**Experiment 6 and 7: Physical Pendulum Harmonic Oscillations and Waves on Vibrating String**

Kubilay Agi

UID: 304784519

Lab Date: 29 August, 5 September 2018

Lab Section 8 – Monday/Wednesday 11:30am

TA: Jordan Runco

Partner: Shannon Largman

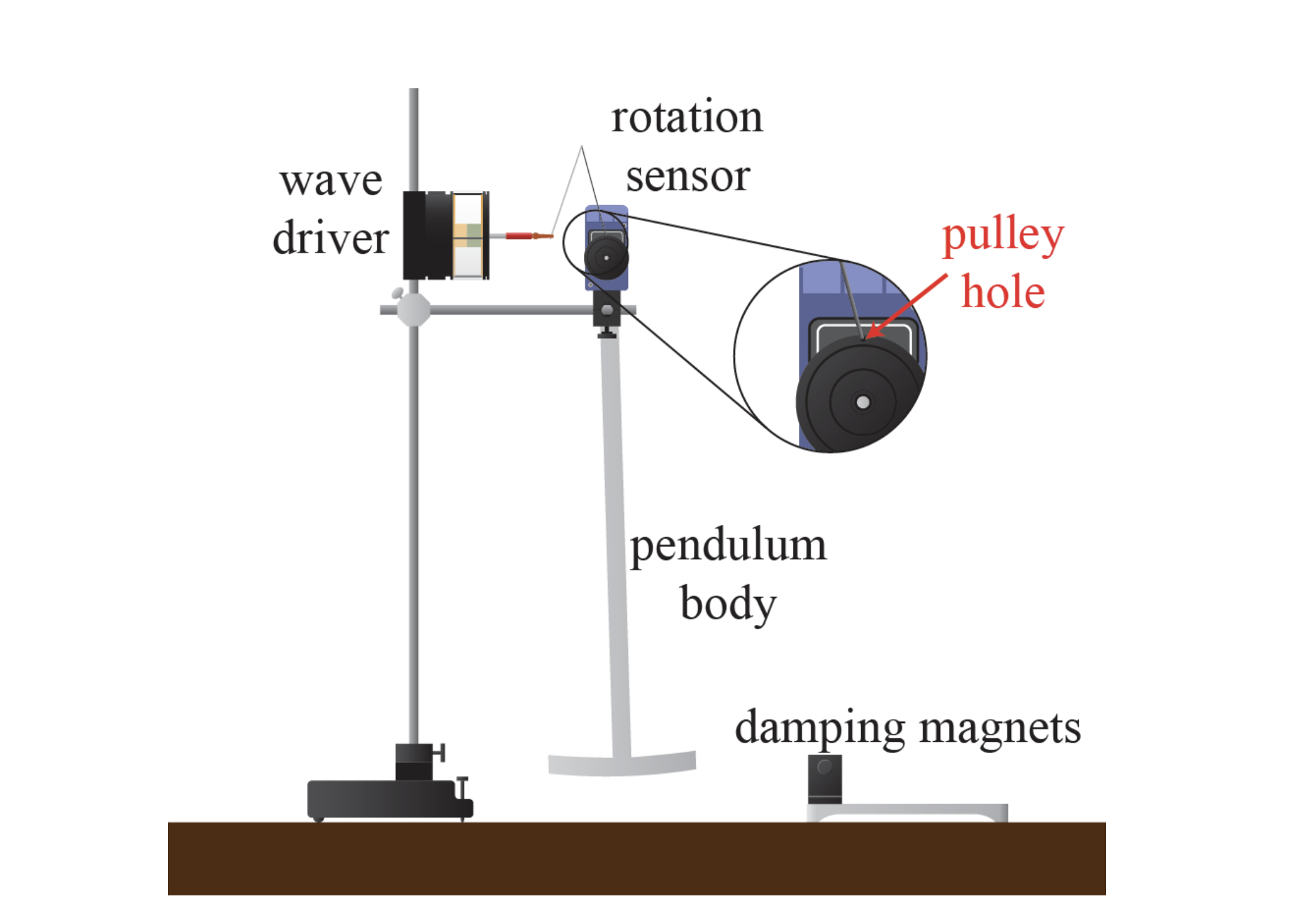
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**Abstract**

**Introduction**

**Methods**

*Pendulum*



**Figure 1, Physical Pendulum Experiment Apparatus**1**:** This image shows the setup of the equipment that was used for the experiment involving a physical pendulum. For the first part of that experiment, the wave driver was off and disconnected from the rotation sensor. In the second part of the pendulum experiment, the wave driver was used to produce waves in the pendulum. We also included a photogate to record the period of the oscillations at the starting point of the pendulum, but this is not illustrated in the image.

