Designing and Testing an Upper Level Physics Lab

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1 Abstract

This project is the design and testing of an upper level physics laboratory experiment. The goal of the project was to design an experiment that would coincide with a lecture topic covered in General Physics III. The chosen topic for these experiments was oscillations, both mechanical and electrical.

General Physics III is the only general physics course at Christopher Newport University without an associated lab course, however, it does still form part of the foundation for physics knowledge attained in the physics major and minor. Lab courses allow students to apply the material learned in the lecture course in a hands-on creative environment. They allow students to reinforce and have a better and deeper understanding of physics concepts.

This project produced two experiments involving mechanical oscillations and created an outline for an experiment in electrical oscillations. It discusses how different oscillations are linked together while also guiding students through an exploration of the physical concepts.

2 Introduction

2.1 Background

This project is the design and testing of an upper level physics lab experiment that corresponds with a concept taught in the General Physics III course. The concept focused on in this project is General Physics III. The experiments cover the concepts of mechanical and electrical oscillations, damping, and resonance. The reasoning behind this project is that it is useful for students to have experience in labs because it reinforces knowledge taught in the lecture course. The labs also allow students to explore the concepts and make their own connections in a creative environment.

2.2 Experiments

The first experiment involves a spring-mass system. The mass is hanging vertically and is displaced to cause it to oscillate. The students measure the position or velocity of the mass using an acoustic sensor and then from the graph produced determine the period from the peaks. From the period the students can then calculate the spring constant.

The second experiment involves a simple pendulum. To start oscillations, the mass is displaced and released. By measuring the period of oscillation using a photogate and the length of the pendulum, the students can then calculate the acceleration due to gravity.

The third experiment involves an RLC series circuit. By having the source be an AC voltage source, the voltage of the inductor and capacitor oscillate. This oscillation can be measured using an oscilloscope. By adjusting the resistance of the resistor in the circuit, the students can find and measure the critical resistance. The setup for all three experiments is shown in Figures 1, 2 and 3.

Figure 1: Spring Mass System

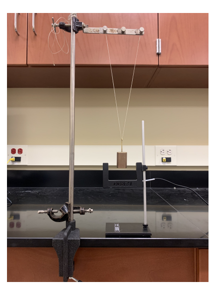

Figure 2: Simple Pendulum

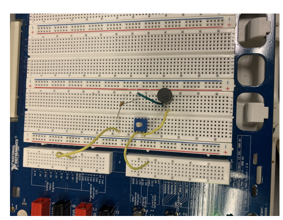

Figure 3: RLC Circuit

3 Theory

3.1 Experiment 1

For a hanging spring-mass system, such as in Figure 4, the mass sits at an equilibrium position that is determined by the balancing of the force generated by the spring with the gravitational force. When the mass is then displaced, the force of the spring increases according to

$$F = -ky.$$

Applying Newton's Second Law of Motion, we get the equations

$$\begin{aligned} m\ddot{x} &= -ky \\ \ddot{y} &= -\frac{k}{m}y \\ 0 &= \ddot{y} + \frac{k}{m}y \end{aligned} \tag{1}$$

Solving this differential equation in equation 1 gives the position as a function of time as

$$y = A \cdot cos(\omega t - \phi).$$

Substituting in $\omega = \sqrt{\frac{k}{m}}$ gives

$$y = A \cdot cos\left(\sqrt{\frac{k}{m}}t - \phi\right) \tag{2}$$

where A is the amplitude, t is the time, and ϕ is the phase angle. Since ω is the angular frequency, we can find the frequency by

$$\nu = \frac{\omega}{2\pi} \tag{3}$$

Also, the relationship between period and frequency is given by

$$T = \frac{1}{\nu} \tag{4}$$

By combining equations 3 and 4 and substituting for ω, we get the equation

$$T = 2\pi\sqrt{\frac{m}{k}}. \tag{5}$$

The spring constant can then be found from the period using the equation

$$k = m\left(\frac{2\pi}{T}\right)^2 \tag{6}$$

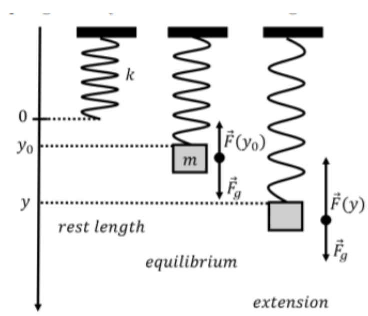

Figure 4: Spring-Mass System Diagram

3.2 Experiment 2

For the simple pendulum, the mass is displaced from its equilibrium position, as in Figure 5, to start the oscillation. The restoring force is the the horizontal component of the gravitational force

