Physics Higher Level Extended Essay

Research Question:

How does the applied tension on a wire influence its resonance frequency?

Word Count: 3810

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Introduction

Wave resonance/ standing waves

A wave is, in general, a disturbance that moves through a medium. It carries energy from one location to another without transporting the material of the medium (*Giancoli 310*). This disturbance creates a momentary displacement, and the object returns to equilibrium position. The reason why it is called a standing wave is that it doesn't appear to be travelling. Standing waves occur at specific frequencies known as natural or resonant frequencies. They result from the interference of two waves moving in opposite directions, having the same magnitude (*Giancoli 315*). A standing wave can also be defined as a wave with no horizontal movement, vibrating only vertically ("*Standing Waves Review*").

Nodes and antinodes

Node is the point where the destructive interference occurs so that the wave stays still; and antinode is the point where the two waves interfere constructively, and the point where the maximum amplitude occurs. There is always a periodic distance between nodes and antinodes

When two standing waves with equal magnitude interfere each other destructively and cancel out each other nodes occur, these are the points were the amplitude is equal to zero. And when two standing waves with equal magnitude interfere each other constructively the amplitude of the two waves add up and antinodes occur at this point where the wave has the maximum magnitude. At standing waves the length between nodes and antinodes are equal (*Giancoli 315*).

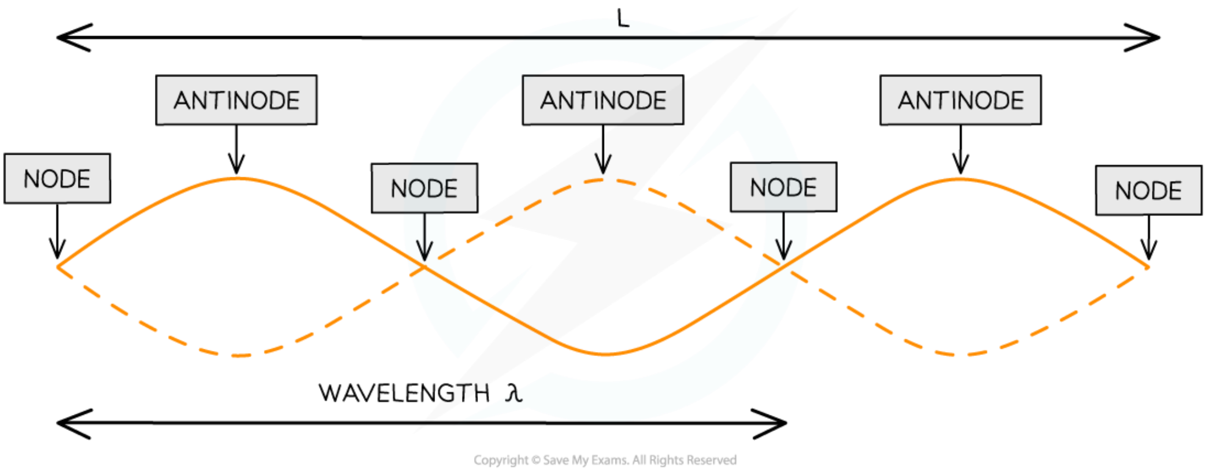


Figure I: Diagram showing the nodes and antinodes on a standing wave

A standing waves minimum frequency occurs at its nodes, that's the position that two waves which have the same magnitude interfere constructively and create a bump, this point is called the natural frequency. At the positions where the two standing waves interfere constructively antinodes occur it can be observed from the figure that antinodes and nodes have a periodic distance equal to $\frac{\lambda}{2}$ between them ("*Standing Waves Review*").

Mechanical Resonance

The word resonance comes from the Latin word "resonantia" which means echo (*"resonance"*). There are many real-life examples of resonance, such as swings, various structures, and suspension bridges. Many sources cite that the Tacoma Narrows Bridge collapsed due to resonance, but the actual reason behind this misconception is aeroelastic flutter (*"Tacoma Narrows Bridge"; Peterson*). The most important application of resonance for this investigation is its effect on musical instruments. If resonance occurs between objects, the other object starts oscillating with a greater amplitude, a phenomenon known as resonance (*Rossing 23*). Amplitude is the oscillating object's maximum displacement from the equilibrium position. According to the principle of resonance, objects and systems fundamentally vibrate at a specific frequency known as the resonant frequency or natural frequency. When an object oscillates at its natural frequency or very close to this value, resonance occurs (*Rossing 45*).

The resonance frequency is impacted by the object's size and shape. For this investigation, only the **length of the wire** is considered, as its thickness is negligible due to its minimal effect on linear mass density (μ). Although resonance frequency is not directly affected by gravitational acceleration, gravity indirectly influences it through tension, which is calculated using the formula $T = mg$. In our experimental setup, gravitational acceleration is assumed to be $9.81ms^{-2}$ (*Giancoli 304*).

Resonance is generally described by systems such as driven pendulums or spring oscillations in which a periodic force is applied at the natural frequency of a system and leads to growth in amplitude. While objects in simple harmonic motion such as free-swinging pendulums and spring-mass systems exhibit periodic motion, resonance is observed only when an external force is at a system's natural frequency and grows vibrations over a duration (*Giancoli)* .