The physical pendulum experiment investigates the damping effect that magnetic field strength has on a swinging pendulum. We investigate the different regimes of damping. \*\*\*\*

In the first part of this experiment, we look at undriven oscillations. We define the equilibrium point as the point where the pendulum is at rest, pointing vertically downward. We also designated the direction toward the vertical rod as the positive direction and the direction toward the damping magnets as the negative direction. We set our data acquisition system (DAQ) to record the angle from equilibrium in time steps of 0.04 seconds.

For the undamped trial, we move the magnets away from the apparatus to avoid any unintended damping on the system. We placed our photogate next to the vertical rod. We started the edge of the pendulum at the point where it begins to block the photogate sensor. We do this so that we can have a consistent starting point, and also so that we can record the period of the pendulum as it swings. To measure oscillation period, we set up our DAQ so that it records times starting when the photogates goes from blocked to unblocked and finishes timing the oscillation when it goes from unblocked to blocked.

For the damped trial, we place the magnets at the equilibrium point so that the point where the vertical bar meets the horizonal bar in the pendulum sits within the two magnets. To identify the magnet separation at which critical damping occurs, we decrease the separation for every trial, until we reached overdamping. We start at a (50.0 ± 0.5) mm separation and decrease the distance by about 10 – 12 mm for each trial. We kept the photogate from the undamped trial in the same place so that we have a consistent starting point for each trial. We still record the angle from equilibrium at each time increment with the DAQ.

Next, we look at driven oscillations. For this part of the experiment, we hook up the wave driver to the rotation sensor. We leave the magnet in the same place as they were for the damped undriven oscillation trials (at the equilibrium point). We used a magnet separation of (26.5 ± 0.5) mm for this trial. We used 4 V as our voltage. We turn on the wave driver and determine the resonance frequency by analyzing the Lissajous graphs. We find the frequency at which the Lissajous plot was horizontal without any tilt. It is useful to find a range of values where it is not possible to find differences between the plots. This provides the uncertainty for the measurement.

Also, to determine the amplitude response to frequency of oscillation, we recorded the amplitudes of oscillation for 13 different frequencies. These data points provide us with another method to calculate the Q-factor.

