What is the relationship between the mass of a damped spring-block oscillator {52.48g, 60.94g, 69.72g, 86.51g, 93.47g, 113.27g} and the damping ratio?

Word count: 2535

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1 Introduction

This essay extends the investigation of simple harmonic motion by studying the damping force of a damped oscillator submerged in water, aiming to scrutinize the relationship between the mass of the block and the damping ratio. By scrutinizing this relationship, the study aims to offer valuable insights that can inform the design of systems seeking to optimize damping levels for safety-related objectives.

1.1 The Research Question

What is the relationship between the mass of a damped spring-block oscillator {52.48g, 60.94g, 69.72g, 86.51g, 93.47g, 113.27g} and the damping ratio?

1.2 Background Information

An ideal and rather theoretical spring-mass system oscillates indefinitely, producing an ongoing sine or cosine curve. In reality, there will be a damping force that can be as minimally consequential as air resistance or as observable as viscous drag in a liquid. Anyway, energy is dissipated to the surroundings and hence the amplitude will gradually decrease until the oscillation stops. This investigation delves into the relationship between the mass m of an oscillator and the damping ratio ζ for each oscillator, which is a measure of how rapid the amplitude of oscillation drops.

Let us now study the foundational model used in this investigation. The motion of the oscillator is modeled by the following differential equation (Miller, 2004):

$$m\ddot{x}(t) + b\dot{x}(t) + kx(t) = 0 \tag{1}$$

where

- m denotes the mass of the oscillator
- b denotes the damping coefficient that is constant in a system of constant fluid viscosity
- k represents the spring constant
- $x(t)$, $\dot{x}(t)$, and $\ddot{x}(t)$ denote the displacement, velocity, and acceleration of the oscillator respectively, at any time t.

It must be noted that, in the above differential equation, the **damping force**, which will tell us about the damping ratio ζ, is represented by $b\dot{x}(t)$, which is proportional to the speed of the oscillator.

Now, let us quantify the variable ζ, the damping ratio, which is defined as the ratio of the damping coefficient to the critical damping coefficient — the damping coefficient when the system returns to equilibrium in the shortest time possible without completing an oscillation. That is

$$\zeta = \frac{b}{c_c} = \frac{b}{2mw_0}$$

where w_0 is the natural frequency of the system

$$w_0 = \sqrt{\frac{k}{m}} \implies \zeta = \frac{b}{2\sqrt{mk}} \tag{2}$$

This gives us some knowledge about our dependent variable ζ, but we need further information about b to make more meaningful deductions. This is where Stoke's Law comes in.

As previously mentioned, the damping force is proportional to the velocity of the oscillator —

this is a desirable property that allows us to estimate this damping force using Stoke's Law, which also uses the fact that force is proportional to the object's velocity. By doing so, we proceed with the assumption that the damping force is just the viscous drag force.

As per the Data Booklet, Stoke's Law determines the drag force acting upon an object traveling through a fluid – proportional to the object's velocity and is the following per the Data Booklet, in newtons

$$F_d = 6\pi r\eta v$$

where

- r (m) is the radius of the sphere
- η ($\mathrm{N\,s\,m^{-2}}$) is the viscosity of the fluid at some temperature
- v ($\mathrm{m\,s^{-1}}$) is the velocity of the object in the fluid

In the upcoming hypothesis, we work under the reasonable assumption that the damping force is the drag force, which allows us to express b using more meaningful quantities.

1.3 Hypothesis

By previous argument, the constant of proportionality of the damping force with speed is given by $b = 6\pi r\eta$, per Stoke's law. We now use eq. (2) to obtain the following

$$6\pi r\eta = 2\zeta\sqrt{mk}$$

$$9\pi^2 r^2\eta^2 = \zeta^2 mk$$

$$\frac{\zeta^2}{m^{-1}} = \frac{9\pi^2 r^2\eta^2}{k} \tag{3}$$

Proposition 1. *For a fixed sphere radius r and viscosity η,*

$$\zeta^2 \propto m^{-1} \tag{4}$$

Equivalently, the graph ζ^2/m^{-1} is ideally a straight line, although not necessarily passing through the origin, as some form of systematic errors are expected.

There exist other physics conditions that we must examine to determine the sensibility of estimating the damping force as the viscous drag of the liquid.