$$F = -mgsin(\theta).$$

For this experiment, the mass only experienced small oscillations, so we can apply the small angle approximation to get

$$F = -\frac{mgs}{L} \tag{7}$$

where s is the horizontal displacement and L is the length of the pendulum. We can compare this to Hooke's Law where $k = \frac{mg}{L}$ and $y = s$. Therefore we can conclude that the position as a function of time is given by

$$s = A \cdot cos\left(\sqrt{\frac{g}{L}}t - \phi\right) \tag{8}$$

and further that the period is

$$T = 2\pi\sqrt{\frac{L}{g}}. \tag{9}$$

The acceleration due to gravity can then be found using

$$g = L\left(\frac{2\pi}{T}\right)^2. \tag{10}$$

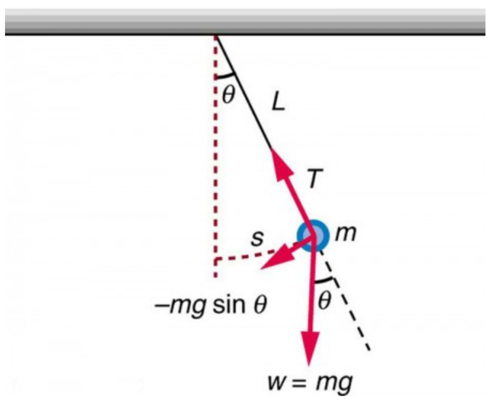

Figure 5: Simple Pendulum Diagram

3.3 Experiment 3

For experiment 3, by having the source be an AC voltage the voltages of the inductor and capacitor oscillate and exchange energy similar to a spring extending and compressing. The response of the system when an alternating current is applied can be modeled as a the second order differential equation

$$\frac{d^2V_c}{dt^2} + \frac{R}{L}\frac{dV_c}{dt} + \frac{1}{LC}V_c = \frac{V}{LC} \tag{11}$$

Where V_c is the voltage of the capacitor in Volts, R is the resistance of the resistor, L is the inductance of the inductor, and C is the capacitance of the capacitor. The two important frequencies of this system are called the neper frequency and the resonant frequency. The neper frequency is also called the attenuation of the circuit and is a measure of how fast the transient response of the circuit will die away after the source has been removed. It is given by

$$\alpha = \frac{R}{2L}\frac{rad}{s}.$$

The resonant frequency is where the impedance of the circuit is at a minimum due to the impedance generated by the inductor and capacitor cancel each other out. The resonant frequency is given by

$$\omega_0 = \frac{1}{\sqrt{LC}} \frac{rad}{s}.$$

The critical resistance is the resistance when $\alpha = \omega_0$. This causes the circuit to be critically damped.

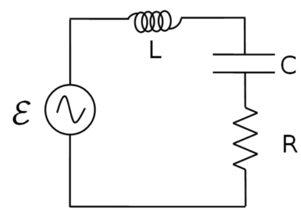

Figure 6: RLC Circuit Diagram

4 Methods

Both Experiment 1 and Experiment 2 were tested by myself and then also tested by other students to ensure the labs' replicability and efficacy. This was done using a lab handout which gave detailed instructions for all three experiments. The lab handout also included a detailed theory and introduction section. I followed the lab handout when testing the labs. When students tested the labs they were given the handout and followed the instructions with minimal guidance from me.

4.1 Experiment 1

First the PASCO Capstone software was setup to collect data. For this the temperature of the room had to be determined to calculate the speed of sound using

$$v = \sqrt{\frac{\gamma RT}{M}},$$

where γ is the adiabatic index of air, R is the gas constant, T is the temperature in Kelvins, and M is the molecular mass. At $50°C$, which was the room temperature on the thermostat, the speed of sound is $360.43\frac{m}{s}$. Using that, the uncertainty on the acoustic sensor was then tested and measured to be 0.0725%. The value of the spring constant was then measured using the equilibrium position. By balancing the gravitational and spring forces, the spring constant could be calculated based on the stretching of the spring. This value was measured to be $23.62 \frac{N}{m}$.