*Waves in a String*

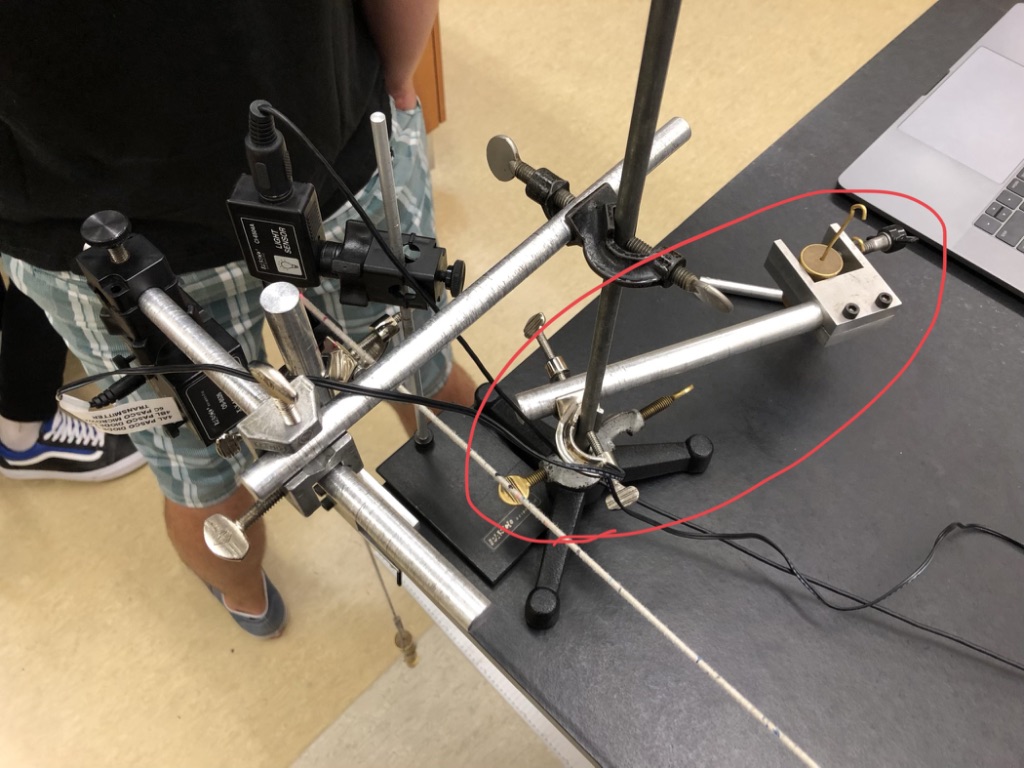


**Figure 2, Vibrating String Experiment Setup:**

For this experiment, we use a wave driver to generate waves on a string. The string is stretched out by running the string over a pulley and hanging a mass off of the end. We tie a knot in the end of the string to hook the masses onto it. We make sure to measure the length of the string used to tie the knot because this length will be subtracted off of the length of the stretched string since it is not stretched.

We point the laser horizontal to the table so that the light covers the upper third of the laser. The photodiode is pointed downward at the string so that its sensor is directly above the portion of the string that the laser is on. The intensity of the laser’s light on the string differs when the string oscillates. Light intensity is the value that we set the data acquisition system (DAQ) to record against time. We also have the DAQ record the output voltage that is sent to the wave driver so that we can see when the waves are generated.

The first sets of data we record do not involve the wave driver. We hang a 100 g, 200 g, and 350 g mass onto the end of the string hanging over the pulley. We measure each segment of the stretched string for each mass. We measure from the clamp by the wave driver to the pulley, and then from the pulley to the start of the knot. We also measure the diameter of the pulley so that we can calculate the length of string that is on the pulley. The sum of these lengths is the stretched length in part one of the experiment. With this data for each mass, we can calculate the linear mass density and applied tension. With these two values, we can determine the predicted wave speed for when each mass is attached. Then we turn the wave driver on at 0.5 Hz and record several seconds of data for each mass that is attached. We record the timestamps in seconds, light intensity as a percentage, and output voltage in volts. With the data that we record, we look at the peaks of the graph of light intensity versus time, and we find the time differences between each consecutive peak to determine the time that it took each wave to travel along the string.



**Figure 3, Counterbalance for Part Two of String Experiment:** This is an image I took of the counterbalance we used to prevent the vertical rod from tipping over. We used an extra rod and masses as the counter balance (circled in red). The laser was attached to this rod, and this made it too top heavy.

After these recordings, we leave the 350 g mass hanging on the end of the string. We move the laser and photodiode to about one centimeter from the apex of the pulley. The apparatus tended to tip over because it was too top heavy. We fixed this issue by adding a counter balance to the apparatus (shown in Figure 3). We now find the fundamental frequency of the string by looking at the parametric Lissajous plots produced by the DAQ by plotting light intensity versus wave driver frequency. From here, we could predict the frequencies for each harmonic. We used these estimations as a starting point when looking at the Lissajous plots and adjusted them to find the actual value according to the results from the DAQ.

Finally, we pinched the string with our fingers halfway between the clamp and the pulley. We run the wave driver at the frequencies that produce the second, fourth, and fifth harmonic. The 350 g mass is still attached to the string for these trials. We keep our finger pinched in the same place for all three trials. We record the times and light intensities for the trials where the string was pinched in the middle. However, we ran out of time, so we were unable to record data for these harmonics when they were not pinched.