Firstly, one must recognize that Stoke's Law requires that the flow is laminar. This is a reasonable assumption to make given that the spheres are relatively small, and the speed is low; the potential for turbulence is negligible, and even if it is present, the impact would be minimal. Furthermore, the buoyancy force on the object

$$F_b = \rho g V$$

given in newtons, where

- ρ is the density of the fluid, in $\mathrm{kg\,m^{-3}}$
- V is the volume of the object, in $\mathrm{m^3}$
- g is the gravitational field strength, in $\mathrm{m\,s^{-2}}$

is always present but is not modeled in the differential equation at eq. (1). Notwithstanding, the absence of considerations of buoyancy has negligible impact on the results. The setup involves spheres of radius 2.5cm and water of density 997kg m^{-3}, then

$$F_b \approx 10 \times 1000 \times \frac{4}{3}\pi(2.5 \times 10^{-2})^3 < 1\text{N}$$

which confirms that the buoyancy force is sufficiently infinitesimal to be neglected in the model.

Null hypothesis (H_0): There is no relationship between the mass and the damping ratio.
Alternative hypothesis (H_1): There is a relationship between the mass and the damping ratio.

2 Research Design

2.1 Variables

Variables		Explanation	Measurement
Independent	Mass m	The masses of the spherical metal bobs	Measured using an electric balance, to two d.p. with uncertainty ± 0.01g
Dependent	Peak Amplitude	3 peaks will be measured. These data points are used to compute the damping ratio.	Ruler, with uncertainty ± 0.1cm

Table 1: Variables of investigation

Control Variables		
Variable	Rationale	Means of Control
Liquid viscosity 0.85 ($\mathrm{N\,s\,m^{-2}}$)	To keep the drag coefficient per Stoke's Law constant	Using **water from the same source** throughout the experiment, and keep the **room temperature** constant by turning off the air conditioning. In fact, during the experiment, the room temperature was 27°C
Radius of the sphere, r = 2.5cm	This is so that the drag force, per Stoke's law, is constant	Using spherical masses of the same diameter
Spring constant, k = $100\mathrm{N\,m^{-1}}$	This is so that the natural frequency of the system is constant	Using the same spring throughout the experiment. Read from the label on the box.
Initial amplitude, $A_0 = 5$cm	So that the damping ratio is not affected by the initial conditions	Pulling the spring down by equal distances for every mass. Measured by a ruler with ±0.1cm
Damping coefficient	Linearizes relationship between damping ratio and mass	Previous means of control keep fluid viscosity and object dimensions constant, so the damping coefficient will be constant.

Table 2: Control variables

2.2 Apparatus and Materials

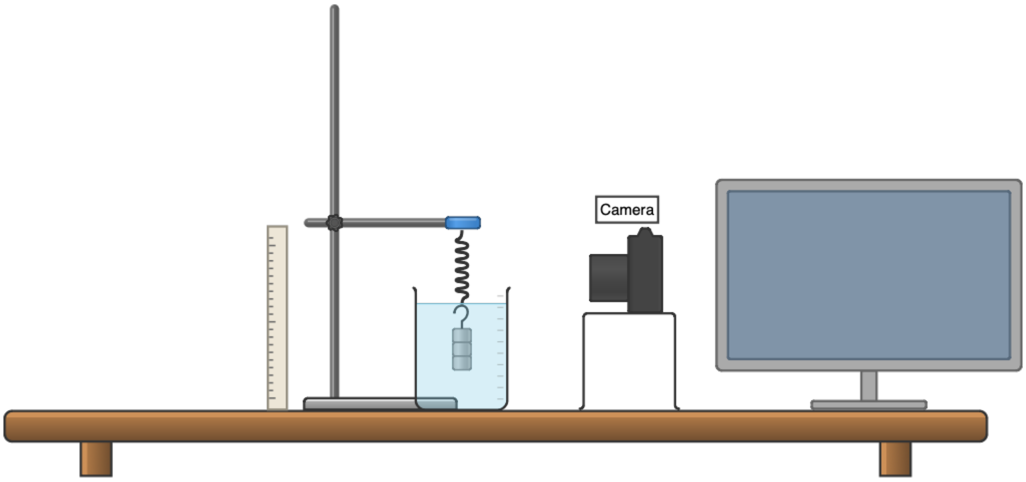

Figure 1: The experimental setup

1. Ruler ($\pm$0.1cm)
2. Electric balance ($\pm$0.01g)
3. Spring with spring constant $k = 100\mathrm{N\,m^{-1}}$
4. Mass set with six spherical masses of diameter 2.5cm
5. Beaker
6. Tap water
7. Camera — keeps a record for future reference
8. Thermometer — to ensure that the liquid stays at a constant temperature
9. Retort stand
10. Clamp

