide the distance between the point before the end point and the point after the end point by the time required to travel between these points. This will give us the average speed in the interval between these two points, which corresponds approximately to the speed at the end point.

For the gravitational energy of the suspended mass, the initial height of the suspended mass must be known. If we set that the origin $y = 0$ is at the final position of the suspended mass, its initial height is simply the distance between the initial and final position of the puck. This distance (L) is also stretching of the spring.

To calculate the final speed, the distance (d) and time (t) between the point before the end point and the point following the final point must be measured.

In the lab report, give the following values:

- The mass attached to the spring (m) to calculate the spring constant
- The time required to make 50 oscillations
- The mass of the puck (M_1)
- The mass of the suspended mass (M_2)
- The distance between the starting point and the end point (L)
- The distance between the point preceding the final point and the point following the end point (d).
- The time between the point preceding the final point and the point following the end point (t).

Calculations

Initial Energy

The mechanical energy is

$$E = \frac{1}{2}M_1v^2 + M_1gy_1 + \frac{1}{2}M_2v^2 + M_2gy_2 + \frac{1}{2}kx^2$$

As the puck and the suspended mass do not move at the start, the kinetic energies are zero. As we will put the y_1 = 0 for the puck (M_1) at its initial position, the gravitational energy of the puck is zero. As the spring is not stretched at the start, the spring energy is zero. Therefore, only the gravitational energy of the suspended mass remains

$$E = M_2gh_2$$

As we set that the origin y_2 = 0 is located at the final position of the suspended mass, its initial height corresponds to the fall distance, thus the distance between the starting point and the end point of the path (L). The initial energy then becomes

$$E = M_2gL$$

- Calculate the value of the initial energy using g = 9.81 m/s² ± 0.01 m/s².

Final Energy

The mechanical energy is

$$E' = \frac{1}{2}M_1v'^2 + M_1gy_1' + \frac{1}{2}M_2v'^2 + M_2gy_2' + \frac{1}{2}kx'^2$$

As the puck remains at the same height, it is still at y_1 = 0, and its gravitational energy is still 0. As the suspended mass is now at its final position and it has stipulated that y_2 = 0 at its final position, the gravitational energy of the suspended mass is now zero. The final mechanical energy is therefore

$$E' = \frac{1}{2}M_1v'^2 + \frac{1}{2}M_2v'^2 + \frac{1}{2}kx'^2$$

To calculate this final energy, the speed of the system and the spring constant are required.

Speed of the System

- Calculate the final speed of the system with

$$v' = \frac{d}{t}$$

Spring Constant

- Calculate the period of one oscillation.

- Calculate the spring constant using the formula

$$k = \frac{4\pi^2 m}{T^2}$$

The final energy can now be calculated. Since the spring was not stretched initially, the stretching the spring corresponds to the displacement of the puck, so to the distance from the starting point to the end final (L). The energy is therefore

$$E' = \frac{1}{2}M_1 v'^2 + \frac{1}{2}M_2 v'^2 + \frac{1}{2}kL^2$$

- Calculate the value of the final energy.

Data Analysis

- Compare the initial mechanical energy and final mechanical energy.

Attach the large lab sheet to the lab report.

LAB 6

COLLISIONS

Goal

Check the momentum and the mechanical energy conservation in elastic collisions between two objects.

Theory

The momentum of an object is a vector quantity defined as the product of mass and velocity of an object

$$\vec{p} = m\vec{v} \qquad \textbf{(1)}$$

In a collision between two objects, the forces exerted on the two objects are internal forces. Then, the total momentum of the two objects is conserved. This is the law of conservation of momentum.

$$\vec{p}_1 + \vec{p}_2 = \vec{p}\,'_1 + \vec{p}\,'_2 \qquad \textbf{(2)}$$

If this equation is resolved into components, we obtain

$$p_{1x} + p_{2x} = p'_{1x} + p'_{2x} \qquad \textbf{(3)}$$

and

$$p_{1y} + p_{2y} = p'_{1y} + p'_{2y} \qquad \textbf{(4)}$$

The kinetic energy of an object of mass m and speed v is a scalar quantity defined by

$$E_k = \frac{1}{2}mv^2 \qquad \textbf{(5)}$$

If the collision is elastic, then the total kinetic energy is the same before and after the collision. This means that

$$E_{k1} + E_{k2} = E'_{k1} + E'_{k2} \tag{6}$$

Method Used

To verify the conservation of momentum (equations 3 and 4) and of kinetic energy (equation 6) in an elastic collision, it seems obvious that it is necessary to cause a collision. We will, therefore, make a collision between two pucks on an air cushion table. Using the air cushion table, the friction that normally would make it difficult to verify conservation principles is eliminated.

