Physics IA

Research Question: How does the angle of an inclined plane affect the loss of energy of a cylinder rolling down the inclined plane?

Introduction

I used to play with hotwheel cars a lot. I always wondered why when I launched two different cars from higher ground, they would cover different distances. In mechanics, I have learnt about the dynamic friction and static friction and their effects. I realized that each of the cars probably had different coefficients of both dynamic and static friction which caused them to cover different distances. This caused them to lose different amounts of kinetic energy. I realized there's a similar effect even when I cycle. I remember trying to cycle down slopes as a child but didn't realize energy considerations are important to ensure I know how much force to use on the pedal, and when to use the breaks in relation to how steep the slope is. After doing further research[1], I found other factors affecting energy loss in a cylinder rolling down a plane, such as the mass of the cylinder, the mass distribution of the cylinder and angle of inclination of an inclined plane. Since I found the angle of inclination affecting energy to be the most prominent in my life, I hence decided to make my independent variable the angle of the plane, and my dependent variable the energy loss. To perform this experiment, I will be using an inclined plane and will release a cylinder from rest from the higher end of the plane. Once the cylinder reaches the bottom of the plane, I will measure both the kinetic energy and the rotational kinetic energy of the cylinder and using that information, calculate the energy loss.

Background Information

The concept of Torque

Torque is a force that can cause an object to rotate about an axis, hence causing rotational motion.[2] In the case of a cylinder rolling down an inclined plane (**Figure 1**), the torque force is provided by the frictional force. This is also seen in the diagram as the frictional force is the only force acting perpendicular to the surface of the cylinder. Without frictional force, the cylinder would instead slide down the plank. Torque is denoted by the symbol τ (tau).

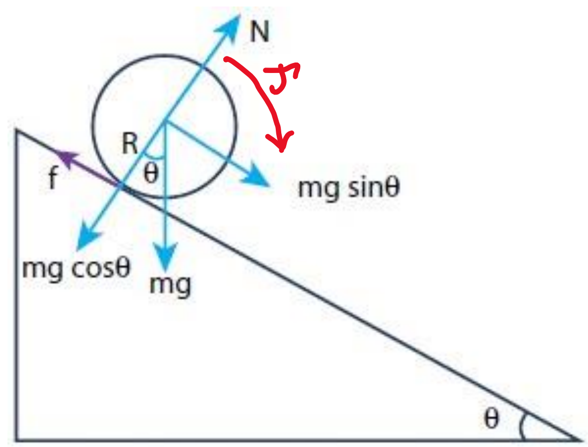


Figure 1: Visulization of a cylinder rolling down a plane. The force labelled in red is the torque.

Deriving the equation of energy loss of a cylinder rolling down an inclined plane (make this a big subheading)

When a cylinder rolls down an inclined plane (**Figure 1**[3]), initially it has only potential energy. This potential energy is converted into two sources of kinetic energy[4], translational kinetic energy (linear) and rotational kinetic energy when the cylinder is released. The sum of the final translational (linear) kinetic energy and rotational kinetic energy should be equal to the initial potential

[1] UKEssays. (November 2018). Factors Affecting Velocity of a Sphere Rolling Down Incline. Nov 23 2022, Retrieved from https://www.ukessays.com/essays/physics/factors-affecting-velocity-sphere-rolling-9299.php?vref=1
[2] Khan, Sal, "Torque", Khan Academy, 31 May 2022, https://www.khanacademy.org/science/physics/torque-angular-momentum/torque-tutorial/a/torque#:~:text=Torque%20is%20a%20measure%20of,Torque%20is%20a%20vector%20quantity.
[3] "Rolling on Inclined Plane", brainkart, 10 July 2022https://www.brainkart.com/article/Rolling-on-Inclined-Plane_34631/
[4] Homer, David, Oxford IB Diploma Programme Physics Course Companion, 2014 Edition, 556

energy if there are no energy losses, but in the real world this is not the case. I will be using this explanation to make a formula for energy loss.