2.3 Methodology

1. Take a scotch tape, and cut into segments of 8 cm in length.
2. Arrange the six masses in increasing order, i.e. $m_1 < m_2 < ... < m_6$
3. Fill in the beaker with A mL of tap water
4. Measure the temperature of the water, and record as T_0
5. Attach the clamp to the retort stand.
6. Fix the ruler vertically against the retort stand.
7. Place the beaker directly under the clamp such that the clamp lies at the center of the beaker in bird's eye view.
8. For i from 1 to 6 inclusive, repeat the following
   (a) Measure the water temperature and wait until it stays constant at 27°C.
   (b) Take the ith mass, m_i, and attach its hook to the spring.
   (c) Take a piece of tape, wrap it as many times as possible across the point of connection.
   (d) Attach the spring-mass pair to the clamp and let the mass hang freely.
   (e) Adjust the height of the clamp so that the mass is submerged in the water.
   (f) Measure the height of the mass from the surface of the desk, and record as h_0
   (g) Adjust the vertical camera position such that it levels with the reading $(h_0 - \frac{A_0}{2})$cm to minimize parallax error of the camera.
   (h) For j from 1 to 5 inclusive, repeat the following (this represents the 5 repeats)
      i. Pull the mass down by A_0 cm by reading $h_0 - A_0$ from the ruler at eye level. The center of the mass should be the height a which readings are taken.
      ii. Start the camera recording.
      iii. Release the mass.

iv. Record the clip until the 3rd negative peak is reached.

v. Save the clip as `Mass_i_Trial_j.mp4`

vi. Open the clip in a video viewer.

vii. Identify the first 3 negative peaks, one in each cycle.

viii. Record the respective heights above the desk as $\{h_k\}_{k=1}^{5}$.

ix. Then the corresponding peak amplitudes are $A_k = h_0 - h_k$

(i) Take the average values across the three trials for each peak amplitude.

2.4 Preliminary Trials

Preliminary trials were conducted to identify and resolve potential challenges, as well as to refine the experimental conditions. As planned, lighter masses were used but during the experiment, more material was used to assemble heavier masses; this is because the trial proved that spheres with insufficient masses do not oscillate. Initially, no mechanism was utilized to attach the masses to the spring, which led to slipping. To improve the attachment's security and uniformity, Scotch tape was tested and found to be more effective, significantly reducing variability and enhancing setup repeatability. Precise measurement of the initial height (h_0) and consistent displacement of the mass by A_0, cm were also challenging. Aligning the ruler vertically proved crucial for accuracy. Adjustments to the clamp and careful ruler leveling minimized parallax error, further reduced by positioning the camera at eye level.

2.5 Risk Assessment

Consideration	Relevance and Mitigation
Safety	All valuable assets are kept away from the experimental setup to prevent accidental detachments of the spring-mass system leading to the mass being thrown out and causing damage. Moreover, the amplitude was kept low to prevent fierce movements of the spheres that could break the beaker or computer camera. Also, water spillage is minimized to keep electrical devices safe.
Ethical	No use of animals or human bodies involved. However, the recording selects the location and angle that avoids the storage and exposure of any personal information or objects of the lab owner, ensuring maximum privacy protection.
Environmental	The entire experiment aims to reuse the same water throughout to minimize water wastage. Furthermore, the spring was carefully pulled to prevent it from passing its elastic limit and becoming unusable for future experiments.

Table 3: Risk Assessment

3 Results

3.1 Raw Data

3.1.1 Qualitative Data

During the entire experiment, there is no spillage of water, which means that the volume is kept constant. Moreover, the spring is always able to return to its original length without any permanent deformation, indicating that the spring is not stretched beyond its elastic limit and that Hooke's Law applies throughout.

3.1.2 Quantitative Data

Let m denote the mass of a bob, and A_n denote the n-th peak height.

$m \pm 0.01$ (g)	$A_1 \pm 0.1$ (cm)					$A_2 \pm 0.1$ (cm)					$A_3 \pm 0.1$ (cm)				
52.48	2.9	2.9	2.8	2.8	2.9	1.7	1.8	1.7	1.7	1.7	1.0	1.0	1.0	1.1	1.0
60.94	2.9	3.0	3.0	2.9	3.0	1.8	1.9	1.8	1.8	1.8	1.1	1.1	1.1	1.2	1.1
69.72	3.1	3.1	3.1	3.1	3.1	1.9	2.0	1.8	1.9	1.9	1.2	1.2	1.2	1.3	1.2
86.51	3.3	3.3	3.3	3.3	3.3	2.1	2.1	2.2	2.1	2.1	1.4	1.4	1.4	1.4	1.3
93.47	3.5	3.3	3.4	3.3	3.5	2.4	2.2	2.4	2.2	2.2	1.5	1.5	1.5	1.5	1.5
113.27	3.5	3.5	3.7	3.6	3.5	2.3	2.4	2.4	2.5	2.3	1.6	1.4	1.5	1.7	1.4

Table 4: Raw data of peak amplitudes

3.2 Data Processing

3.2.1 Transformation

For the sake of consistency, let us start with the following definition.

