Galileo's Damped Oscillator

University Lab Report

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Abstract

In this experiment, we explored how different cylindrical objects roll and lose energy on a V-shaped ramp, aiming to understand how their internal structure, the type of fluid they contain, the fluid's viscosity, and the ramp's angle influence their motion. By carefully analyzing displacement vs time and velocity vs displacement graphs, we were able to see how energy is retained or lost in each case. Solid cylinders, with their uniform internal structure, tended to keep their mechanical energy longer and showed less damping, moving more smoothly along the ramps. Cylinders that were almost fully filled with fluids, on the other hand, experienced noticeably higher damping because the fluid inside moved independently, creating internal friction and dissipating energy more quickly. Among these, the cylinders with more viscous fluids showed even greater damping, as the internal fluid causes greater damping. This eventually slows the transfer of momentum and causes the cylinders to lose energy faster. We also observed the effect of ramp angle. Increasing the angle of one ramp caused the cylinders to travel farther on the opposite ramp. This happened because a steeper ramp gave the cylinders more potential energy at the start, which converted into greater kinetic energy as they rolled down. This allowed them to cover a longer distance. Overall, the experiment highlighted how factors like internal structure, fluid properties, and ramp angle influence the motion and energy dissipation of rolling cylinders, providing a clear picture of how damping occurs in these systems.

1 Introduction

The purpose of this experiment is to explore how different cylindrical objects lose energy as they roll back and forth on a V-shaped ramp. Several factors influence how quickly their motion dies out, such as the material and mass of the cylinder, the angle of the ramps, and whether the cylinder contains any fluid. In our study, we focused mainly on how the presence and type of fluid inside the cylinder, along with the ramp angle, affect the damping. By comparing the motion of different cylinders under these conditions, we aimed to get a clearer understanding of how these factors shape the loss of energy and the gradual reduction of oscillation.

2 Apparatus

Equipment

- Two identical ramps with the same slope (same angle of inclination).
- Small cylinders (solid aluminum cylinder, deodorant cylinder, soda can cylinder, ketchup-filled cylinder).
- Marker to mark the top release position on the ramp.
- Smartphone attached to a tripod.
- Meter scale or reference object in the video (for calibration).
- Protractor (to confirm ramp angle).
- Whiteboards to make the ramps.
- Wooden blocks to increase and vary the slope.

Experimental Setup

- Place the two ramps side-by-side and adjust their inclination so that both have the same slope. Confirm this using a protractor.
- Mark a fixed release point near the top end of one ramp using a marker.
- Place a marker on the lower end of the cylinder to track its motion using the tracker software.
- Set up the camera so it records the full length of each ramp and remains fixed during all trials.

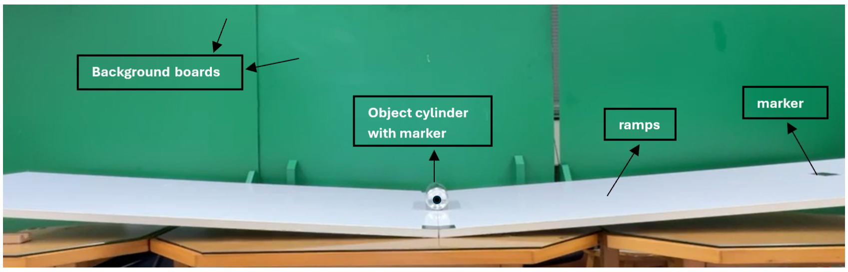

Figure 1: Experimental setup.

Procedure

The cylinder was released from rest at the marked point. After rolling down the first ramp, it crossed the center and moved along the second ramp, continuing to oscillate back and forth between the two ramps. Due to energy loss from rolling friction and air resistance, the amplitude of oscillation gradually decreased until the cylinder eventually came to rest near the bottom. The complete motion(from release to rest)was recorded by a camera attached to the tripod. The video was imported into the Tracker software, where the length scale was calibrated using built-in tools and the marker on the cylinder was tracked frame-by-frame. The data obtained from tracker was then imported into Google Colab and displacement vs time and velocity vs displacement graphs were obtained.

3 Variable 1: Type of Fluid in the Can

The experiment was carried out with a solid aluminum cylinder, a soda can, a ketchup can and a deodorant bottle.

Observations

During the trials, the aluminum cylinder stayed in motion for the longest time. Its oscillations died out very slowly, and it kept moving back and forth smoothly, with only a small decrease in height each cycle. The soda can and deodorant bottle didn't last as long. Their motion faded more quickly, and the oscillations became noticeably smaller from swing to swing, most likely because the liquid inside each can shifted around and resisted the motion. The ketchup bottle was the quickest to stop. Because the fluid inside it is so thick, it lost almost all the energy in a few oscillations on the v-shaped ramp, and its oscillations disappeared. This showed that the thick, viscous fluid inside caused the greatest resistance to the motion of the can. Overall, the damping increased noticeably from the aluminum cylinder, to the soda can and deodorant bottle, and finally to the ketchup bottle, which showed the fastest decay in motion.