By the principle of resonance, any system and any object will vibrate at the natural frequency or the system/object's resonant frequency depending on the object's size and shape and the substance it's made of. The vibrating frequency of an original object will match the resonant frequency of a second object such that the latter's oscillations will be larger if the vibrating frequency of the original object matches the latter's resonant frequency. The principle of resonance dictates that a small vibration of the original object will induce a large vibration of the second system/object. However, if the original vibration does not match the second system/object's resonant frequency, the object will not be subjected to resonance.

The simplest formula that's used in waves are $v = \lambda f$ where v is the velocity of the wave, λ is the wavelength; the distance between two troughs or crests and f is the frequency of the wave also when needed we can manipulate this equation by substituting $\frac{1}{T}$ where f is seen.

Standing waves have a sinusoidal shape and has an equation $y = \sin(kx)$ where k is a constant also from our previous knowledge (*Tsokos*), we know how standing waves are created we assume that the graph of the equation starts from the point $x = 0$ and ends at the point $x = L$ the domain of this wave is between $0 \leq x \leq L$. Since that we know the x-intercepts of the sinusoidal equations, for simplest calculations and interpretations $kx = 0, \ldots$ I will use the point where $x = 0$ which's the solution in the existing domain for this problem.

To calculate the resonance frequency of a wire we will firstly use the formula known as fundamental frequency of a sonometer wave stated below:

$$f = \frac{1}{2L}\sqrt{\frac{T}{\mu}}$$

This formula comes from a combination of other formulas linked to linear mass density (μ). Which's equal to :

$$\mu = \frac{m}{L}$$

Where *m* represent the mass, *L* represents the length of the wire and *T* represents the tension on the wire which can be calculated by

$$T = m \times g$$

Where *g* represents the gravitational acceleration of the location where the experiment is conducted, approximately $g = 9.81$.

At this experiment we will firstly measure the fundamental frequency is represented by f_1 and then multiply it by ten because we will use the resonance frequency of the tenth harmonic. We will use the formula:

$$f_n = n \times f_1$$

At this investigation we will use the frequency of the tenth harmonic oscillation to gain precise data because for example if we used the first harmonic the value of the frequency will be much lower so that the uncertainty increases and eventually .precision decreases.

Research question:

The goal of this investigation to see how does a change at the tension applied on a wire affect the frequency of resonance determined by using a Sonometer.

Hypothesis:

If the tension of the wire increases the resonance frequency will also increase.

The force that tightens each part of the wire increases with the higher tension of the wire and this will require a higher wave speed in an effort to propagate the disturbances through the entire length of the wire. Physically a tighter wire will pull with a stronger restoring force if any part of it is disturbed and this will propagate the wave faster. Algebraic representation of this physical scenario comes with the equation of the wave speed of a stretched string,, with the linear mass per unit of the string and the string tension. The higher the tension the larger the.

Variables

Dependent and independent variables

Type of Variable	What Variable?	Unit	Justification	What if not controlled
Dependent Variable	Frequency of Resonance	Hertz	This is the variable being measured at this experiment. When tension increases it increases as well.	The relationship between tension and frequency would be measured wrongly.
Independent Variable	Tension applied on the wire	Newton	This variable is changed intentionally to observe	If it is not controlled properly, external forces may interfere

			impact on the dependent variable. When the tension is increased the resonance frequency will also increase.	leading to inaccurate frequency readings.

Table I: Dependent and Independent Variables

<u>Controlled Variables</u>

	What Variable?	Unit	Justification	What if not controlled
Controlled Variables	Mass of wire	grams	The mass of the wire was held constant because a change in its mass would directly affect linear mass density (μ), which impacts the resonance frequency calculation.	The formula used for resonance frequency will no longer be valid, which will lead to errors.
	Length of wire	meters	The length of the wire was held constant because a change in the length of a wire would directly affect the resonance frequency, leading to errors at the experiment.	If changed, resonance frequencies would shift, making the comparisons unreliable.
	Distance between wedges	meters	The distance between the wedges was held constant because the wedges set the vibrating length of the wire. Any change at this distance will change the	This tension would change unpredictably and directly affect the frequency calculations.

			pattern of the standing wave.	
	Number of Trials per Measurement	n/A	Increasing the trial number reduces the effect of random errors and increases the data reliability.	Low number of trials will increase uncertainty and error, making results less reliable.
	Position of Pulley	Fixed Position	Ensures uniform force transmission to the wire so that any misalignment doesn't affect the tension.	Increased friction or uneven tension could alter resonance frequency measurements
	Measuring Equipment Consistency	n/A	Using the same balance, ruler and frequency analyser ensures accuracy.	Different instruments have different uncertainties, or even if they have the same uncertainty, calibration errors may occur.
	Mass Placement for Tension Calculation	Consistent	The hanging mass should be directly below the wire so that the tension is applied vertically.	If the mass is misplaced, the tension will not be fully transferred due to the angle, as the force will be separated to components.
	Observation Method for	n/A	The same method must be used for every trial.	Using inconsistent detection methods will make this

	Resonance Detection			experiment non-scientific.
	Method of Inducing Resonance	n/A	The wire should always be vibrated by the same manner.	Using different methods or equipment to excite the wire may produce inconsistency at standing waves.
	Wire Material	Fixed Type	The same type of wire must be used to keep the linear mass density (μ) constant.	The formula used for resonance frequency will no longer be valid, which will lead to errors.