Definition 1. *Let the tuple* (i, j) *denote the pair of peaks at* i *and* j *respectively, with* $i < j$.

Using the *logarithmic decrement* method per Inman (2008)

$$\delta_{(i,j)} = (j - i) \ln \left(\frac{A_i}{A_j} \right) \text{ and } \delta = \frac{2\pi\zeta}{\sqrt{1 - \zeta^2}}$$

where A_i and A_j denote the peak height measurements at the i-th and j-th peaks respectively. It then follows that

$$\begin{aligned} \delta^2 &= \frac{4\pi^2\zeta^2}{1 - \zeta^2} \\ \delta^2 - \delta^2\zeta^2 &= 4\pi^2\zeta^2 \\ \delta^2 &= \zeta^2 \left(4\pi^2 + \delta^2 \right) \\ \zeta &= \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} \end{aligned}$$

ζ, by definition, may be considered as a function of a pair of peaks. This function is applied to **every pair**, producing a set of values of ζ, across which we will take the average to most accurately identify the damping ratio — computing ζ from a mere peak-pair poses vulnerability to random error and lacks reliability. This step is encapsulated in the Python snippet attached in the appendix section at section 5.1, which belongs to an overall script for processing the data and generating the graph.

Note that $\overline{A_i}$ denotes the average value of the i-th peak across the five repetitions.

$m \pm 0.01$ (10^{-3}kg)	$\overline{A_1}$ (10^{-2}m)	$\overline{A_2}$ (10^{-2}m)	$\overline{A_3}$ (10^{-2}m)	$\zeta^2/10^{-3}$ (unitless)
52.48	2.9	1.7	1.0	7.13
60.94	3.0	1.8	1.1	6.33
69.72	3.1	1.9	1.2	5.67
86.51	3.3	2.1	1.4	4.63
93.47	3.4	2.3	1.5	4.22
113.27	3.6	2.4	1.5	4.83

Table 5: Processed data

3.2.2 Uncertainty Analysis

In this section, one will learn about how uncertainties propagate through the calculation of the damping ratio.

We will adopt the following method for the computation of uncertainties: Let Δx denote the absolute uncertainty of x. For $\Delta x \ll x$, the uncertainty of $f(x)$ is given by the following (Vacher, 2001)

$$\Delta f(x) \approx \frac{\mathrm{d}f(x)}{\mathrm{d}x} \times \Delta x \tag{5}$$

From the raw data of the peak heights to ζ, as seen in the data transformation section at section 3.2.1, the initial measurements have gone through a series of functions to finally arrive at a value for ζ. Thus, to visualize the propagation of uncertainty, we will consider how the uncertainty is propagated in each individual step of the transformation linearly. The highlighted rows represent the final stages of the uncertainty propagation for the independent and dependent variables respectively.

Let i, j be the indices of any pair of peaks such that $i < j$, and also let $\gamma_{i,j} = \dfrac{A_i}{A_j}$, the following table summarizes the uncertainties involved in the calculation of the damping ratio from a pair of peaks indexed with (i, j). The right-most column is obtained by applying the procedure outlined by eq. (5).

Variable	Represented Transformation	Propagated Absolute Uncertainty
m		$0.01\,\mathrm{g} \equiv 10^{-5}\,\mathrm{kg}$
m^{-1}		$(m^{-2} \times 10^{-5})\ \mathrm{kg}^{-1}$
$A_k,\ \forall k$		0.1cm
$\gamma_{i,j}$	$\frac{A_i}{A_j}$	$\Delta\gamma_{i,j} = \frac{A_i}{A_j}(\frac{\Delta A_i}{A_i} + \frac{\Delta A_j}{A_j})$
$\delta_{i,j}$	$\frac{1}{j-i}\ln\gamma_{i,j}$	$\Delta\delta_{i,j} = \frac{1}{j-i} \times \frac{\Delta\gamma_{i,j}}{\gamma_{i,j}}$
$\zeta_{i,j}$	$\frac{\delta_{i,j}}{\sqrt{4\pi^2+\delta_{i,j}^2}}$	$\Delta\zeta_{i,j} = \dfrac{\mathrm{d}\zeta}{\mathrm{d}\delta} \times \Delta\delta$
$\zeta_{i,j}^2$		$2(\zeta_{i,j}) \times (\Delta\zeta_{i,j})$

Table 6: Uncertainty Propagation

Let us manually carry out this procedural analysis for one of the data points in section 3.2.1 to visualize the propagation of uncertainty:

