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

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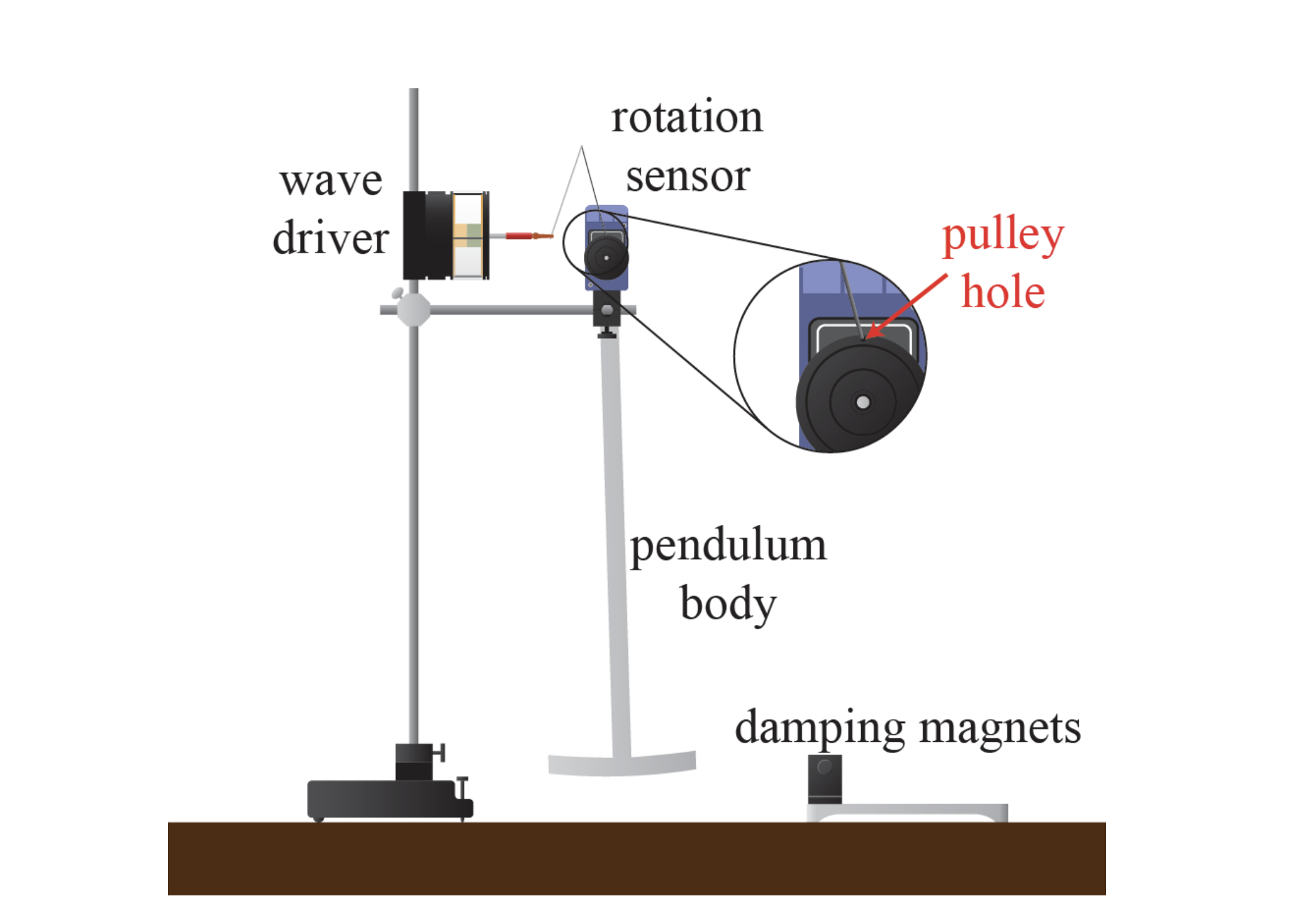
Partner: Shannon Largman

**Abstract**

**Introduction**

**Methods**

*Pendulum*



**Figure X, 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 X, Vibrating String Experiment Setup:** alsdasdf

**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.

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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.

**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]

[how to improve it]

**Bibliography**

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