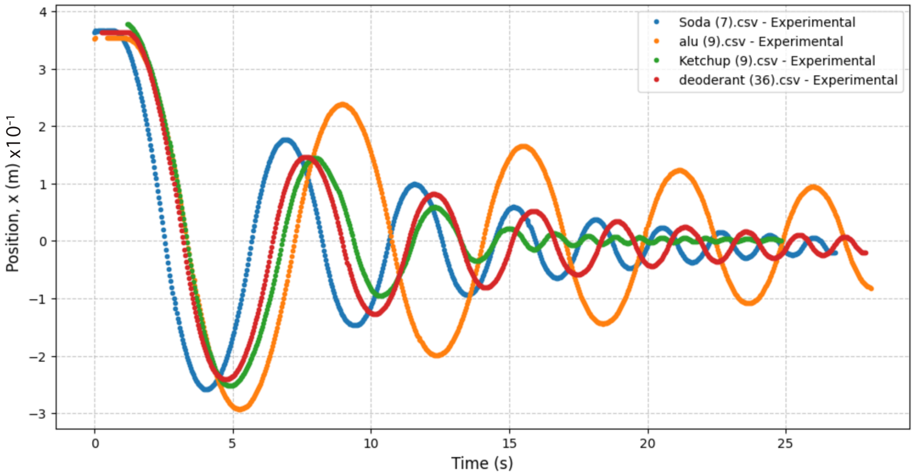

Figure 2: Displacement–time graphs for the motion of all cans over the two ramps.

Phenomenon Explanation

As can be seen from the graphs above, the damping is greatest in the case of ketchup and lowest in the case of the solid aluminum block. In our experiment, the cylinders have both **rotational** and **translational** motions. Initially, as the ramp is tilted, there is some static friction acting on the cylinder in the opposite direction. This friction provides **torque** to the object when dropped; thus, the object not only slides down the plane but also rotates. By the law of conservation of energy, the kinetic energy is conserved between translational and rotational forms.

Then why does the aluminum block stop? Why does the graph show damping? Considering minimal air resistance and internal material deformation, energy is lost due to rolling friction with the surface. This causes loss of energy in the system; the distance it covers along the ramp reduces with each subsequent cycle, and it eventually stops as all the energy is lost to **rolling friction**.

Why do other objects cause more damping? According to Newton's first law of motion, a body continues in its state of rest or uniform motion in a straight line provided no net force acts on it. Thus, when the soda or deodorant can is dropped, the fluid inside wants to continue its state of rest due to its inertial property. The walls of the container accelerate first, so the fluid applies a backward resistive force on the can. Some of the kinetic energy of the can is lost, which causes the motion to be damped.

Now, why do different fluid-filled containers cause different amounts of damping? This is due to the different **viscosities** of the liquids. When the container accelerates, the liquid layer that is in direct contact with the container accelerates with it, but the layers deeper in the liquid are still not in motion. Momentum is slowly transferred to the inner layers. Thus, the outer layers move with the container while the inner ones start moving after a while. When the container accelerates, the wall drags the first thin layer of fluid, then this layer must drag the next, and so on. This dragging is the **momentum transfer**.

In a **high-viscosity fluid**, the molecules stick to each other strongly and resist relative movement. So when one layer tries to move, the next layer follows slowly. It takes time for the motion to spread from the wall into the interior. Thus, the greater the viscosity, the greater the time taken to transfer momentum throughout the liquid. Therefore, the bottle with high viscosity causes the greatest damping due to the resistive force from the inertial property of the fluid.

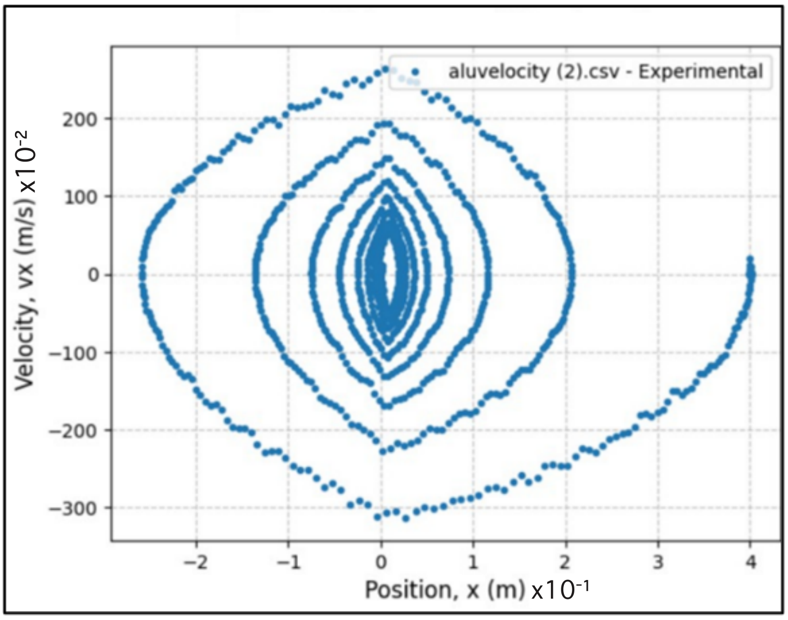

Figure 3: Displacement–time graph for aluminum block.