*Table II :*Controlled Variables

Materials

1) Tuning forks
2) Sonometer ($\pm 0.05\ Hz$)
3) Wire
4) Newton meter
5) Ruler ($\pm 0.05cm$)
6) Scissors
7) Little pieces of paper
8) Digital scale$\pm 0.05kg$)
9) Set of slotted masses with hanger(0.25,0.50,0.75,1.00,1.25,1.50,1.75,2.00,2.25 and 2.50kg)
10) Pulley with low friction
11) Clamp stand

Safety Considerations

When cutting the wire, the experimenter must be careful due to the highly dangerous and sharp apparatus, after the cutting step is finished this apparatus must be moved to a safe location away from the experimental setup to avoid potential harm to any living beings nearby.

Some people are more sensitive to high decibel sounds than others, so it is important to keep the tuning fork away from the experimenter's ear and any other potential listeners.

Be aware of the procedure of all materials before starting the experiment to avoid serious health consequences.

Experimentation Setup

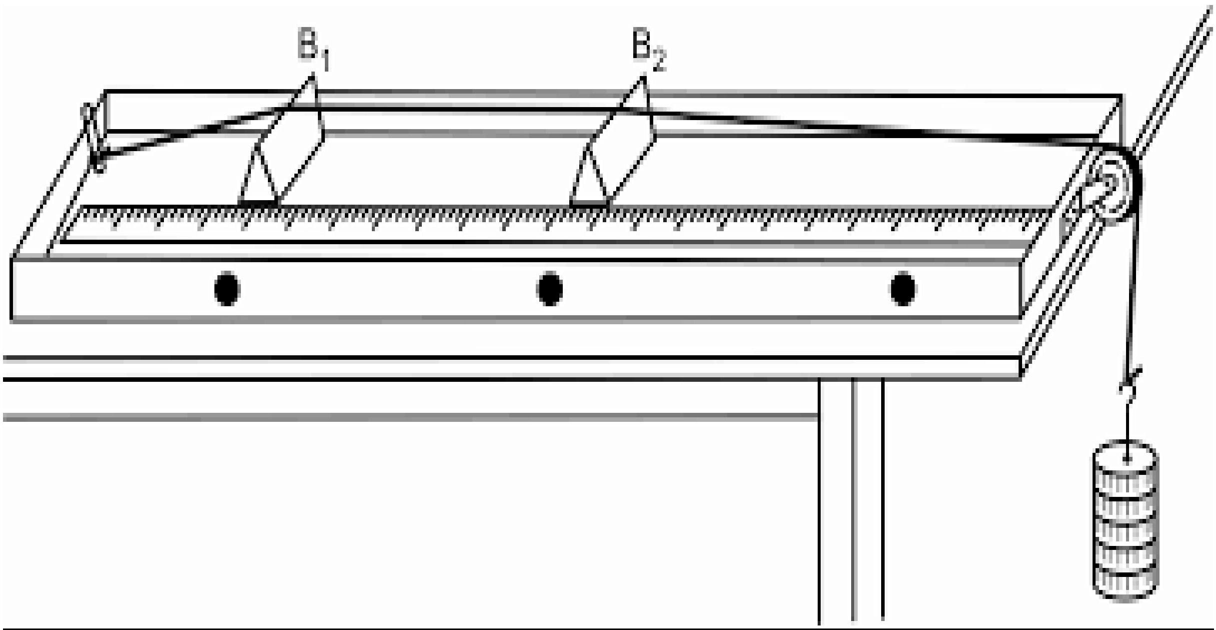


Figure II: Diagram showing the experimental setup

Methodology

1. Begin by preparing the sonometer, ensuring it is placed on a stable surface to minimize vibrations that could interfere with the waves at the measurements.
2. Measure and cut the wire to a precise length (5.7m), ensuring consistency across all trials to minimise any error or miscalculation due to the length of the wire.

3. Secure the wire onto the sonometer, verifying that it is tense and properly positioned.
4. Position the movable bridges at an appropriate distance apart to distribute tension evenly along the wire.
5. Conduct preliminary trials by striking a tuning fork and placing it near the wire to check whether the distance between bridges is appropriate for proper resonance, if not adjust the distance.
6. To observe the effect of resonance, place a small, lightweight piece of paper gently on the midpoint of the wire.
7. Strike tuning forks of varying frequencies and hold them close to the wire.
8. Observe when the paper falls off, indicating the wire has reached its resonance frequency.
9. Record the frequency of the tuning fork that causes this effect on the paper.
10. Attach a mass to the wire to change the applied tension.
11. Repeat the process of striking tuning forks and recording resonance frequency for the nine different masses applied.
12. Conduct seven trials for each mass to ensure accuracy and consistency in results.
13. Record the resonance frequencies corresponding to each mass applied.
14. Ensure measurements are taken precisely, and any anomalies in the results are noted for the further analysis and error analysis part.