**Analysis**

*Regimes of Damping*

**Figure X, Regimes of Damping with Different Magnet Separations:** This plot shows the angle of the pendulum from equilibrium during trials damped with magnets. The underdamped data points were produced using a magnet separation of (28.5 ± 0.5) mm. The overdamped oscillation was generated with a magnet separation of (7.5 ± 0.5) mm. The critically damped oscillation used a magnet separation of (13.0 ± 0.5) mm.

Before the experiment, we hypothesized that larger gaps would result in underdamping and smaller gaps would produce overdamped results. We also expect to see that somewhere in between is the gap length where the system is critically damped. Our results confirm our hypothesis. (28.5 ± 0.5) mm was the larger gap and yielded underdamping, and (7.5 ± 0.5) mm was the smaller gap which yielded overdamping. Finally, (13.0 ± 0.5) mm is the separation that we found produces critical damping.

*Resonance*

**Figure X, Undamped Undriven Pendulum Oscillation:** asldkaf

By looking at Figure X above, we see that for each *n* maxima, there are *n* – 1 cycles between each pair of adjacent extremum. To find the angular frequency of oscillation, we need to divide the number of cycles that occur within a certain time range by the magnitude of that time range.

To find the uncertainty, we take the difference between the amplitudes of each adjacent pair of maxima and take the standard deviation. Then we divide by the square root of the number of data points that we used. In our case, *n* is 7 and is 0.002 radians.

With these equations, we find that the angular frequency of oscillation for the pendulum in the undamped, undriven trial is (0.711 ± 0.001) Hz.

*Q-Factor and Line Widths*

This is the first method we will use to determine the Q-factor of the oscillating pendulum. The quality factor (Q-factor) in an oscillation describes how damped an oscillator is. Oscillators with low quality factors have resonant frequencies in undriven, undamped cases that are significantly different than the resonant frequency during driven, damped oscillation.1 Higher quality factors mean less difference between these two measured angular frequencies. 1

To calculate the Q-factor for our oscillator with this method, we need to know the angular frequency during the damped, driven oscillation trial, and we need to know the damping time. The damping time is the time it takes the amplitude to decrease by a factor of 1/*e*. We measured the resonance frequency of driven, damped oscillations to be (0.657 ± 0.005) Hz at a voltage of 4 V and a magnet width of (26.5 ± 0.5) mm. We used plots of Lissajous to determine the value of resonance frequency. The range in which we could not discern each plot from the others was 0.652 – 0.662 Hz, hence we have an uncertainty of ± 0.005. To find damping time, we can solve Equation 6.121 for the damping time.

Now we can find the Q-factor for this experiment.1

Our Q-factor is (1.71 ± 0.02). Q-factor is a dimensionless value and thus has no units. Our Q-factor here is relatively low. Our two values for damped angular frequency are (0.711 ± 0.001) Hz and (0.657 ± 0.005) Hz. These two values fall out of each other’s error windows and their difference is statistically significant. We would expect that our values of angular frequency for undamped, undriven oscillation would match that of driven, damped oscillations.

It is possible that this result is because of …

*Q-factor via Ratio of Angular Frequencies*

We can also the find the Q-factor by looking at the ratio of angular frequencies. This is our second method to determine the Q-factor. The ratio of the damped, driven resonance frequency to the undamped, undriven resonance frequency is1:

Solving for Q, we get the following equation:

Plugging in our values for and , our value for the Q-factor is (1.71 ± 0.01). This result agrees with our Q-factor from the previous method. The uncertainty for this Q-factor was determined through the propagation of uncertainties with and , which are the only two values with uncertainty in the equation.

**Figure X, Damped Undriven Pendulum Oscillation:** This plot shows how the angle of the pendulum (in radians) from equilibrium changed as time went on. The magnet separation in this damped trial was (38.0 ± 0.5) mm.

**Figure X, Title:** This is the Lissajous plot at the resonance frequency (0.657 ± 0.005) Hz. This major axis of this ellipse is horizontal, which indicates that it is at the resonance frequency.

**Figure X, Title:** This Lissajous plot was generated with a frequency (0.637 ± 0.005) Hz, which is below the resonance frequency. The major axis of the ellipse is tilted so that the right side is slightly higher than the left side.

**Figure X, Title:** This is Lissajous plot generated by using a frequency of (0.677 ± 0.005) Hz. This is above the resonance frequency of (0.657 ± 0.005). The major axis of the ellipse is tilted so that the left side is slightly higher than the right side.