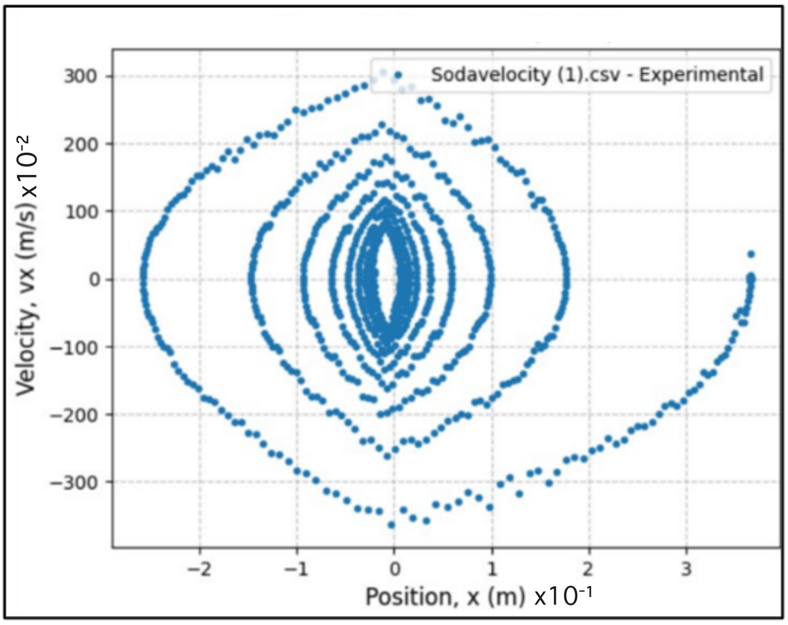

Figure 4: Displacement–time graph for soda can.

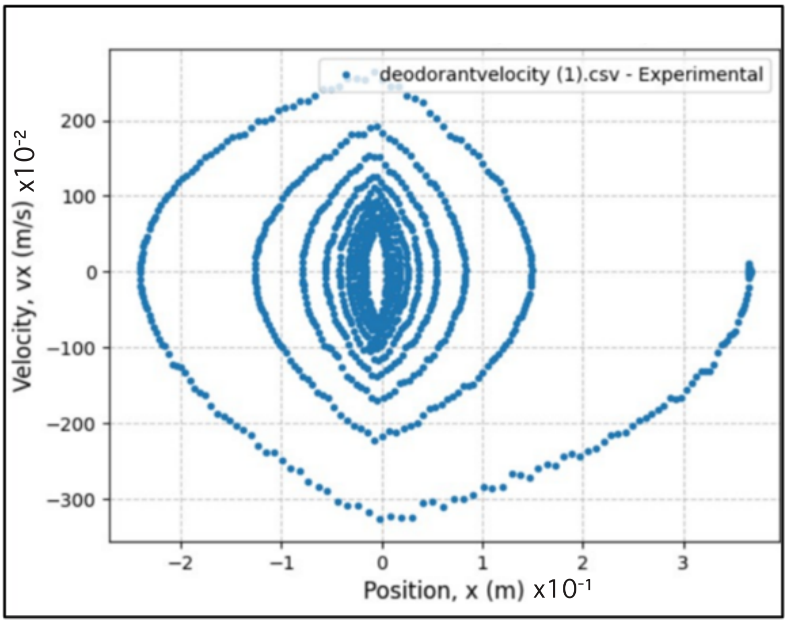

Figure 5: Displacement–time graph for deodorant can.