Energies due to rotation and movement of the cylinder

The energy from the translatory motion of the cylinder rolling down the plane is the linear kinetic energy (where m is the mass of the cylinder and v is the velocity of the cylinder down the plane) – [5]

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

The energy that arises due to the rotation of the cylinder along its center of gravity is different. This is because this energy arises due to rotational motion, hence we must use the rotational kinetic energy formula (Where I is the moment of inertia and ω is the angular velocity) – [6]

$$E_{k_{rot}} = \frac{1}{2}I\omega^2 \qquad (2)$$

This can be re-written using the angular velocity formula –

$$\omega = \frac{2\pi}{T} \qquad (2.0.1)$$

Substituting (2.0.1) – Angular velocity into (2) – Rotational Kinetic energy, we get –

$$E_{k_{rot}} = \frac{1}{2}I\left(\frac{2\pi}{T}\right)^2 \qquad (2.0.2)$$

Note that both the energies in the context of my exploration refer to the final kinetic energy and final rotational energy respectively.

Potential Energy

We know that at the beginning of the experiment, the cylinder will be rolled from the top of the inclined plane at rest. This means that at the beginning of the experiment there is only gravitational potential energy equal to (where m is the mass of the cylinder, g is the acceleration due to free fall and h is the height from the surface of the ground) –

$$E_p = mgh \qquad (2.1)$$

Note that potential energy in the context of my exploration refers to only initial potential energy

Energy Loss Formula

As explained previously, all the initial potential energy is converted into final kinetic energy and final rotational energy.

By law of conservation of energy – [7]

$$E_p = E_k + E_{k_{rot}}$$

[5] Issacphysics, ”Kinetic Energy: Linear and Rotational”, University of Cambridge, 12 July 2022 https://isaacphysics.org/concepts/cp_kinetic_energy?stage=all

[6] OpenStax, “Moment of Inertia and Rotational Kinetic energy, University of Florida, 15 July 2022, ”https://pressbooks.online.ucf.edu/osuniversityphysics/chapter/10-4-moment-of-inertia-and-rotational-kinetic-energy/

[7] Homer, David, Oxford IB Diploma Programme Physics Course Companion, 2014 Edition, 556

Though we get this as the formula, there is always loss of energy in the form of sound and heat given off to the surroundings. Hence to find the energy loss, we can make a formula as follows (according to the explanation given previously) –

$$Energy\ Lost = E_p - (E_k + E_{k\,rot}) \qquad (3)$$

This is because there is a loss of energy due to frictional and air resistance forces which causes the initial energy to be higher than the final energy.

Relationship Derivation

In this part of the exploration, I will be focusing on finding a relationship between energy lost and the angle. Note that all formulas in this section will be with reference to **Figure 1:** Visulization of a cylinder rolling down a plane.

Potential Energy

We know that

$$E_p = mgh$$

But in the context of this experiment, all those values are constants. This is because the mass of the cylinder is kept the same. The acceleration due to free fall remains the same at the same altitude and location and the height of the inclined plane remains constant for any single angle of inclination used (though it changes once we change the value of the angle).

Rotational Energy

Considering rotational energy, using the rotational kinetic energy formula (2.0.2), we get,

$$E_{k_{rot}} = \frac{1}{2} I \left(\frac{2\pi}{T}\right)^2$$

All the values in this equation are also constant (for the same angle) as they remain unchanged in theory. The moment of inertia remains constant as the same mass is used. The time period also remains constant in theory, as in theory energy loss would not be considered. This would lead to the exact same acceleration and final velocity in theory; hence the same time period will be derived for every trial of the experiment.