For Figures X and X, it would have been beneficial if we recorded data at frequencies that were further away from the resonance frequency to exaggerate the differences between the plots.

**Figure X, Title:** This plot shows the amplitude of oscillation at various frequencies. The orange line indicates the height which is times the maximum amplitude of the graph. The resonance width is (0.20 ± 0.05) Hz. From the graph, the two values that intersect with the horizontal line are 0.60 Hz and 0.80 Hz.

We can see from this plot that the peak corresponds to the resonance frequency of (0.711 ± 0.001) Hz, which is what we expect. Our plot does not have the complete Lorentzian shape because some values were measured to be the same for different frequencies. However, if we had increased the precision of the measurement, we would likely have the correct shape.

*Q-Factor via Amplitude Response*

The two frequencies that we measured to have amplitude of times the peak amplitude are 0.57 Hz and 0.8 Hz. The plot in Figure X nearly captures this, but we did not have the precision that we used when we were trying to find the exact frequencies. These values provide us with a way to calculate the Q-factor with another method.

**Figure X, title:** This plot shows the Lissajous plots of the two frequencies we measured an amplitude response times the response generated by resonance frequency. Our Lissajous plot for 0.57 Hz produced a cleaner, more rounded graph than 0.80 Hz. We collected more than 500 data points for the trial using 0.80 Hz. The data points from each cycle were repeated from the last cycle. The graph overlaps and does not look as smooth as the plot for 0.57 Hz.

Our first and second method of determining the Q-factor produced nearly identical values. The first method yielded the Q-factor (1.71 ± 0.02) and the second method yielded a Q-factor of (1.71 ± 0.01). With the third method, our Q-factor was determined to be (3.09 ± 0.22). The third method produced a higher value than the first two methods and therefore implies that the undamped, undriven resonance frequency is closer to the

All three methods have their own drawbacks. The first method involves doing more multiplications, which propagates uncertainty more than the second method. This yields a final uncertainty for the first method higher than the second method. However, this method works well when Q >> 1.1 Since we found that our Q-factor was relatively low, this indicates that this method was not entirely reliable. The third method uses the amplitude width . This method is imprecise because our amplitude response data was recorded with too low of a precision. Therefore, we had to estimate our value for the width . This makes the calculation more inaccurate and yields higher uncertainty. Additionally, our graph showed that the horizontal line that was the magnitude of our peak amplitude intersected our Lorentzian data plot in multiple places for the lower bound.

With high values of Q, the ratio of the driven, damped frequency to the undamped, undriven frequency should converge to one. Our value of = (0.657 ± 0.005) is 7.6% off from our undamped, undriven frequency. We expect the ratio to have a value of 0.924. If we plug in each Q-factor from each method into Equation 6.15, we can see which method returned the most accurate Q-factor.

When we plug in the Q-factors from method one and method two into the equation, we receive the value of 0.924, which aligns with the expected value of 0.924. The Q-factor of the third method returns a result of 0.975. Although a higher Q-factor means that our experiment produced the expected result that the two resonance frequencies are similar, the Q-factor from the third method does not accurately reflect the actual results of the experiment.

1

We see that the third method does not produce an accurate Q-factor for our experiment. The first two methods produce same result with similar uncertainties. The second method is the better method to use, even though it returned the same value as the first method. The second method yields a slightly lower uncertainty than the first method. The second method also uses only measured values whereas the first method requires more calculation, increasing the propagation of uncertainty to its results.

**STRING SHIT**

The unstretched string has a length of (16.5 ± 0.4) cm and it has a mass of (15.1 ± 0.2) g.