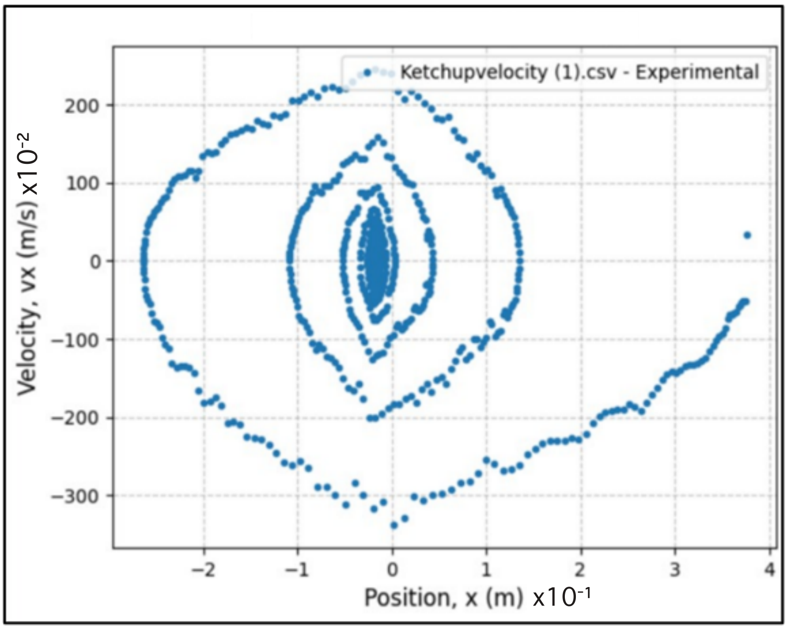

Figure 6: Displacement–time graph for ketchup can.

The loops for the aluminum block are wide and gradually shrink as we move toward the center. This means that as the block rolls up and down the ramp, its displacement from the mean position decreases slowly. The loops are almost symmetrical along both axes, showing that the motion is quite uniform back and forth. The area inside each loop is very small, which tells us that very little energy is lost per cycle. Essentially, aluminum has the lowest damping among all the cylinders in our experiment, so it keeps rolling with minimal resistance.

For the soda can, the loops are narrower than aluminum's. This indicates that the

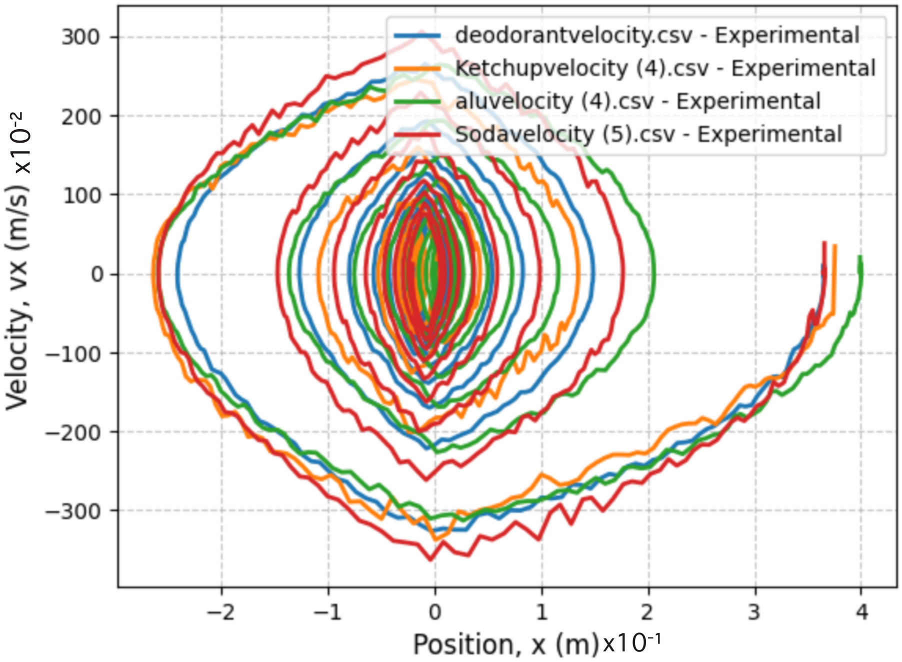

Figure 7: Velocity–displacement graphs for the motion of all cans over the two ramps.

can's displacement along the ramps reduces more quickly—its oscillations die down faster. This is because the liquid inside the can resists motion, dissipating some energy with every swing. The velocity peaks are smaller for the same displacement, which also shows moderate damping.

The loops of the deodorant can are narrower than those of the soda can but wider than those of the ketchup bottle. The motion slows down because the liquid inside moves and resists the rolling, though not as violently as ketchup (which has greater viscosity). The displacement decreases at a moderate rate, showing moderate-to-strong damping.

The ketchup bottle shows the strongest damping. Its loops are very compressed toward the center, meaning the displacement decreases rapidly. The velocity drops sharply, indicating that most of the kinetic energy is being absorbed by the viscous ketchup inside. The motion dies out very quickly, and each cycle shows a relatively large area within the loop compared to retained energy. This makes it clear that ketchup has the highest damping.

Mathematical Model (Displacement vs Time)

In assessing the displacement in the experiment, two scenarios arise:

- For a **solid cylinder** like the aluminum one, the rolling motion causes it to rub against the track. This rolling friction slowly drains energy at a fairly steady rate, which shows up as a constant loss over time ($-Ct$).