Linear Kinetic Energy

According to formula (1) – Kinetic energy, we need both the mass of the cylinder and the linear velocity. To calculate the linear velocity, we first must calculate the acceleration perpendicular to the plane. Acceleration in this case remains constant.[8] Now using the formula –

$$F = ma$$

$$a = \frac{F}{m}$$

Now substituting the values according to **Figure 1** (Note that the numerator contains the net force in the component perpendicular to the surface of the plane)

[8] Sholtz, Sophia, “Ball rolling down inclined plane”, UCSC Physics demonstration room, 12 September 2022, https://ucscphysicsdemo.sites.ucsc.edu/physics-5a6a/ball-rolling-down-inclined-plane/

$$Acceleration\ horizontally\ = \frac{(mg\ \times \sin\theta) - f}{Mass}$$

(Where f is the frictional force according to **Figure 1**)

Additionally, since we know that acceleration is constant, we can use the equation (where v is final velocity, u is initial velocity, t is the time taken to roll down the plank and a is the constant acceleration of the cylinder down the ramp),

$$v = u + at$$

We know the cylinder starts from rest so u = 0cm/s and we also know that when an object rolls down an inclined plane, it does so with constant acceleration[9], so we get

$$v = at$$

Substituting this in the previous equation we get

$$v = \frac{t \times (mg \times \sin\theta) - f}{Mass}$$

Substituting this into (1) – Kinetic Energy, we get

$$E_k = \frac{1}{2}Mass \times \left(\frac{t \times (mg \times \sin\theta) - f}{Mass}\right)^2$$

All the values in this equation are constant. The frictional force is also constant as the same surface was used throughout all trials of the experiment. This means the coefficient of both dynamic and static friction remains the same. This means the only value that is not constant is $\sin^2(\theta)$.

Substituting the values for E_k, $E_{k_{rot}}$ and E_p into equation (3) – Energy loss we get the following,

$$Energy\ loss = \ mgh - \left(\frac{1}{2}Mass \times \left(\frac{t \times (mg \times \sin\theta) - f}{Mass}\right)^2\right) - \frac{1}{2}I\left(\frac{2\pi}{T}\right)^2$$

We see that all the values in this equation are constant other than $\sin(\theta)^2$, hence we get the relation,

$$Energy\ loss\ \propto \sin(\theta)^2$$

Note the relationship between the angle and energy loss cannot be taken directly as that would require using the small angle approximation. My experiment uses angles until the value of 30° and the approximation holds only until 15°

Hypothesis

Therefore, my hypothesis is that the loss of energy is proportional to $\sin(\theta)^2$ of an angle.

$$Energy\ loss\ \propto \sin(\theta)^2$$

Experiment

Uncertainties

[9] Sholtz, Sophia, “Ball rolling down inclined plane”, UCSC Physics demonstration room, 12 September 2022, https://ucscphysicsdemo.sites.ucsc.edu/physics-5a6a/ball-rolling-down-inclined-plane/

Inclined Plane – The protractor of the inclined plane had a least count of 1°. This means that the reading uncertainty due to the inclined plane is ± 0.5°. Though this is taken as the uncertainty, there is a possibility that due to the manufacturing process, the values on the protractor are not exactly accurate which could lead to systematic error.

Meter Scale – A meter scale was used to measure the height of the inclined plane above the ground. The least count of this scale was 0.1cm, hence the reading uncertainty is ± 0.05cm.

Caliper – A digital caliper of least count 10^{-5} cm was used to measure the radius of the cylinder. Hence an uncertainty of $\pm 10^{-5}$ cm in the radius of the cylinder.

Weighing balance – When measuring the mass of the cylinder, there were fluctuations in the measurement. Hence, I measured the mass of the cylinder for ten seconds and used the formula-

$$\frac{max - min}{2} \qquad (4)$$

The maximum and minimum value had a difference of 0.06g, hence the uncertainty taken was ± 0.03g.

Time for translatory motion – The time was measured by recording each clip at 240 fps and re-watching it frame by frame. The time was calculated based on the number of frames taken for the ball to roll down the plane. The uncertainty was calculated using formula (4).

The recording was taken such that the phone was placed in a 90° to the plane to ensure the least amount of parallax error. The uncertainty for time taken due to the recording is taken as 1/240s, or $\pm 0.0042s$. The larger value of both was taken.