1. Consider the first row, with $m = 52.48 \times 10^{-3}\,\mathrm{kg}$
2. We start by calculating the x-axis uncertainty
   (a) The uncertainty of the mass reciprocal is calculated as

$$(52.48 \times 10^{-3})^{-2} \times 10^{-5} \approx 0.003631$$

3. We now calculate the uncertainty along the y-axis
   (a) Take a pair of peaks' average heights, say $(\overline{A_1}, \overline{A_2}) = (2.9, 1.7)$
   (b) We compute $\gamma_{1,2} = \frac{2.9}{1.7} \approx 1.706$ and $\Delta\gamma_{1,2}$

(c) We move along the uncertainty formulae table in section 3.2.2 to calculate the $\zeta^2_{1,2}$ and its uncertainty.

(d) We repeat a similar procedure to arrive at a value of 2.71×10^{-3} for $\Delta(\zeta^2_{1,2})$.

(e) The process is repetitive by nature, for the sake of clarity, the numeric working is omitted.

(f) We iterate over previous steps to compute $\Delta(\zeta^2_{1,2})$, $\Delta(\zeta^2_{2,3})$, $\Delta(\zeta^2_{3,1})$, among which we will take the average as the final y-axis uncertainty for the sake of reliability.

To implement the above logic in Python, the previous code snippet in fig. 4 under section 5.1 is extended to include the uncertainty calculations. See section 5.2 for the full code snippet. Running the script again yields the following table of uncertainties:

$\Delta m/10^{-3}$ (kg)	$m^{-1}(\text{kg}^{-1})$	$\Delta m^{-1}(\text{kg}^{-1})$	$\Delta\zeta^2/10^{-3}$ (unitless)
52.48	19.23	$0.003631 \approx 0.00$	2.71
60.94	16.39	$0.002693 \approx 0.00$	2.24
69.72	14.29	$0.002057 \approx 0.00$	2.17
86.51	11.49	$0.001336 \approx 0.00$	1.91
93.47	10.75	$0.001145 \approx 0.00$	1.63
113.27	8.850	$0.000779 \approx 0.00$	1.62