The unused length of string was (16.50 ± 0.05) cm. We need to subtract off this portion from the total unstretched length of the string. The string at the clamp and the loose end on the clamp side are one unstretched portion, and the string used in the knot at the hanging mass end is also unstretched. Then we find the ratio of the trimmed length to the total length and find that corresponding portion of the total mass of the spring. We find that the mass of the trimmed, stretched string is (12.4 ± 0.2) g. To find the linear density, we need to divide the mass of the stretch string by the length of the stretched string. We already have the stretched mass of the string because this stays constant for each case. We need to find the length of the stretched string by subtracting each unstretched portion length from the stretched length in each trial.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Trial | Mass (g) | Stretched String Length (m) | Applied Tension (N) | Linear Mass Density (kg/m) |
| 1 | 99.8 ± 0.2 | 0.228 ± 0.001 | 1.07 ± 0.05 | 0.00650 ± 0.00012 |
| 2 | 199.7 ± 0.3 | 0.230 ± 0.001 | 2.05 ± 0.05 | 0.00645 ± 0.00012 |
| 3 | 349.5 ± 0.5 | 0.234 ± 0.001 | 3.52 ± 0.05 | 0.00632 ± 0.00012 |

**Table X, Title:** This table presents the string length, applied tension, and linear mass density of the system depending on the mass that was attached to the end of the string. The applied tension was calculated by finding the total mass hanging off of the pulley (hanging mass and string mass) and multiplying by the gravitational constant 9.80 m/s2.

Applied tension has units (kg\*m/s2) and linear mass density has units of (kg/m). We can attain the predicted wave speed if we divide the applied tension by the linear mass density and take the square root of the result.

To find the experimental wave speed, we can measure the distances between the peaks on the graphs which give us the time that the wave took to travel two lengths of the stretched string between the pulley and the clamp. The waves do not travel past the pulley when they are produced by the wave driver, so the pulley is where we end the measurement. We measure two lengths because the positive peaks in the graph are when the wave leaves the wave driver, and then comes back (it has traveled down the string and then back again).

**Figure X, Title:** asldfjklaf. The peaks that we measured to find the experimental wave speed are the top left of each ‘M’ shape.

**Figure X, Title:** asldfkjasldf

**Figure X, Title:** asldfkjasldf.

There is less noise in the oscillations for when the 350 g was attached to the string. We noticed that there was some sag in the string for the two smaller masses. This is might be the reason for the extra noise in the oscillations when 100 g and 200 g were attached.

|  |  |  |
| --- | --- | --- |
| Mass (g) | Predicted Wave Speed (m/s) | Experimental Wave Speed (m/s) |
| 99.8 ± 0.2 | 12.8 ± 0.6 | 12.83 ± 0.07 |
| 199.7 ± 0.3 | 17.8 ± 0.5 | 17.96 ± 0.01 |
| 349.5 ± 0.5 | 23.6 ± 0.6 | 24.05 ± 0.04 |

**Table X, title:** asldfj

OUR VALUES ARE SIMILAR!!!!!! Etc.

We can find the expected frequency of each harmonic using equation 7.3 from the lab manual1. We kept the (349.5 ± 0.5) g mass attached to the string during these trials, so we use the experimental wave speed for that mass. Our stretched length of string is (1.212 ± 0.006) m.

|  |  |  |
| --- | --- | --- |
| nth harmonic | Predicted Frequency (Hz) | Measured Frequency (Hz) |
| 1 | 9.92 ± | 9.81 ± 0.03 |
| 2 | 19.84 | 19.3 ± 0.1 |
| 3 | 29.76 | 28.6± 0.1 |
| 4 | 39.69 | 40.2 ± 0.2 |
| 5 | 49.61 | 49.0 ± 0.04 |
| 6 | 59.53 | 60.5 ± 0.6 |
| 7 | 69.45 | 71.2 ± 0.6 |
| 8 | 79.37 | 79.7 ± 0.8 |
| 9 | 89.29 | 91 ± 1 |

**Table X, Title:** lasdkjfasdjf;laskjf;laskfj

Unfortunately, we ran out of time while conducting the experiment, so we were only able to attain data for the constrained cases. However, we would expect the plots of the graphs for the n=2 and n=4 harmonic to look similar to their restricted plots below. They may have a slightly reduced amplitude because we used our fingers to pinch the string instead of a ring. This is because these two harmonics have a node where the string is pinched. However, the unrestricted n=5 harmonic plot will not look like the restricted plot because the string is pinched at an antinode. We can extrapolate our findings and say that the restricted oscillation plots of even harmonics will look like their unrestricted counterparts. In contrast, plots of restricted oscillations for odd harmonics will not look like the unrestricted oscillation plots. The restriction needs to be at a node for the plot of the restricted oscillation to look like the plot of the unrestricted oscillation.