- For **fluid-filled cylinders** we have to account for other sources of friction too. As the object rolls, the liquid inside doesn't move with it immediately. Rather, it lags. This lag creates an internal resistive force that grows the faster the cylinder moves, leading to a damping effect that follows an exponential pattern (e^{-bt}).

General Displacement Model

$$x(t) = A(t)\cos(\omega t)$$

$$A(t) = \begin{cases} A_0 - Ct, & \text{solid cylinders (linear decay)} \\ A_0 e^{-bt}, & \text{fluid-filled cylinders (exponential decay)} \end{cases}$$

Parameters:

- A_0: starting amplitude
- ω: angular frequency
- C: rolling-friction damping constant (solids)
- b: exponential damping constant (fluids)

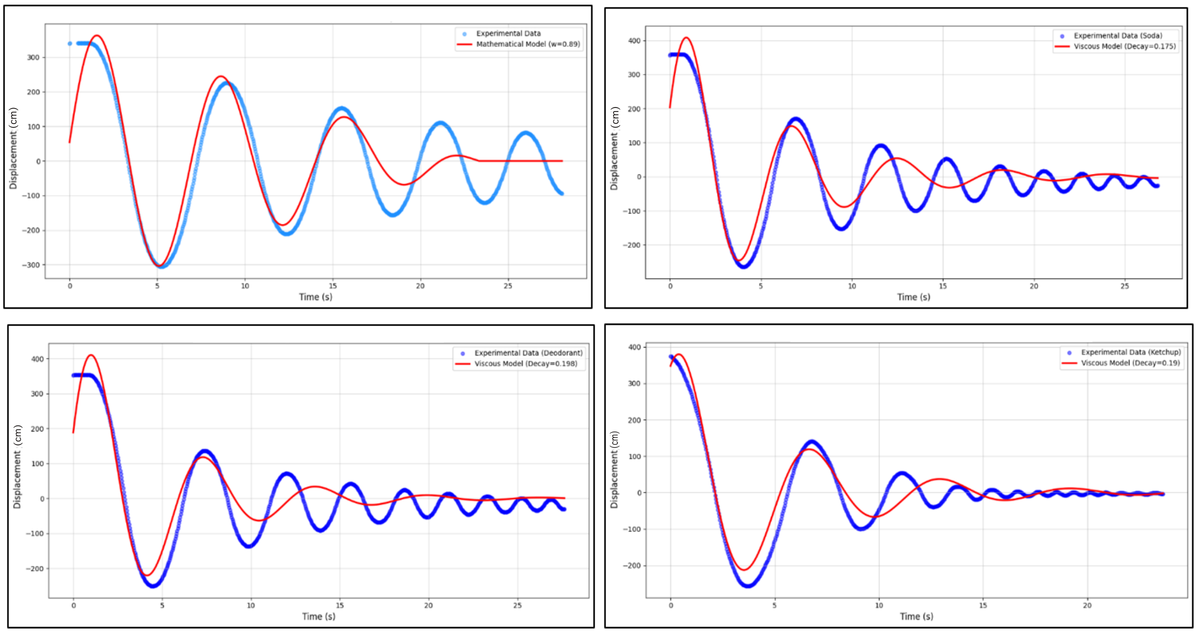

Figure 8: Curve fitting for displacement vs time using the mathematical model. Aluminum (top left), soda can (top right), deodorant (bottom left), ketchup (bottom right).

Mathematical Model (Velocity vs Displacement)

For the velocity–time assessment, we simply derive the displacement function of the material:

General Velocity Model

For the velocity–time assessment, we simply derive the displacement function:

$$x(t) = A(t)\cos(\omega t)$$

For solids (aluminum):

$$A(t) = A_0 - (Ct)$$

Deriving using the product rule gives:

$$v(t) = -(A_0 - Ct)\,\omega\sin(\omega t) \;-\; C\cos(\omega t)$$

or equivalently,

$$v(t) = -\omega(A_0 - Ct)\sin(\omega t)$$

—

For fluids (soda, deodorant, ketchup):
Amplitude decays exponentially:

$$A(t) = A_0 e^{-bt}$$

Taking the derivative:

$$v(t) = -A_0 e^{-bt}\left[\,\omega\sin(\omega t) + b\cos(\omega t)\,\right]$$

which simplifies to:

$$v(t) = -\omega A_0 e^{-bt}\sin(\omega t)$$

Parameters:

- A_0: starting amplitude
- ω: angular frequency
- C: rolling-friction damping constant (solids)
- b: exponential damping constant (fluids)

To model the phase-space trajectory (the spiral graph), we used a parametric approach. We calculated the theoretical displacement $x(t)$ and velocity $v(t)$ using the linear decay model derived for aluminum. By plotting these two time-dependent variables against each other, we generated a theoretical spiral that moves inward, representing the continuous loss of mechanical energy due to rolling friction.