Length of wire:

5.7m ∓ 0.5

Distance between wedges:

4.2m ∓ 0.5cm

Mass of wire :

0.323 g $\pm 0.05 cm$

Data

Raw Data Table

Mass attached to wire (kg) $\pm$ 0.05 kg	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7
0.25	196.0	190.0	185.0	188.0	191.0	187.0	189.0
0.50	268.0	262.0	260.0	270.0	265.0	267.0	263.0
0.75	288.0	292.0	285.0	295.0	289.0	290.0	286.0
1.00	390.0	398.0	397.0	395.0	392.0	399.0	394.0
1.25	412.0	408.0	415.0	405.0	409.0	413.0	407.0
1.50	452.0	449.0	455.0	447.0	450.0	453.0	448.0
1.75	463.0	468.0	467.0	460.0	462.0	465.0	461.0
2.00	502.0	498.0	505.0	495.0	499.0	503.0	497.0
2.25	522.0	518.0	525.0	515.0	520.0	523.0	517.0
2.50	542.0	538.0	545.0	535.0	540.0	543.0	537.0

Table III: Mass vs. Resonance Frequency

Processed Data

	Resonance frequency ($\pm$0.05Hz)					
Mass (kg) ∓ 0.05	Absolute uncertainty for the mass	Percentage uncertainty	Average frequency (Hz)	Frequency (Hz)		Standard deviation
				Uncertainty type		
				absolute	percentage	
0.25	0.05	20%	189	0.05	2.6×10^{-2}	4.12
0.50	0.05	10%	265	0.05	1.9×10^{-2}	3.87
0.75	0.05	6.7%	289	0.05	1.7×10^{-2}	3.94
1.00	0.05	5.0%	395	0.05	1.3×10^{-2}	3.63
1.25	0.05	4.0%	410	0.05	1.2×10^{-2}	3.72
1.50	0.05	3.3%	451	0.05	1.1×10^{-2}	3.64
1.75	0.05	2.9%	464	0.05	1.1×10^{-2}	3.60
2.00	0.05	2.5%	500	0.05	1.0×10^{-2}	3.62
2.25	0.05	2.2%	520	0.05	9.6×10^{-3}	3.58
2.50	0.05	2%	540	0.05	9.3×10^{-3}	3.56

Table IV: Mass vs. Average frequency

Exemplar Calculation (for the tenth data set)

1. Percentage uncertainty of mass:

$$Mass\ percentage\ uncertainty = \frac{absolute\ uncertainty}{Value\ of\ mass} \times 100$$

$$\frac{0.05}{2.50} \times 100 = 2\%$$

2. Percentage uncertainty of frequency:

$$\text{Percentage uncertainty of frequency} = \frac{absolute\ uncertainty}{value\ of\ frequency} \times 100$$

$$= \frac{5 \times 10^{-2}}{540} \times 100 = 0.09259259 \approx 9.3 \times 10^{-3}$$

3. Calculation of standard deviation:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \mu)^2}{N - 1}}$$

Where μ is the mean of the mean of the tenth data set and N is the trial number.

Computing each deviation from the mean and then squaring:

$$542 - 540 = 2.00 \Rightarrow 4.00$$

$$538 - 540 = -2.00 \Rightarrow 4.00$$

$$545 - 540 = 5.00 \Rightarrow 25.0$$

$$535 - 540 = -5.00 \Rightarrow 25.00$$

$$543 - 540 = 0.00 \Rightarrow 0.00$$

$$543 - 540 = 3.00 \Rightarrow 9.00$$

$$542 - 540 = -3.00 \Rightarrow 9.00$$

Now computing the variance:

$$\frac{(4.00 + 4.00 + 25.00 + 25.00 + 0.00 + 9.00 + 9.00)}{7 - 1} = \frac{76.00}{6} = 12.67$$

After compute the standard deviation:

$$\sigma = \sqrt{12.67} = 3.55949435 \approx 3.56$$

<u>Theoretical Data</u>

Theoretical frequencies (Hz)	Theoretical frequency absolute uncertainty	Theoretical frequency percentage uncertainty
189.4	0.05	2.6×10^{-2}
267.8	0.05	1.9×10^{-2}
328.0	0.05	1.5×10^{-2}
378.7	0.05	1.3×10^{-2}
423.4	0.05	1.2×10^{-2}
463.8	0.05	1.1×10^{-2}
500.1	0.05	1.0×10^{-2}
535.6	0.05	9.3×10^{-3}
568.0	0.05	8.8×10^{-3}
598.8	0.05	8.4×10^{-3}

Table V: Uncertainty table of theoretical frequencies.

Exemplar Calculation

1. Calculate the Linear Mass Density(μ):

$$\mu = \frac{m}{L}$$

$$\mu = \frac{0.323 \times 10^{-3} kg}{5.7m}$$

$$\mu = 5.26316 \times 10^{-5} kgm^{-1}$$

2. Calculating the Tension in the wire:

$$T = m \times g$$

$$T = 2.5kg \times 9.81ms^{-1}$$

$$T = 24.52\ N$$

3. Calculating the Fundamental Frequency:

$$f = \frac{1}{2L}\sqrt{\frac{T}{\mu}}$$

$$f = \frac{1}{2 \times 5.7m}\sqrt{\frac{24.525N}{5.26316 \times 10^{-5}kgm^{-1}}}$$

$$f = 59.879Hz \ \approx 59.88Hz$$

(Solved using Desmos)

4. Calculating the Resonance Frequency at the tenth harmonic:

$$f_n = n \times f_1$$

$$f_{10} = 10 \ \times \ 59.88 = 598.8Hz$$

5. Calculating percentage uncertainty:

$$\frac{0.05}{598.8} \times 100 = 8.4 \times 10^{-3}$$

Mass (Kg) $\pm$ 0.05kg	Average resonance frequency (Hz)	Theoretical frequency	Percentage error
0.25	189.8	189.4	0.21%
0.50	265.0	267.8	1.04%
0.75	290.0	328.0	11.6%
1.00	395.0	378.7	4.30%
1.25	410.0	423.4	3.16%
1.50	450.8	463.8	2.80%
1.75	464.5	500.1	7.12%
2.00	500.0	535.6	6.65%
2.25	520.0	568.0	8.45%
2.50	540.0	598.8	9.82%

Table VI: Comparison of Average and Theoretical Resonance Frequencies at Various Masses.