Time Period (Time taken by cylinder for one rotation along its circumference) – The time period was measured by marking the cylinder on the circumference as it was rolling. This was then analyzed through video and the uncertainty was calculated using formula (4) .

The uncertainty for time period due to the recording is taken as 1/240s, or $\pm 0.0042s$. The larger value of both was taken.

<u>Variables</u>

Independent Variable – Independent variable is the angle of the plane against the surface. It can be changed by changing the angle of the inclined plane in my experimental setup. The values taken were 5°, 10°, 15°, 20°, 25°, 30°.

Dependent Variable – My dependent variable is energy loss. It must be calculated from the values obtained in the experiment using formula **(3).**

Controlled Variable	Why is it controlled	How it is controlled
Radius of the cylinder	Changing the radius of the cylinder will change the moment of inertia value as implied by equation (2). If a larger radius is used, this drastically increases the moment of inertia value and if a smaller radius is used, this drastically decreases moment of inertia value.	It is controlled by using a single cylinder of fixed radius $1.3 \pm 0.00001cm$.

Length of the plank	Increasing the length of the plank increases the time for which the cylinder is affected by the force of friction as a longer distance at the same angle also leads to a longer time taken to travel & vice versa.	Using the exact same inclined plank for all readings to get a consistent distance travelled throughout all trials of the experiment. Length of the plank = 53.5 $\pm$ 0.05 cm
Mass of the cylinder	Increasing the mass of the cylinder increases the moment of inertia proportionally as seen in formula (2). Hence a constant mass is required.	It is controlled by using a single cylinder of fixed mass = 22.05 $\pm$ 0.03g
Surface of inclined plane	Changing the surface (material of the surface) of the inclined plane will change the coefficient of dynamic friction. This will in-turn affect the time taken for the ball to roll down and energy losses	It is controlled by using a plank made out of wood for all trials of the experiment.

Calculated Variables –

Potential energy – Value was calculated by using the mass of the cylinder and the height of the cylinder from the surface.

Final Velocity – When rolling down a plank, the cylinder does so with constant acceleration (assuming no frictional force). Hence using the formula of

$$S = \frac{(v+u)t}{2} \quad (5)$$

Since the initial velocity is constant, rearranging the equation and substituting u = 0cm/s we get,

$$v = \frac{2S}{t} \qquad (5.1)$$

We can find the value of the final linear velocity of the cylinder. Final velocity is used when we must calculate the linear kinetic energy of the cylinder.

Angular Velocity – When rolling down the plank, this is the velocity with which the cylinder itself rotates. The formula was given in background information (2.0.1 – Angular velocity)

Apparatus

Item	Quantity	Uncertainty
Inclined Plane with a protractor	1	$\pm 0.5°$
Meter Scale	1	± 0.05cm
Cylinder	1	Mass - $\pm 0.3g$ Radius - ± 0.00001cm
Davinci Resolve 17 Editing Software	1	Time uncertainty = $\pm\ 0.0042s$