To take data, the acoustic sensor began recording and the mass was displaced. The sensor tracked the masses position and velocity overtime and plotted as in Figure 7. Then, after a few periods were recorded, using either the position or velocity plots, peaks of the plot were selected to determine what the period of oscillation was. After collecting the period of oscillation, the spring constant was then measured.

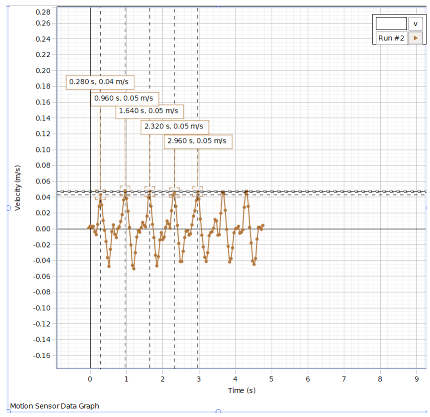

Figure 7: Acoustic Sensor Output

4.2 Experiment 2

Once again the PASCO software had to be setup. After the photogate was connected, the mass being used then had its diameter measured to put into the software. A table was then selected to record the period as the pendulum oscillated.

To take data, the mass was displaced and then released and the "record" button was pressed. After the PASCO software had recorded 5 to 6 periods, as in Figure 8, the average was then taken to calculate the acceleration due to gravity.

Period of Simple Pendulum

		▼ Run #1
	Time (s)	Period (s)
1	1.648	1.53
2	3.179	1.53
3	4.710	1.53
4	6.240	1.53
5	7.771	1.53
6	9.302	1.53

Figure 8: Pendulum Period Data Table

5 Data and Data Analysis

For the first experiment, the average calculated spring constant was 22.79$\frac{N}{m}$ with an accuracy of -8.83% from the given value of 25$\frac{N}{m}$. Although the given value from PASCO was 25$\frac{N}{m}$, the measured value of the spring was 23.62$\frac{N}{m}$. The accuracy for this value was -3.51%. The standard deviation of the data was 1.22$\frac{N}{m}$ with a total range of 4.31$\frac{N}{m}$.

Table 1: Experiment 1 Data

Average Spring Constant ($\frac{N}{m}$)	Standard Deviation ($\frac{N}{m}$)	Percent off Given Value	Percent off Measured Value
22.79	1.22	-8.38%	-3.51%

For the second experiment, the average calculated acceleration due to gravity was 9.803$\frac{m}{s^2}$ with a precision of 0.848%. The accuracy of this value, using the acceleration due to gravity as 9.807$\frac{m}{s^2}$, is -0.102%. The standard deviation of the values is 0.08132$\frac{m}{s^2}$ with a total range of 0.337$\frac{m}{s^2}$.

Table 2: Experiment 2 Data

Average Acceleration due to Gravity ($\frac{m}{s^2}$)	Standard Deviation ($\frac{m}{s^2}$)	Percent off Actual Acceleration due to GRavity
9.803	0.08132	-0.102%

6 Discussions and Conclusion

As can be seen from the data, the two experiments tested yielded a small margin of error. Also, given the small size of the standard deviation and the size of the percent error the experiments can be considered replicable and precise. While I was testing the labs multiple students chose to explore beyond what was written in the lab handouts and make their own connections. This shows that not only do the experiments produce accurate and precise results but they also achieve the secondary goal of allowing students to explore the concepts at the core of the lab.

Based on the data these two lab experiments would be very good should a general physics III lab course ever be added to the curriculum. These experiments would produce good results while also allowing students to explore the core physical concepts of the lab.

Due to the rigor and time put into the first two experiments, I was not able to complete the third experiment the RLC circuit. I was unable to solve the problems with data collection that came up when I began testing the experiment in the time allotted and as such this portion of the project remained incomplete.

Should a future capstone student wish to continue this project, a good continuation would be to design an experiment focusing on electrical oscillations that would then allow students to make the connections between physical and electrical oscillations. This could be done through a lab with an RL, an RC, and an RLC circuit.