Calculating the percentage error:

$$percentage\ error = \frac{|\text{calcuated frequency} - \text{average frequency}|}{calculated\ frequency} \times 100$$

$$= \frac{|598.8 - 540|}{598.8} \times 100 \approx 9.82\%$$

<u>Quantitative data:</u>

From the calculated data we can see that there is a positive correlation indicating that as the tension on the wire increased the resonance frequency also increased meaning the mass and resonance frequency are directly proportional. The minimum resonance frequency calculated was 189.4Hz with a percentage error of 0.21%. Adding on, the maximum value calculated was 598.8Hz with a high percentage error of 9.82 %

This could have been due to the very limited

range of tuning forks. Moreover, the value that was the most accurate was when the mass being applied was 0.25kg and from this result the frequency from the experiment was 189.8Hz and the theoretical frequency was 189.4Hz which left us with a percentage error of 0.21%. Although most of the results were in range of the percentage error of 10% this shows that the experiment is conducted accurately.

Qualitative Data

The objective of this experiment was to determine the resonance frequency using a sonometer while minimizing measurement discrepancies. The lowest recorded percentage discrepancy was 0.26%, while the highest reached 11.26%. The experiment aimed to identify factors contributing to these variations, such as instrumental limitations, environmental conditions, human errors, and theoretical assumptions deviating from real-world conditions. Understanding these influences helps refine measurement accuracy and improve experimental precision in future studies.

Strengths of the Experiment

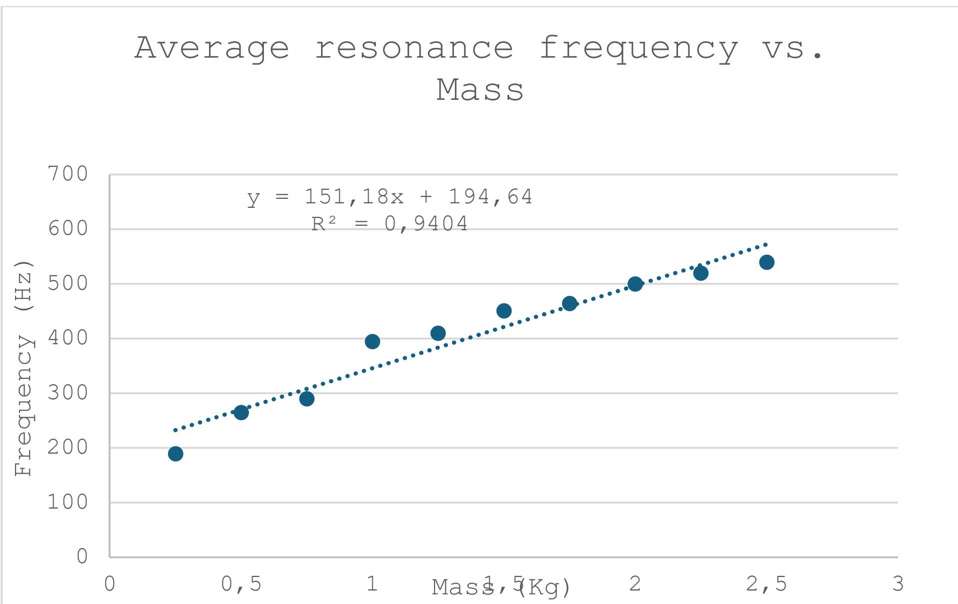
1. The apparatus used in the experiment were highly precise and accurate.
2. The length of the wire and the mass were both checked many times with a variety of tools to minimise experimental errors.
3. The experimental setup was carefully arranged to prevent external disturbances that could affect the resonance frequency readings.
4. External environmental factors, such as room temperature and air resistance, were considered when analysing results.

5. Data was recorded in a structured manner to prevent mistakes and facilitate accurate comparisons between measured and theoretical values

Graphs

Mass (Kg)	Average resonance frequency
0.25	189.8
0.50	265.0
0.75	290.0
1.00	395.0
1.25	410.0
1.50	450.8
1.75	464.5
2.00	500.0
2.25	520.0
2.50	540.0

Table VII: Mass vs. Average resonance frequency



*Graph I:*Graph of average frequency against mass

We can say that from the value of Pearson's correleation constant whichs $r \approx 0.97$ for this model but still this doesn't have a perfectly linear bestfit line because when we look to the formula of fundamental frequency we can see that frequency is not directly proportional to mass, indeed its directly proportional to the square root of mass:

$$f = \frac{1}{2L}\sqrt{\frac{T}{\mu}}$$

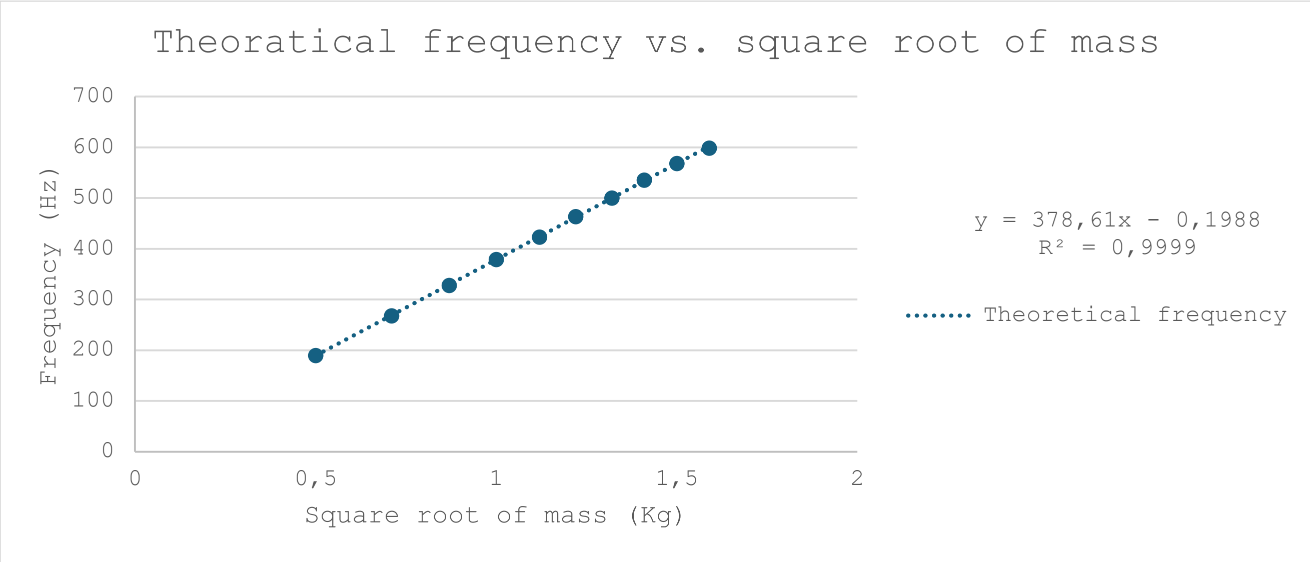
After the value $m \times g$ is substituted for *T* we get the equation:

$$f = \frac{1}{2L}\sqrt{\frac{m \times g}{\mu}}$$

From this equation its observable that frequency is directly proportional with the square root of mass:

$$f \propto \sqrt{m}$$

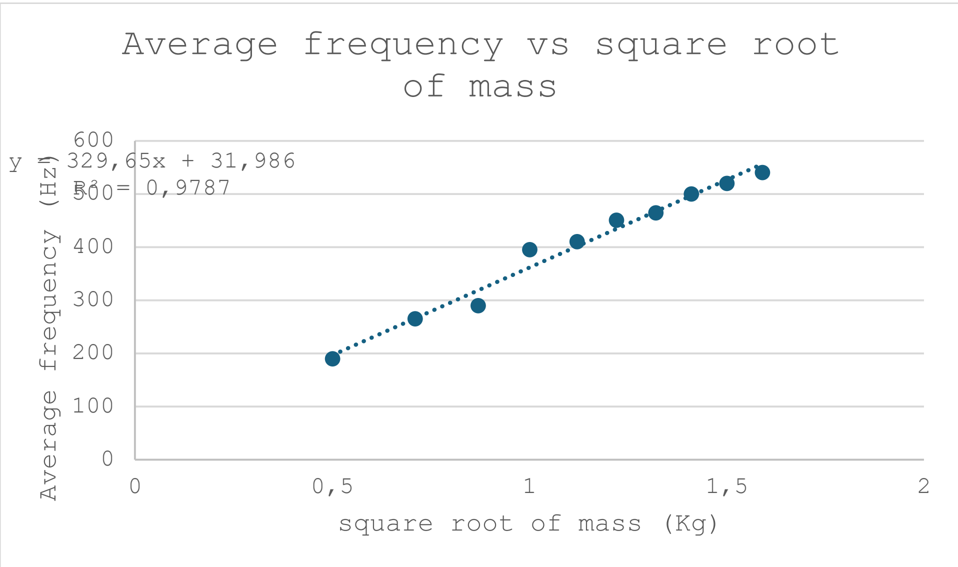
To show the perfect positive correleation between the theoretical resonance frequency and mass I have plotted the graph below.



Graph II: The graph of Theoratical frequency vs. square root of mass

As observed from the graph positioned at left $R^2 = 0.9999$ which makes R an even greater value than that because if x is between the range one and zero its square root will be greater than its initial value(if $0 < x < 1$ then $0 < \sqrt{x} < x < 1$).

Even though we get a recurring decimal we can interpret that this limit reaches the value 1 at infinity so this can be interpreted as a perfect positive correlation.