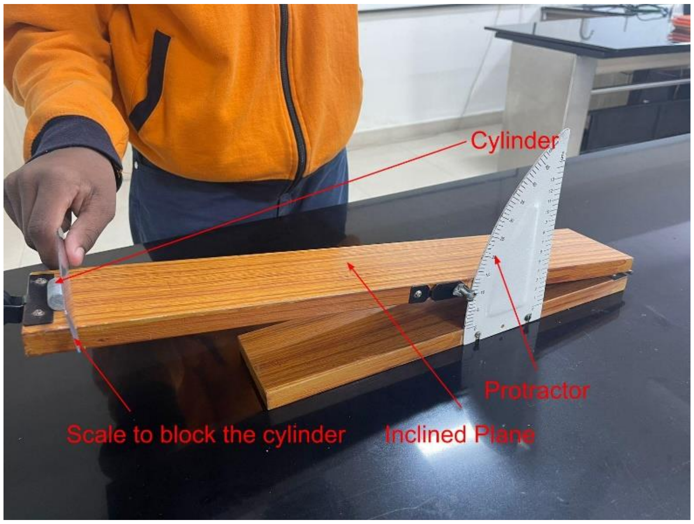


Figure 2: Apparatus Setup

Figure 3: Angle the video was taken at

Data Collection Procedure

1. All equipment was first arranged as given in **Figure 2.**
2. Set the angle of inclination to 5° and measure the height
3. Remove the scale and let the rolling start and recording using the video camera.
4. Recording of the video camera is stopped when the cylinder reaches the bottom of the plane.
5. The same procedure is repeated 4 more times for 5° angle.
6. Then repeat steps 2 to 5 times for angles 10°, 15°, 20°, 25°,30°

Safety, Environmental and Ethical considerations

The risk associated with this experiment is extremely low. Though there may be a possibility of injury due to dropping the heavy inclined plane or clamping the fingers between the inclined plane, it was handled carefully on a flat surface and the protractor lock was screwed tight before performing the experiment with any value. The cylinder used was of low mass and hence even if it fell, it's likely there would be no chance of injury. Still, it was ensured that the experiment was done in a corner of the classroom where there is minimal chance of the cylinder to fall on someone. There are no environmental and ethical considerations in this experiment

Data Analysis

Note that SI units were not used in this experiment as it would lead to extremely small values. Since we only need to find a relationship, this will still help us confirm the hypothesis.

Raw Data Collection

For each angle, the time taken for the cylinder to roll down the plank and the time period were measured. The table below shows the raw data table.

Angle	Time for rolling down the ramp (s) ± 0.0042	Time period rotation (s) ± 0.0042

	Trial1	Trial2	Trial3	Trial4	Trial5	Trial1	Trial2	Trial3	Trial4	Trial5
5°	1.4499	1.3801	1.4198	1.4301	1.4301	0.1153	0.1110	0.1129	0.1137	0.1137
10°	1.0002	0.9698	0.9801	0.9599	1.0100	0.0800	0.0771	0.0800	0.0763	0.0803
15°	0.7900	0.8160	0.8000	0.8159	0.8001	0.0632	0.0651	0.0649	0.0648	0.0638
20°	0.7001	0.6809	0.6809	0.7001	0.7100	0.0557	0.0541	0.0541	0.0553	0.0565
25°	0.6301	0.6249	0.6298	0.6250	0.6251	0.0501	0.0497	0.0500	0.0495	0.0497
30°	0.5801	0.5699	0.5831	0.5749	0.5700	0.0461	0.0453	0.0464	0.0457	0.0453

Table 1: Raw data table

Data constant for experiments

Radius of Cylinder (±0.0001) (cm)	Mass of Cylinder (±0.03) (g)	Height above the surface (±0.05) (cm)	
1.3000	22.05	Angle - 5°	4.7
		Angle - 10°	9.3
		Angle - 15°	13.8
		Angle - 20°	18.3
		Angle - 25°	22.6
		Angle - 30°	26.8

Table 2: Constant data for all experiments

Data Processing

This section will consider only trial 1 for the angle of 5°. I will be doing a sample calculation to show how the rest of the values in this exploration are calculated.

Height error calculation

Since the height remains constant for every angle of the experiment, the uncertainty can be taken as the uncertainty on the meter scale.

$$Uncertainity\ in\ height\ above\ the\ surface = \pm 0.05cm$$

Then the uncertainty in time is calculated formula (4 – Uncertainty (max-min)/2), which is

$$\frac{1.45-1.38}{2} = \pm 0.035s$$

Final Velocity, Moment of Inertia and Angular Velocity magnitude and error calculation