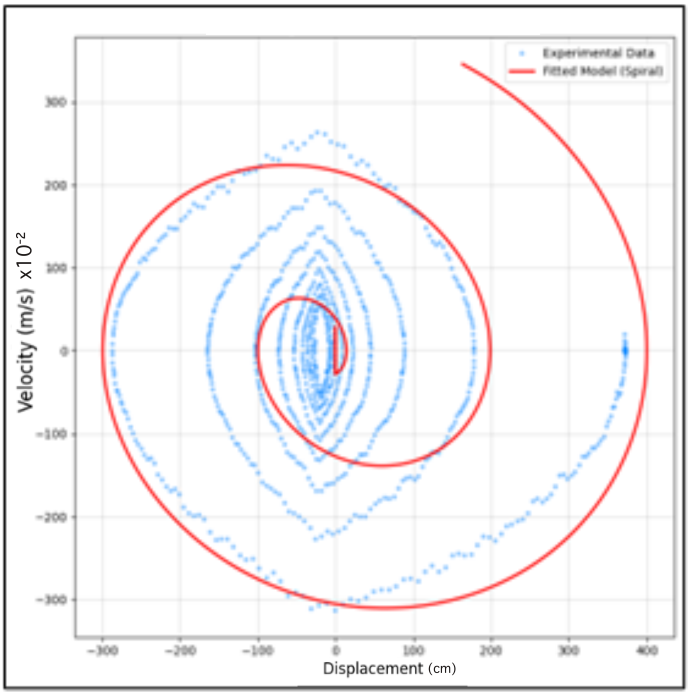

Figure 9: velocity–time graph for aluminum block.

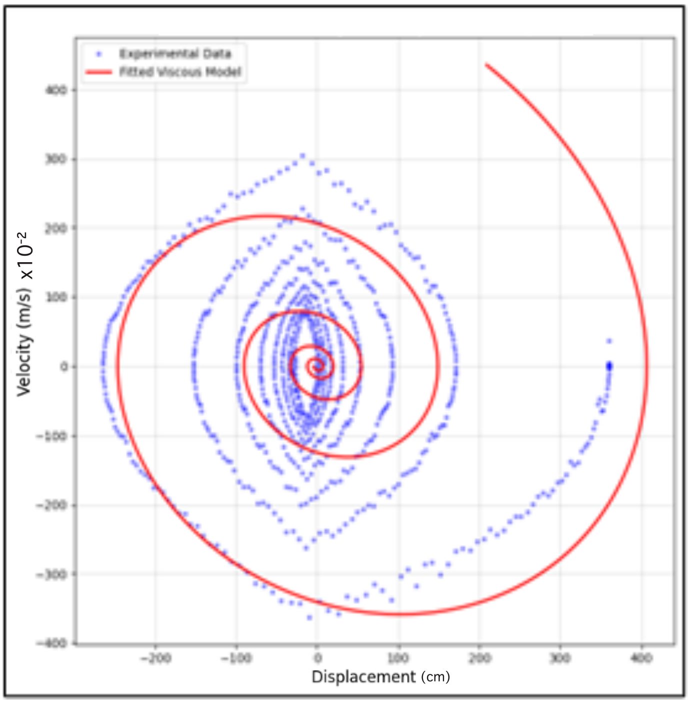

Figure 10: velocity–time graph for soda can.

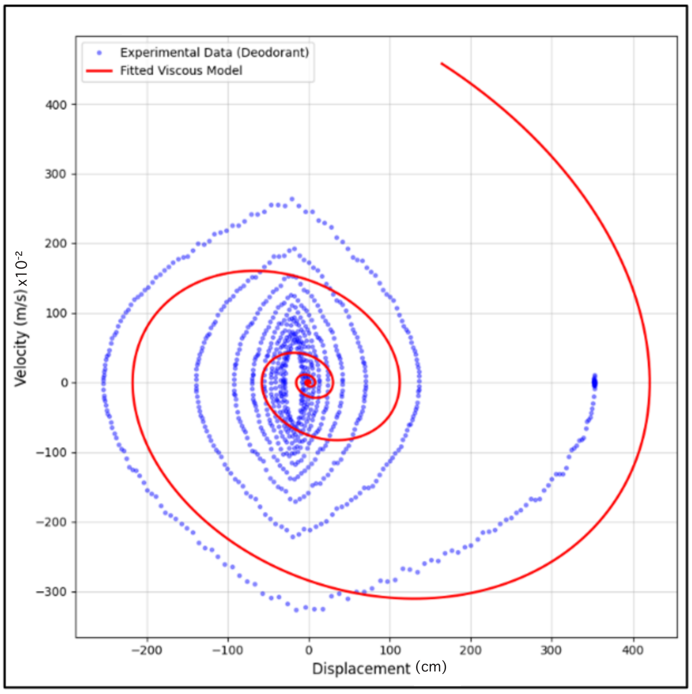

Figure 11: velocity–time graph for deodorant can.