Table 7: Absolute uncertainties

3.3 Graphical Interpretation

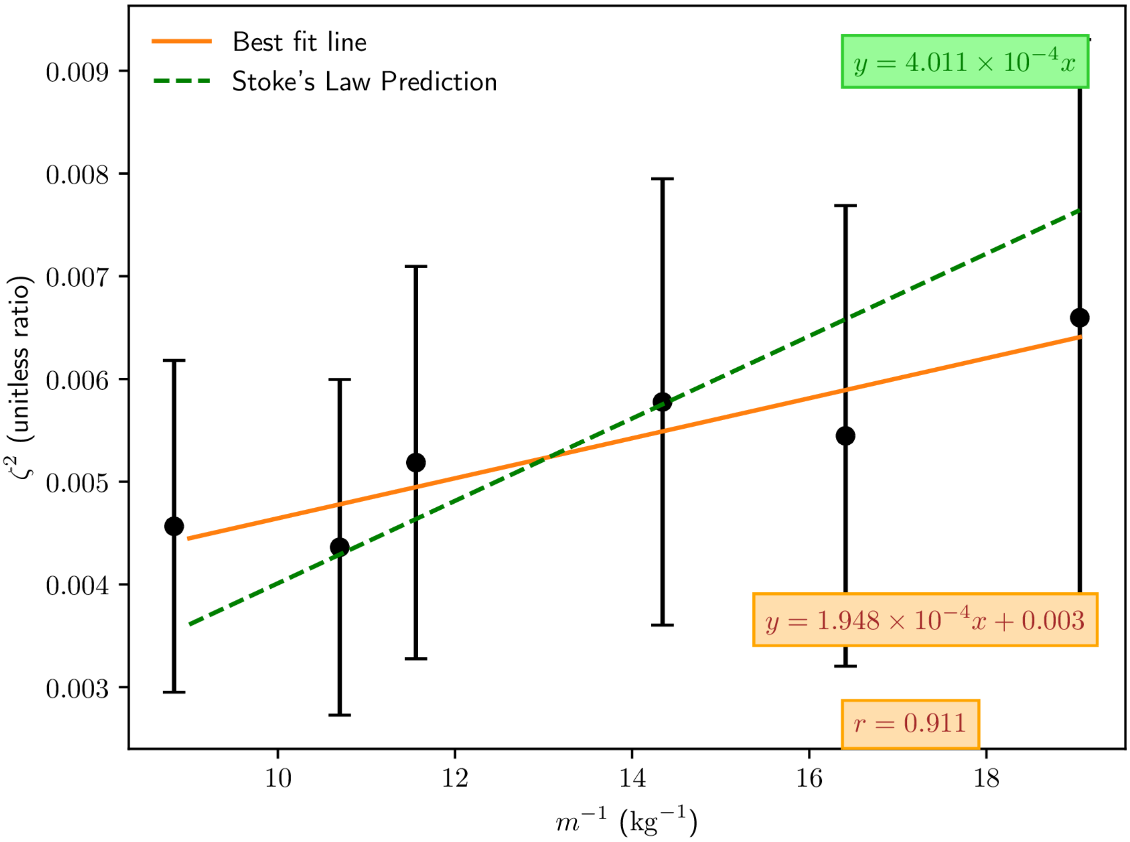

Figure 2: Graph of ζ^2 against m^{-1}, with best-fit line and predicted line

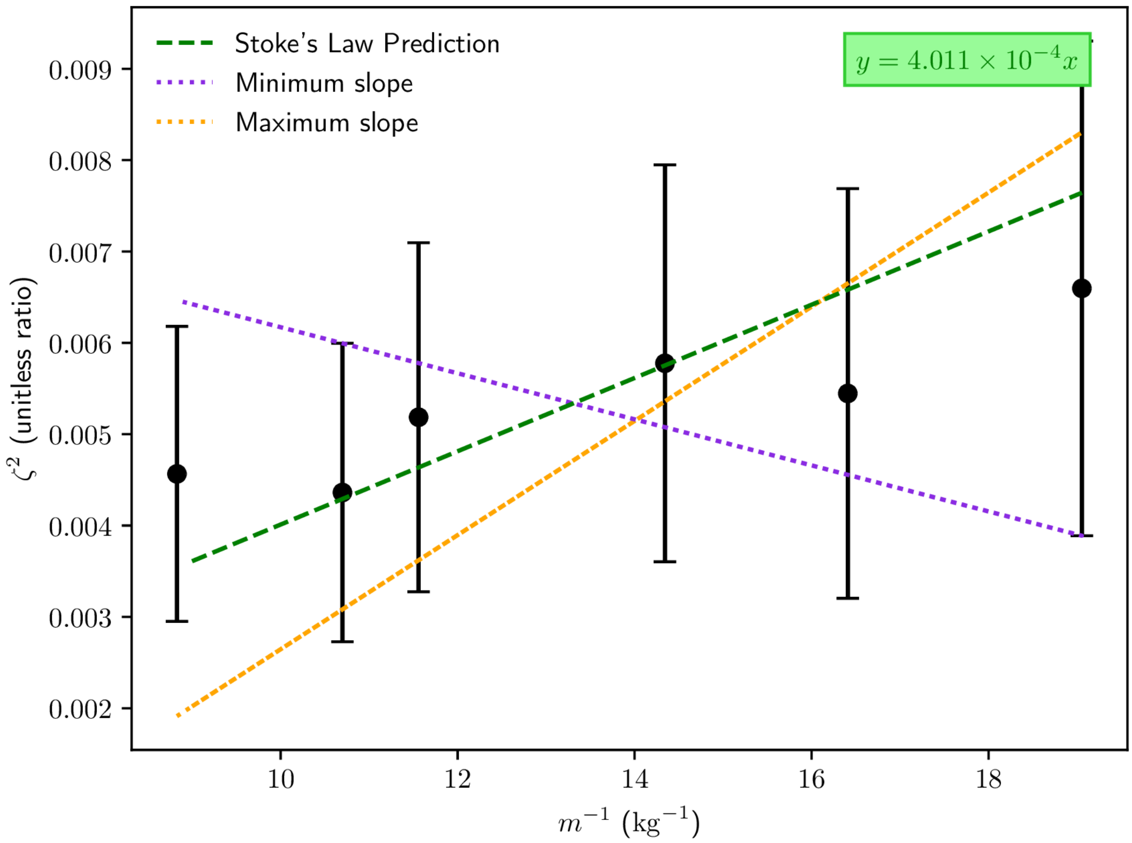

Figure 3: Graph of ζ^2 against m^{-1} — literature review

The two graphs above show the relationship between the damping ratio squared and the inverse of the mass from the resultant dataset, with error bars plotted. The first graph, fig. 2, shows a scatter plot of the data points from section 3.2.1, with the best-fit line and the line predicted using Stoke's Law stated in the hypothesis proposition section. The data points suggest a linear relationship between ζ^2 and m^{-1}, with the Pearson correlation coefficient $r = 0.684$. The second graph, fig. 3, shows the prediction line in comparison to the maximum and minimum-slope lines resulting from the propagation of uncertainty — indeed, the theoretical prediction does lie within the error bars of the data points.