Using formula (5.1 – Final velocity), the final velocity is calculated -

$$v = \frac{53.5\ \times 2}{1.4499} = 73.798\ cm/s$$

Then by using (5.1 – Final velocity), the uncertainty in velocity is found -

$$v = \frac{2S}{t}$$

$$\frac{\Delta v}{v} = \frac{\Delta S}{S} + \frac{\Delta t}{t}$$

$$\Delta v = 73.798\ \times \left(\frac{0.05}{53.5} + \frac{0.035}{1.45}\right) = \pm 1.850cm/s$$

Then, the moment of inertia was calculated along with its uncertainty using the formula[10]

$$I = \frac{1}{2}MR^2$$

$$\frac{1}{2} \times 22.05 \times 1.3^2 = 18.63gcm^2$$

Now uncertainty is calculated as follows -

$$\Delta I = I \times \left(\frac{\Delta M}{M} + 2 \times \frac{\Delta R}{R}\right)$$

$$18.63 \times \left(\frac{0.03}{22.05} + 2 \times \frac{0.0001}{1.3}\right) = \pm 0.0282gcm^2$$

Then the uncertainty in angular velocity was calculated using formula (4 – uncertainty (max-min)/2), after analyzing the video frame by frame on DaVinci resolve -

$$\frac{0.1153 - 0.1110}{2} = \pm 0.0021\ rad/s$$

<u>Magnitude and error calculation for linear kinetic energy, rotational kinetic energy and energy loss</u>

Now, we must calculate the value of both the kinetic energy and rotational energy along with their uncertainties and add them to find the total energy when the cylinder reaches the bottom of the plane. (Calculated for each trial separately, from formulas (1) and (2) (Kinetic and rotational energy)). Note that for trial 1 the angular velocity is calculated using formula (2.0.1 – Angular velocity). Now calculating the sum of final linear kinetic energy and final rotational energy, we get -

$$\frac{1}{2} \times 22.05 \times 73.798^2 + \frac{1}{2} \times 18.63 \times 54.494^2 = 87705.533\ gcm^2s^{-2}$$

The uncertainty in each these values can be calculated by using formulas (1 – Kinetic energy and 2 - rotational energy) -

$$Uncertainty\ in\ K.E = K.E \times \left(\frac{\Delta M}{M} + 2 \times \frac{\Delta v}{v}\right)$$

$$60043.746 \times \left(\frac{0.03}{22.05} + 2 \times \frac{1.85}{73.798}\right) = \pm 3092.097\ gcm^2s^{-2}$$

$$Uncertainty\ in\ K.E_{rot} = K.E_{rot} \times \left(\frac{\Delta I}{I} + 2 \times \frac{\Delta \omega}{\omega}\right)$$

$$27661.787 \times \left(\frac{0.0282}{18.63} + 2 \times \frac{0.0021}{54.494}\right) = \pm 44.003\ gcm^2s^{-2}$$

So total uncertainty in total final energy (in trial 1) is the sum of both the uncertainties.

$$3092.097 + 44.003 = \pm 3136.100\ gcm^2s^{-2}$$

Now to calculate energy loss, we must calculate the initial potential energy. This is calculated using formula (2.1 – potential energy) as,

[10] "Moment of Inertia of a Cylinder: Wolfram Formula Repository." Moment of Inertia of a Cylinder | Wolfram Formula Repository. Accessed October 12, 2022. https://resources.wolframcloud.com/FormulaRepository/resources/Moment-of-Inertia-of-a-Cylinder.

$$mgh = 22.05 \times 981 \times 4.7 = 101665.935\ gcm^2s^{-2}$$

The uncertainty in g is taken as ± 10^{-11} cm/s^2 per NCBI[11]. Now we calculate uncertainty in potential energy using formula (2.1 – Potential energy)

$$\Delta mgh = mgh \times \left(\frac{\Delta m}{m} + \frac{\Delta g}{g} + \frac{\Delta h}{h}\right)$$

$$101665.935\ \times \left(\frac{0.03}{22.05} + \frac{10^{-11}}{981} + \frac{0.05}{4.7}\right) = \ \pm 1219.874\ gcm^2s^{-2}$$