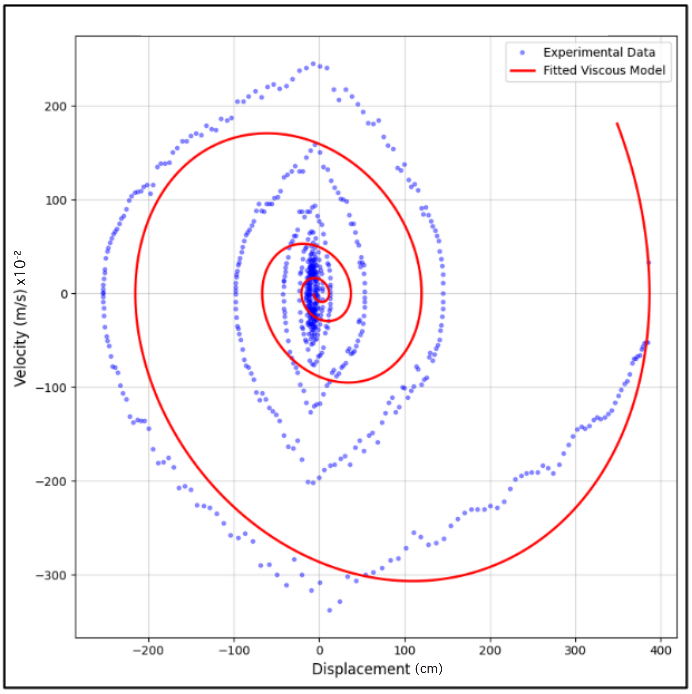

Figure 12: velocity–time graph for ketchup can.

Sources of Error and Uncertainties

The fitted models showed that the mathematical descriptions captured the overall behaviour of the cylinders remarkably well, with only minor differences between the predicted curves and the experimental motion. For the solid aluminum cylinder, the linear decay model closely followed the gradual loss of amplitude, reflecting the nearly constant rate of energy dissipation expected from rolling friction. For the fluid-filled objects, the exponential decay model reproduced the rapid drop in amplitude and the faster damping characteristic of internal fluid lag and viscosity. Small deviations appeared at later times, especially for the viscous cylinders, as real fluids introduce nonlinear and time-dependent effects that are not perfectly described by a single damping constant. Some discrepancies can also be attributed to practical sources of error such as slight inconsistencies in release height, variations in ramp friction(ramp may not be uniform throughout), shaking as the heavy cylinder rolls or angle mismatch of the ramps or imperfect frame tracking in the video analysis.

Despite these limitations, the fitted functions clearly represented the key trends: slow, almost linear damping in solids and sharp exponential decay in fluid-filled cylinders.

4 Variable 2: Angle of Ramp

The experiment was carried out by varying the angle of one of the slopes. The following graphs show the variation of velocity with displacement for the aluminum cylinder.

Observations

When we released the block from the ramp set at a larger angle, it clearly travelled farther on the opposite ramp than it did in the trials with a smaller angle. Even though the displacement on the second ramp gradually decreased over time because of damping, each swing still reached a visibly greater height when starting from the steeper ramp.

This pattern continued throughout the motion. The amplitudes became smaller with each oscillation, but the values for the greater-angle release always remained higher. The velocity graph also reflected this difference. The block released from the steeper ramp reached the highest speed at the mean position, shown by the tallest velocity peak, and this remained noticeably higher than the peaks from the lower-angle trials. Overall, the runs with the greater incline produced larger displacements and higher velocities throughout the oscillations.

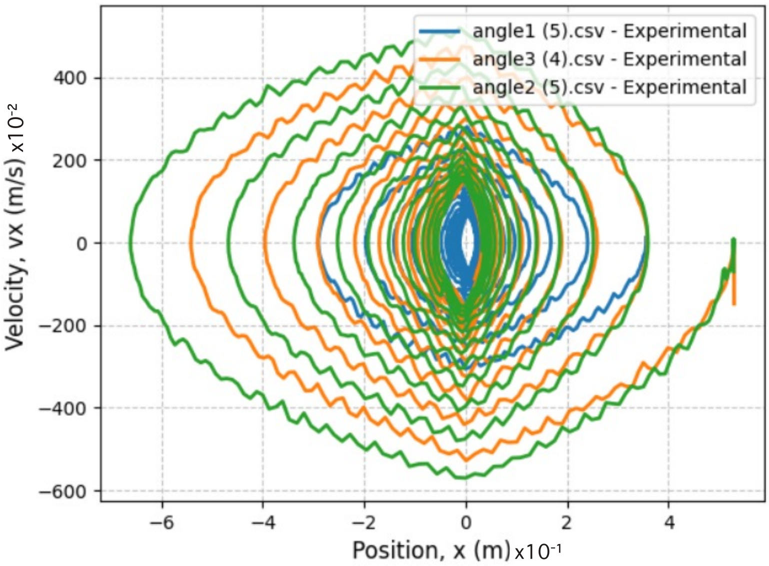

Figure 13: Velocity–displacement graphs for all three ramp angles.