Graph III: Graph of Average frequency vs. square root of mass

Uncertainty of the gradient

$$m = \frac{y_2 - y_1}{x_2 - x_1}$$

1. Minumum gradient:

$$m_{min} = \frac{539.95 - 189.85}{2.55 - 0.2} = \frac{350.1}{2.35}$$

$$m_{min} = 148.9787 \approx 149$$

2. Maximum gradient:

$$m_{max} = \frac{540.05 - 189.75}{2.45 - 0.3} = \frac{350.3}{2.15}$$

$$m_{max} = 162{,}9302 \approx 163$$

3. Uncertainty of the gradient:

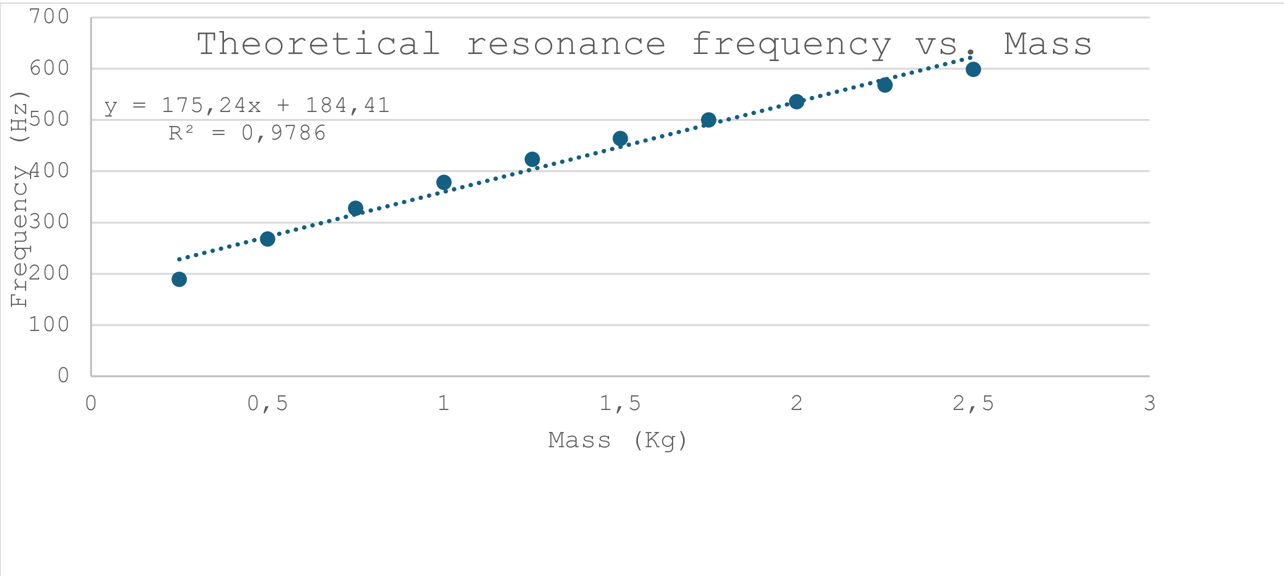
$$uncertainty\ of\ gradient = \frac{m_{max} - m_{min}}{2}$$

$$\frac{163 - 149}{539.95 - 189.85} \approx 0.04$$

Mass (Kg)	Average frequency (Hz)	Average frequency Minumum	Average frequency maximum
0.25	189.8	189.75	189.85
0.50	265	264.95	265.05
0.75	290	289.95	290.05

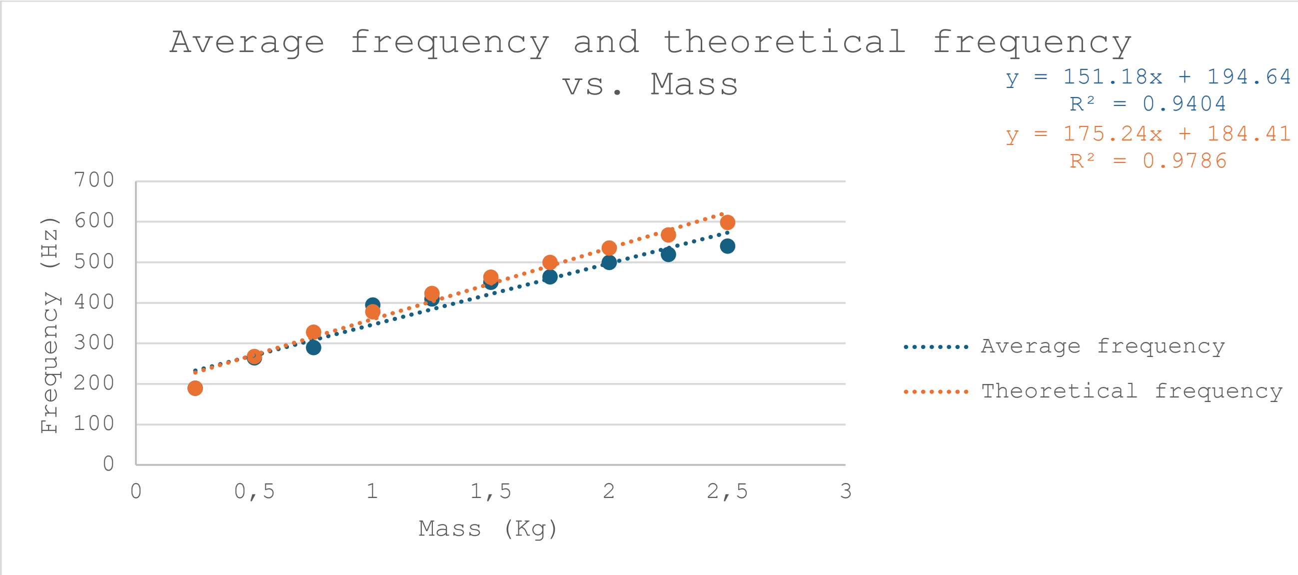
1.00	395	394.95	395.05
1.25	410	409.95	410.05
1.50	450.8	450.75	450.85
1.75	464.5	464.45	464.55
2.00	500	499.95	500.05
2.25	520	519.95	520.05
2.50	540	539.95	541.05

Table VIII: Minumum and maximum value of average frequency



Graph IV: Graph of Theoretical frequency against mass.