Now subtracting the values and adding the uncertainties (using formula (3), energy lost), we get

$$(101665.925\ \pm 1219.874) - (88705.533 \pm 3136.1) = 12960.392\ \pm 4355.974\ gcm^2s^{-2}$$

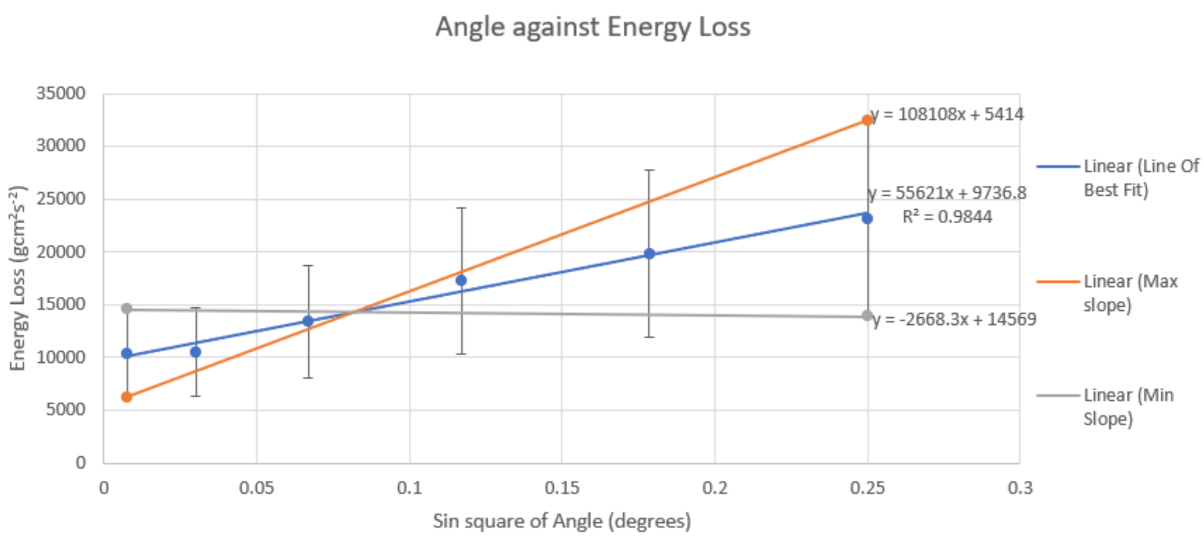
This process was repeated for all data points. The average of the magnitude and the uncertainty was taken.

Processed Data

Angle	Average Total K.E (gcm^2s^{-2})	Average P.E (gcm^2s^{-2})	Average Energy Loss (gcm^2s^{-2})
5°	91274.913 ± 3251.239	101665.935 ± 1219.874	10391.022 ± 4471.113
10°	190633.613 ± 6646.173	201168.765 ± 2413.201	10535.187 ± 9059.973
15°	285095.271 ± 7046.173	298508.490 ± 3581.648	13413.321 ± 10627.821
20°	378586.748 ± 8014.628	395848.215 ± 4749.720	17261.467 ± 12764.348
25°	469041.800 ± 10256.276	488861.730 ± 5865.775	19819.930 ± 16122.051
30°	556539.439 ± 12814.628	579712.140 ± 6955.874	23172.561 ± 19770.502

Table 3: Processed Data Table

Uncertainty in graph



Graph 1: Line of Best Fit, Maximum and Minimum Gradient

[11] Xue, Chao, "Precision Measurement of the Newtonian Gravitational Constant." National science review. U.S. National Library of Medicine, July 22, 2020. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8290936/#:~:text=As%20a%20result%2C%20the%20gravitational,kg%E2%88%921%20s%E2%88%922.