**Figure X, Title:** This plot shows the oscillations of the stretched string in the second harmonic. The string is pinched with two fingers in the middle of the string. Since the second harmonic is an even harmonic, there is a node where we pinched the string. This allowed to plot to resemble the plot of an unrestricted oscillation plot of the same harmonic. However, since we ran out of time to record the unrestricted oscillation data, that plot is not shown. The maxima and minima are fairly consistent throughout the data set. This indicates that we pinched the string in the correct place on the string (almost exactly at the node).

**Figure X, Title:** This is the plot of the string’s oscillations at the fourth harmonic. This is also an even harmonic, so the plot likely resembles the unrestricted oscillation plot. We pinched the string in the middle, and the fourth harmonic has a node in the middle. The shift of the graph up and down was likely because we pinched the string with our fingers. The shakiness of our hands would have shifted the string up or down, causing the laser to shine more or less on the string, causing the light sensor to have varying readings.

**Figure X, Title:** This plot shows the oscillation of the string at the fifth harmonic while pinched in the middle. It does not resemble the plot for the unrestricted oscillation because the string is pinched in a place where the string has an antinode at the fifth harmonic.

**Conclusion**

In the physical pendulum experiment, we look at the three damping regimes, the resonance frequencies for damped and undamped oscillations, and the Q-factors of the oscillator systems. [\*\*explain what we did to get the result here i.e. params that were used: undriven trial, we did not use the magnets or the wave driver. Magnets separated 26.5 mm etc\*\*]

For the undamped, we measured a resonance frequency of (0.711 ± 0.001) Hz. We determined this result by looking at the number of oscillation cycles were completed within a certain time span. The resonance frequency in the damped, driven trial was determined by looking at the Lissajous plots of different frequencies and looking for which value produced an ellipse with a horizontal major axis. We expected to find that the two resonance frequencies would be the same. However, we measured a resonance frequency of (0.657 ± 0.05) Hz in the damped trial.

We calculated the Q-factor of the oscillator with three different methods. The first and second method produced values of (1.71 ± 0.01) Hz and (1.71 ± 0.02) Hz respectively. These results agree with the expected Q-factor considering the difference between our resonance frequency in the drive, damped oscillations and undriven, undamped oscillations. The third method produced a higher Q-factor of (3.09 ± 0.22). This value did not accurately represent the relationship between the two resonance frequencies. Because of the minimal propagation of uncertainty, it was determined that the second method was the most accurate method of finding the Q-factor, even though that method is meant to be used for Q >> 1.1

This discrepancy between our resonance frequencies for each trail could have been caused by several reasons. It is possible that the rotation sensor introduced friction that affected the undamped trial more than the damped trial. The oscillation in the undamped trial had a much higher amplitude of angular displacement than in the damped trial. Additionally, it was difficult to hold the pendulum at the correct depth during each release. After releasing the pendulum, it would shake back and force along the axis of torque in the system.

To prevent these discrepancies, we could use the same angular displacement amplitude for both trials. This way, the friction would affect both trials the same. Additionally, we could use a release mechanism to prevent the shaking of the pendulum. The releases would be consistent for each release and the releases would be smooth. Also, we should increase the precision of our measurements to improve our plot of amplitude response. With higher precision, we would get the Lorentzian shape that we are looking for.

[Results of the string wave thing]

[where the errors came from]

The amplitudes of oscillation were likely reduced in the third part of this experiment because we used fingers to pinch the string.

Some of the data we took was not as precise as we would have liked it to be, especially in the second and third parts of the experiment. We had to make rough estimates for some of the frequencies of each harmonic frequency because we did not have enough time to narrow down to the precise value for each one.

[how to improve it]

We should work more efficiently so that we have enough time to record each set of data accurately and precisely.

We should figure out a way so that we can avoid having to hold up the meter ruler in the air to measure the length of the string that is hanging off

**Bibliography**

1. Campbell, W. C. et al. Physics 4AL: Mechanics Lab Manual (ver. June 27, 2018). (Univ. California Los Angeles, Los Angeles, California).