4 Conclusion

This essay delved into the effect of mass m on the damping ratio ζ of a damped spring-block oscillator submerged in water, with the hypothesis that

$$\zeta^2 \propto m^{-1}$$

The results from the experiment suggest a linear relationship between the damping ratio squared and the inverse of the mass, with a Pearson correlation coefficient of $0.684 \approx 0.7$, indicating a relatively strong linear trend. This evident linearity confirms our implied conjecture that the damping force can be estimated using the viscous drag force per Stoke's Law.

Let us now evaluate our result against the expected gradient K predicted by eq. (3). By substituting the control variables, we obtain

$$K = \frac{9\pi^2(0.025)^2(0.85)^2}{100} \approx 4.011 \times 10^{-4}$$

This theoretically predicted gradient falls within the interval of the maximum- and minimum-slope lines, namely the range $[-2.264 \times 10^{-4}, 5.086 \times 10^{-4}]$, validating the hypothesis that the damping ratio squared is inversely proportional to the mass and that the constant of proportionality is correctly estimated by our hypothesis, within the experimented range of 52.48 to 113.27 grams.

The observation that the data points are not perfectly collinear is a consequence of the uncertainties that arise from the limitations of measuring devices and human errors. One primary source of random error is the unintentional but inevitable extra force applied when releasing the spring in the liquid. Nonetheless, the mass set did not produce anomalies and massive systematic errors, suggesting that the environment and the experimental setup were controlled effectively.

Finally, it should be noted that the error propagation procedure does create rather significant error bars due to the already small values of ζ^2, particularly for smaller masses. However, this should be expected since ζ^2 is very sensitive to a change in mass, and this high sensitivity would naturally lead to larger ranges of uncertainty.

4.1 Evaluation

4.1.1 Strengths

Strength	Observations
Attempt to minimize random error in peak amplitudes	Across the three peaks, all possible pairs were used to calculate a value of ζ, across all of them an average is taken. This produces the $\overline{\zeta}$ that is closer to the true value for each possible oscillation, as the average measurement is less susceptible to arbitrary changes in the system.
Error minimization procedures	The experiment was designed to minimize random and systematic errors. Taking fix trials and computing the average builds upon the attempt to minimize error by averaging pairs across three peaks, further diminishing the impact of potential anomalies and outliers in the dataset.
Consistency	The entire experiment followed a sequence of algorithmic and rigid instructions to ensure that each trial was conducted in the same conditions.
Preliminary tests	Preliminary tests were conducted to identify potential challenges and refine the experimental conditions, ensuring that the final experiment was conducted under optimal conditions.

4.1.2 Weaknesses — Random Errors

Weakness	Observations	Improvements
Inaccuracy of manual identification from video clip	The manual identification of the peaks from the video clip may have introduced human error, leading to further inaccuracies in the peak amplitude measurements. These uncertainties may not have been captured by the data analysis.	Integrating computer vision can automatically identify the peaks would reduce human error and improve the accuracy of the measurements.
Release of the oscillator	The release of the oscillator may have introduced an additional force, leading to inconsistencies in the peak amplitude measurements.	Using tongs, for instance, would ensure a consistent force and minimize the introduction of additional forces.
Scotch tape attachment	At times the attachment demonstrated signs of slipping or looseness, which may have affected the oscillation and effect of damping.	Using a more secure attachment method, such swivel connectors, would ensure the mass' hook is firmly attached to the spring.

4.1.3 Weaknesses — Systematic Errors

Weakness	Observations	Improvements
Limited sample strength.	The experiment only used six masses, which may not be sufficient to draw generalized conclusions. This was due to limited equipment provided by the laboratory. Moreover, it does not cover a great range of masses either, hence the model failed to inspect the behavior of the oscillatory motion for larger masses and validate the hypothesis for them.	Increasing the range of masses tested would provide a more comprehensive dataset and enhance the reliability of the results.
Varying spring constant	The spring constant was assumed to be constant, but in reality, it may have varied slightly with use, leading to inaccuracies in theoretical prediction of the gradient.	Preparing a set of identical springs and consistently switching between them would minimize fatigue.
Camera positioning	The camera positioning may have introduced parallax errors, leading to systematic errors in all of the peak amplitude measurements.	Through calculations, find the optimal position to minimize the average uncertainty across the peak measurements.

Large uncertainty ranges in ζ^2	The error spans in ζ^2 were large, particularly for smaller masses.	Using more accurate measuring devices, such rulers and electric balances with even finer resolutions.