$$\frac{Max - Min}{2} = Error\ in\ slope$$

$$\frac{108108 - (-2668)}{2} = 55388$$

This means the slope = 55621 $\pm$ 55388

Percentage uncertainty in slope is

$$\frac{55388}{55621} \times 100 = 99.581\%$$

Now let's find the uncertainty in the y-intercept

$$\frac{Max - Min}{2} = Error\ in\ intercept$$

$$\frac{14569 - 5414}{2} = 4577.5$$

This means the intercept = 9736.8 $\pm$ 4577.5

Now, finding the percentage uncertainty in the intercept –

$$\frac{4577.5}{9736.8} \times 100 = 47.01\%$$

Analysis

The hypothesis predicted that as the $\sin^2(\theta)$ of the angle increased, there is a subsequent increase in the energy loss. This is also what is seen in the graph (include the graph number). We observe that as the $\sin^2(\theta)$ value increases, the energy loss also increases. We also see that this relationship is excellent as the R-squared value of the graph is 0.9844.

Though the initial relationship is excellent, we reach contradictions due to the large error bars. Since the error bars are extremely large, this goes against the fact that a constant value is added. This is seen in the high percentage uncertainty in the intercept.

There is also ambiguity in the value of the slope due to the large error bars. We also observe that the minimum slope line has a negative relationship with the increase in the angle. This contradicts the hypothesis as the hypothesis predicts that as the $\sin^2(\theta)$ value increases, the energy loss also increases. Additionally, there was very high percentage uncertainty in the gradient. This shows that there were significant random errors present in the experiment. The high percentage uncertainty in the y-intercept shows that significant systematic errors were also present in the experiment.

Though the error bars are extremely large, we see that almost all ranges of values within the error bars accept the hypothesis. Though the line does not pass through the origin due to systematic errors, as the $\sin^2(\theta)$ increases, the energy loss also increases. Additionally, we should also note that the large error bars are likely due to subtracting the magnitudes of Initial Kinetic energy and final kinetic energy. The percentage uncertainty in both those values themselves are not large, but because the values are subtracted, the uncertainties are added leading to very high percentage uncertainty in the energy lost.

This means that for most of the values calculated the hypothesis is followed, but due to large systematic and random errors in the experiment, the graph at its lowest gradient could also predict a negative relationship.

Evaluation

The method of investigation allowed for satisfactory collection of data points, allowing for a confirmation of the hypothesis. However, as mentioned earlier there were large systematic and random errors.

Problem Identified	How did the problem impact the final result?	How significant was the problem?	How was the problem overcome/how could it be overcome?
Air resistance slowing down the cylinder	Air resistance caused the cylinder to move slower down the plank, hence affecting the final velocity of the cylinder which also affected both the final rotational and kinetic energy.	The problem was significant as it led to additional energy losses apart from the frictional force. It also affected the energy loss in larger angles as the air resistance force is higher when the velocity is high	Air conditioner was turned off and all windows were closed to ensure that air resistance is reduced as much as possible. If I had performed the experiment again, I would have performed this experiment in a sealed container with a small hole on top to release the cylinder.
Roughness of the inclined plane and the cylinder	This caused the cylinder to move slower down the plank, affecting both kinetic and rotational energy negatively hence causing higher energy losses.	The problem was significant but is also important for the rolling motion itself as without friction, rolling motion would not be possible. So, though it was significant, slight roughness is also necessary for the cylinder to roll.	It was ensured that the surface of the inclined plane and cylinder were cleaned with alcohol wipes before performing the experiment. Additionally, they were allowed to dry for 20 minutes before the measurement of the first data point.

Future Scope

I have found the relationship between energy loss and the angle of the inclined plane successfully, but there is large ambiguity in this value due to the magnitude of percentage uncertainty. Using more accurate measurement tools, it would be possible to drastically reduce this uncertainty and derive the relationship. Additionally, rather than trying this experiment with only cylinders, we could try this experiment with balls and hoops as well. This could lead to interesting conclusions as they have a different moment of inertia formula. Lastly, we could also increase the mass, or radius of the cylinder and see how this affects energy loss at a constant angle.

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