A fourth experiment involving mechanical oscillations was initially proposed. This experiment involved a cart and a spring that would oscillate. I was unable to find a spring that would allow for the proper type of oscillation due to the need that a spring that could store energy through extension and compression was needed.

7 Appendix

7.1 Data Tables

7.1.1 Experiment 1

Table 1: Trial 1

Time 2 (s)	Time 1 (s)	Period (s)	Spring Constant($\frac{N}{m}$)
2.52	1.88	0.64	24.54
3.20	2.52	0.68	21.74
3.80	3.20	0.60	27.92
4.32	3.80	0.52	37.17
5.16	4.32	0.84	14.24
5.92	5.16	0.76	17.40
6.76	5.92	0.84	14.24

Table 2: Trial 2

Time 2 (s)	Time 1 (s)	Period (s)	Spring Constant($\frac{N}{m}$)
1.50	0.950	0.55	33.23
2.20	1.50	0.70	20.51
2.95	2.20	0.75	17.87
3.45	2.95	0.50	40.20
4.50	3.45	1.05	9.117
5.15	4.50	0.65	23.79

Table 3: Trial 3

Time 2 (s)	Time 1 (s)	Period (s)	Spring Constant($\frac{N}{m}$)
1.65	0.95	0.70	20.51
2.35	1.65	0.70	20.51
3.00	2.35	0.65	23.79
3.70	3.00	0.70	20.51
4.30	3.70	0.60	27.92
5.00	4.30	0.70	20.51
5.50	5.00	0.50	40.20
6.40	5.50	0.90	12.41

Table 4: Trial 4

Time 2 (s)	Time 1 (s)	Period (s)	Spring Constant($\frac{N}{m}$)
2.1	1.45	0.65	23.79
2.80	2.10	0.70	20.51
5.95	5.2	0.75	17.87
6.7	5.95	0.75	17.87

Table 5: Trial 5

Time 2 (s)	Time 1 (s)	Period (s)	Spring Constant($\frac{N}{m}$)
0.84	0.24	0.60	27.92
1.60	0.84	0.76	17.40
3.60	3.00	0.60	27.92
4.36	3.60	0.76	17.40
4.96	4.36	0.60	27.92

Table 6: Trial 6

Time 2 (s)	Time 1 (s)	Period (s)	Spring Constant($\frac{N}{m}$)
0.96	0.28	0.68	21.74
1.64	0.96	0.68	21.74
2.32	1.64	0.68	21.74
2.96	2.32	0.64	24.54
3.64	2.96	0.68	21.74

Table 7: Trial 7

Time 2 (s)	Time 1 (s)	Period (s)	Spring Constant($\frac{N}{m}$)
1.44	0.84	0.60	27.92
2.20	1.44	0.76	17.40
2.80	2.20	0.60	27.92
3.48	2.80	0.68	21.74
4.20	3.48	0.72	19.39

Table 8: Trial 8

Time 2 (s)	Time 1 (s)	Period (s)	Spring Constant($\frac{N}{m}$)
1.40	0.68	0.72	19.39
2.04	1.40	0.64	24.54
2.76	2.04	0.72	19.39
3.40	2.76	0.64	24.54

Table 9: Trial 9

Time 2 (s)	Time 1 (s)	Period (s)	Spring Constant($\frac{N}{m}$)
1.20	0.64	0.56	32.05
1.88	1.20	0.68	21.74
2.56	1.88	0.68	21.74
3.24	2.56	0.68	21.74

Table 10: Trial 10

Time 2 (s)	Time 1 (s)	Period (s)	Spring Constant($\frac{N}{m}$)
1.32	0.64	0.68	21.74
2.04	1.32	0.72	19.39
2.72	2.04	0.68	21.74
3.28	2.72	0.56	32.05

7.1.2 Experiment 2

Table 1: Experiment 2 Data

Trial	Length of Pendulum (m)	Period (s)	Acceleration Due to Gravity($\frac{m}{s^2}$)
1	1.49	0.5495	9.771
2	1.33	0.4375	9.764
3	1.37	0.4645	9.770
4	1.36	0.4600	9.818
5	1.47	0.5300	9.683
6	1.50	0.5640	9.896
7	1.30	0.4210	9.835
8	1.31	0.4275	9.835
9	1.40	0.4915	9.900
10	1.45	0.5275	9.905