4.1.4 Extensions

A possible extension of this experiment involves investigating the effect of different fluid densities on the damping ratio of the oscillating system. By repeating the experiment with fluids of known densities (e.g., water, glycerol, oil) whose values can be found on the Internet, and keeping control variables constant, i.e. mass, initial amplitude, spring constant, and temperature, one can analyze how changing densities influence the damping behavior. As a hypothesis, the higher the density is, the larger the viscous drag force, and thus the greater the damping ratio.

Alternatively, one may also explore the impact of varying the spring constant on the damping ratio. By using springs varying in stiffness, one can investigate how the damping ratio changes with the spring constant. The hypothesis, based on Proposition 1, would be that the higher the spring constant, the lower the damping ratio, as the spring would exert a greater force to counteract the damping force.

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5 Appendix

5.1 Python Script for Data Processing

```python
# Calculate the average damping ratio for each row in the dataframe
def avgDampingRatio(row: pd.Series):
    ratios = np.array([])  # Create an empty array to store the damping ratios

    # Iterate over the range of peak indices
    for i in range(PEAK_IND[0], PEAK_IND[1] - 1):
        # Iterate over the range of peak indices starting from i+1
        # the purpose of this double loop is to calculate the damping
        # ratio between every possible pair of peaks
        for j in range(i + 1, PEAK_IND[1]):
            n = j - i  # Calculate the number of cycles between i and j
            delta = (1 / n) * math.log(
                (row.iloc[i]) / row.iloc[j]
            )  # Calculate the logarithmic decrement between the peaks
            zeta = delta / math.sqrt(
                4 * (math.pi) ** 2 + delta**2
            )  # Calculate the damping ratio using the logarithmic difference
            ratios = np.append(
                ratios, zeta
            )  # Append the damping ratio to the ratios array

    return np.average(ratios)  # Return the average damping ratio

def processData():
    # reads the data tables and find the average across 5 trials
    df = averageData()
    # ...

    # populate the column of damping ratio in the table for each mass
    df["Damping Ratio"] = df.apply(
        avgDampingRatio,
        axis=1,
    )
```

Figure 4: Calculating the damping ratio with pandas in Python

5.2 Extended Script with Uncertainty Propagation

```python
# Calculate the average damping ratio for each row in the dataframe
def avgDampingRatio(row: pd.Series, mode: Union["uncertainties", "vals"]):
    if type(row.iloc[-1]) == str:
        return 0
    ratios = np.array([])  # Create an empty array to store the damping ratios
    zetaSqUncertainties = np.array(
        []
    )  # Create an empty array to store the uncertainties of the damping ratios

    # Iterate over the range of peak indices
    for i in range(PEAK_IND[0], PEAK_IND[1] - 1):
        # Iterate over the range of peak indices starting from i+1
        # the purpose of this double loop is to calculate the damping
        # ratio between every possible pair of peaks
        for j in range(i + 1, PEAK_IND[1]):
            n = j - i  # Calculate the number of cycles between i and j
            A_i, A_j = row.iloc[i], row.iloc[j]  # Get the amplitudes of the peaks

            if type(A_i) != float:
                break

            gamma = A_i / A_j  # Calculate the ratio of the amplitudes of the peaks

            delta = (1 / n) * math.log(
                gamma
            )  # Calculate the logarithmic decrement between the peaks

            errAbsGamma = (A_i / A_j) * (
                (peakError / A_i) + (peakError / A_j)
            )  # Calculate the absolute error of gamma

            # Calculate the absolute error of delta
            errAbsDelta = errAbsGamma / gamma

            zeta = delta / math.sqrt(
                4 * (math.pi) ** 2 + delta**2
            )  # Calculate the damping ratio using the logarithmic decrement

            dzeta_ddelta = (
                4 * math.pi**2 / math.pow(delta**2 + 4 * math.pi**2, 1.5)
            )  # Calculate the derivative of zeta wrt delta

            errAbsZeta = (
                dzeta_ddelta * errAbsDelta
            )  # Calculate the absolute error of zeta

            errAbsZetaSq = (
                2 * zeta * errAbsZeta
            )  # Calculate the absolute error of the squared damping ratio

            ratios = np.append(
                ratios, zeta
            )  # Append the damping ratio to the ratios array

            zetaSqUncertainties = np.append(
                zetaSqUncertainties, errAbsZetaSq
            )  # Append the uncertainty of the damping ratio

    return (
        np.average(ratios) if mode == "vals" else np.average(zetaSqUncertainties)
    )  # Return the average damping ratio or the average
    #    uncertainties of the damping ratios based on the mode
```

Figure 5: Calculating the damping ratio with uncertainties in Python