This graph shows theoretical frequency against mass an slighly linear approach can be seen because this data is generalized from the formula.



Graph V: Graph of Average frequency and theoretical frequency vs. Mass.

This graph is plotted to show also the trends of theoretical and average frequencies on the same graph to observe the key differences between them but there weren't much visible.

Evaluation

Error type	Weakness/Limitation	Effect of error	Possible solution
Systematic errors	Wire stretching due to high tension	Depending on the elasticity of wire, its length changes due to applied force.	Using a low-stretch, high-tensile strength wire with low elasticity so that it resists stretching more than a standard wire.
	Friction in pulley or clamps	This friction reduces the tension, which leading to a decrease in resonance frequency.	The best approach would be to measure the tension directly, but using materials with a low coefficient of friction can also help.
	Uncertainty at mass calibration	Slight miscalculations in tension can affect the resonance frequency	Using a more sensitive digital balance than the previous one.

Random errors	Human reaction time in detecting resonance	Small variations in the measured frequency per trial occur due to human error, which is considered a random error.	Increasing the number of trials to minimise the mistakes or using a professional microphone and a frequency analysis software.
	Environmental disturbances	Factors such as wind can affect the experimental setup and create fluctuations in the amplitude making measuring the resonance harder.	Preparing and conducting the experiment in a closed environment, such as a room.
	Parallax errors	Errors may occur due to parallax, such as incorrectly measuring the length of the wire. This is a human error, so it is considered a random error.	By using laser meters, this error can be minimised or eliminated.

Table IX: Errors, limitations and possible solution

Data analysis

In conclusion, resonance frequency is directly linked to frequency, and frequency is linked to tension in the wire. From the calculations we have done, it was observed that this tension is equal to the mass times gravitational acceleration at the point where the mass is at rest. According to the fundamental frequency formula, the square root of tension is directly proportional to frequency, and therefore to resonance frequency. There were various methods to calculate resonance frequency. The main reason I chose this method for measuring resonance frequency was that it was simpler than the other alternatives due to material limitations. Alternative methods were using more complex apparatus and formulas. One example of this is placing a high-sensitivity microphone near the experimental setup, which is a more professional technique that would gain more accurate results. This experiment allowed me to enhance my knowledge in the topic of waves. Although my research question was answered through this experiment, there were still many variables I could have investigated to observe their relationship with resonance frequency.

Furthermore, by this experiment I proved that the relationship between resonance frequency and tension is not directly proportional, indeed the relationship between resonance frequency and the square root of tension is proportional . I would like to underline that there were some variables which were not considered at this experiment like the thickness of the wire because these things were not necessary for the calculations even though that they affected the results of the experiment.

Conclusion

In this research, the research question "How does the applied tension on a wire influence its resonance frequency" was well addressed. Results show when the tension applied to the wire is increased the resonance frequency in the wire increases. This is with the theoretical values calculated using the fundamental frequency formula, when simplified shows that resonance frequency is directly proportional to the square root of tension applied on a wire. Experimental data also aligns with this relationship clearly, showing resonance frequency consistently increasing from a minimum average value of 189.8 Hz at a mass of 0.25 kg to a maximum average value of 540.0 Hz for 2.50 kg. Importantly experimental setup demonstrated high consistency and reliable, which can also be as evidenced by relatively low percentage errors at lower tension levels. However, percentage error increased gradually and when the tension increased the value of maximum percentage error obtained to a value of 9.82% which occurred when the maximum mass was used. This variation can be explained by the limitations in the apparatus used at this experiment, namely in range and increments in available tuning forks, which could have prevented precise determination of resonance for greater levels of frequency. There were several strengths in this experimental. The variables such as mass and length where remeasured before each trial, and tension distribution in the wire ensured a standard setup for verifiable and precise readings. Equipment used such as digital scale, sonometer, and frequency analysers were calibrated and used uniformly, thus limiting experimental variability. Several trials for every mass guaranteed a consistent data set, and thus reliability and accuracy in calculated average frequencies. But there were certain limitations for improvement. Systemic faults such as stretch at the wire due to tension may have altered the wire length and thus resonance frequency readings. Other systemic faults may have been occurred due to mistakes at mass calibration and uncertainties at pulley system friction , leading to miscalculations at tension. Random errors such as potential parallax error in readings and human reaction times in observing resonance events were other sources of overall result uncertainty. Future tests would be greatly enhanced with a solution to such limitations. With more sophisticated and sensitive equipment, such as digital frequency meters or electronic resonance detectors may be used. Observational uncertainties would most likely be reduced to a minimum. Ensuring that the wire is constructed from material with low elasticity and taking mass readings with a digital balance would further reduce systematic uncertainties. Carrying out the test in a more shielded apparatus from external vibrations and interference would similarly improve data accuracy and quality. In addition, the experiment leaves open a variety of research areas, with potential studies on how other variables, such as different wire materials, wire diameters, and environmental variables (temperature, humidity, and air pressure) would affect the resonance frequency. Research on those variables could give a broader understanding of physical principles in action. Overall, this extended essay was able to satisfactorily demonstrate evident dependency between resonance frequency and wire tension and give empirical verification for theoretical predictions. The experiment was able to emphasize control and accuracy in physics investigations and give useful information for potential improvements for future research. Overall, conducting this experimental research helped to enhance my hands-on experience in wave phenomena and scientific method and made the research a useful and informative experience.

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