Phenomenon explanation

As seen from the figure, when the angle of only one ramp was increased, the motion of the aluminum block changed, even though aluminum has very low damping.

On the steeper ramp, the **component of gravity along the slope** is larger, producing a greater net force and therefore a higher linear acceleration. This higher acceleration allows the block to reach a larger peak velocity at the mean position, which corresponds to the center of the loop.

Because the block rolls instead of slides, part of its gravitational potential energy converts into rotational kinetic energy and the rest into translational kinetic energy. When the block climbs the shallower ramp, the gravitational component along the slope is smaller, so the block slows down more gradually and its velocity decreases over a longer displacement.

The extra kinetic energy gained while descending the steep ramp enables the block to travel farther up the shallow ramp, converting kinetic energy back into gravitational potential energy. This explains the asymmetry of the loops: the steep ramp side appears narrow with higher velocities, while the shallow ramp side appears wider with slower motion over a larger displacement.

5 Results

Variable 1: Type of fluid in the can

The motion of each object exhibited different damping behaviours:

- Aluminum cylinder: slow decay, minimal damping.
- Soda can: moderate damping due to liquid movement.
- Deodorant bottle: similar behaviour to soda can.
- Ketchup bottle: strongest damping, motion decayed quickly.

Object	**ω (rad/s)**	**C/b**	**Relative Damping**
Soda Can	1.101	0.0955	Medium
Aluminium Cylinder	0.888	0.0444	Lowest
Ketchup Can	1.024	0.1129	Highest
Deodorant	1.017	0.0554	Medium–High

Table 1: Angular frequencies, damping constants, and relative damping.

The data above in the table is the result of the curve fitting through the mathematical model. The table shows the damping constants for each of the objects in harmoninc motion. As shown Aluminium cylinder has the lowest damping as there is no liquid flowing inside the cylinder thus it would be damped less. On the contrary Ketchup Can has the highest damping constant with the largest relative damping, thus confirming that the higher the viscosity of the liquid the greater the damping.

Variable 2: Ramp Angle

Changing the angle of one side of the V-shaped ramp produced clear differences in the motion:

- Steeper ramp: higher velocities were observed due to a larger gravitational component.
- Shallower ramp: lower velocities but greater displacement before reversal.
- Asymmetry: oscillations became uneven between the two sides.
- Energy distribution: the steeper side generated more kinetic energy; the shallower side allowed more travel distance.

Significance Statement

This experiment helps show why different objects lose energy at different rates when they roll. By looking at both solid cylinders and ones filled with liquid, and by changing the ramp angle, we get a clearer sense of how friction, viscosity, and the movement of the fluid inside each container affect the damping. Even though the setup is simple, the behaviour we observe is similar to what happens in real systems like shock absorbers, rolling bottles, or oscillators moving through thick fluids. Because of that, the experiment not only reinforces basic physics concepts but also highlights how these ideas appear in everyday situations.

6 Conclusion

The experiment showed that different cylinders lose energy in very different ways depending on what they contain and how the ramps are arranged. The solid aluminum cylinder kept moving for the longest time because almost all of its energy stayed in the rolling motion, with only a small amount lost through rolling friction. The cylinders that contained fluids slowed down much more quickly because the liquid inside did not move with the container immediately. This internal lag acted like a resistive force, draining energy with every swing. The ketchup bottle, with its thick and sticky fluid, lost energy the fastest and stopped almost right away.

Our mathematical model lined up well with what we observed. The solid cylinders followed a mostly linear decrease in amplitude, while the fluid-filled ones were better described by an exponential decay, which makes sense given how the liquid inside slows the motion. Adjusting the angle of one ramp also made a noticeable difference: the steeper ramp gave the cylinder more speed and resulted in larger swings, whereas the shallower ramp led to slower but broader oscillations. Overall, the experiment showed how the fluid inside the cylinders, its viscosity, and the ramp angle all combine to influence the rolling motion and how quickly the energy dies out.

7 Acknowledgments & References

This report was prepared using data collected during the lab sessions and with reference to the provided lab manual available at the physlab website(official website of the Physics Department, LUMS). Additional clarification on the mathematical modelling of damping was taken from course materials and physics resources to verify the results and support the analysis presented. Physlab was instrumental in the making of the report.

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