With the spark marks of the puck, the speed and direction of the motion of each puck can be found. This will allow us to measure the total momentum and the total kinetic energy before and after the collision.

Equipment

- Air cushion table
- Compressor
- Spark generator
  Uncertainty of the period: ± 0.5%
  Uncertainty of the position of sparks: ± 1 mm
  (Does not include the uncertainty of the ruler)
- Two pucks
- Paper
- Scale
  Uncertainty ± 0.1 g
- Ruler
- Protractor

Procedure

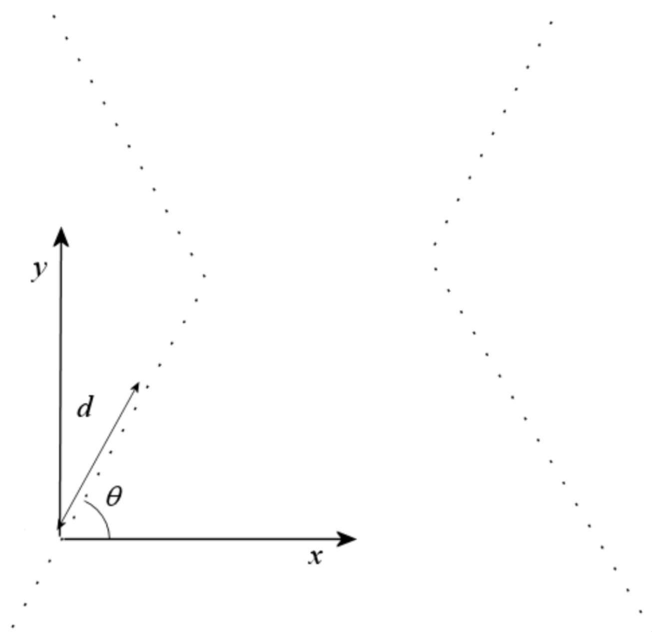
- Measure the mass of the pucks. Clearly identify your pucks to avoid any confusion.

m_1 = ________ ± ________ m_2 = ________ ± ________

- Level the table.
- Select the 50 ms period on the spark generator.
- Record the collision by launching the two pucks so they collided approximately in the centre of the table.

Measurements

The figure shows that the values of d and θ for puck 1 prior to the collision.



- Choose the x and y-axes to resolve the momentum into components. The direction of these axes is quite arbitrary, provided they are perpendicular to each other. However, once the choice is made, the axes must remain the same for all calculations.

- Measure the distance (d) and time (t) between the points near the collision for each of the puck before and after the collision. This distance will allow us to calculate the speed of the puck before and after the collision.

- Measure the angle (θ) between the direction of the velocity and the x-axis for each puck.

In the lab report, give the following values:

- The mass of puck 1 (m_1)
- The mass of puck 2 (m_2)
- The distance between two points for puck 1 before the collision (d_1)
- The time between two points for puck 1 before the collision (t_1)
- The angle between the velocity and the x-axis for puck 1 before the collision (θ_1)
- The distance between two points for puck 2 before the collision (d_2)
- The time between two points for puck 2 before the collision (t_2)
- The angle between the velocity and the x-axis for puck 2 before the collision (θ_2)
- The distance between two points for puck 1 after the collision (d_1')
- The time between two points for puck 1 after the collision (t_1')
- The angle between the velocity and the x-axis for puck 1 after the collision (θ_1')
- The distance between two points for puck 2 after the collision (d_2')
- The time between two points for puck 2 after the collision (t_2')
- The angle between the velocity and the x-axis for puck 2 after the collision (θ_2')

Calculations

- Calculate the velocity of pucks before the collision with

$$v = \frac{d}{t}$$

- Calculate the components of the momentum before the collision with

$$p_x = mv\cos\theta$$
$$p_y = mv\sin\theta$$

- Calculate the components of the total momentum before the collision with

$$p_{xtot} = p_{1x} + p_{2x}$$
$$p_{ytot} = p_{1y} + p_{2y}$$

- Calculate the total initial kinetic energy before the collision with

$$E_{ktot} = \frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 v_2^2$$

- Repeat these calculations for the motions after the collision while keeping the same system of axes.

Data Analysis

- Compare the initial and final *x*-components of the total momentum.
- Compare the initial and final *y*-components of the total momentum.
- Compare the initial and final total kinetic energies.

Attach the large lab sheet to the report.