IBDP PHYSICS HL INTERNAL ASSESSMENT

Resonance of a Wire in a Magnetic Field with Varying Tension

1. INTRODUCTION

1.1 Aim of Investigation

The aim of this investigation is to find the mass per unit length of a wire by measuring the frequency at which the wire resonates at the first harmonic by varying tension, with the equation:

$$f = \frac{\sqrt{\frac{T}{m/L}}}{2L}$$

Where f = frequency, T = wire tension, m = mass of wire, L = length of wire (Oxford University Press, 2020).

1.2 Background

While there are better ways of finding the mass per unit length of a wire, such as using a ruler and a sensitive measuring scale, this method serves to assess the theory of resonance and to prove the above formula, as well as demonstrating the advantages and disadvantages of using an oscilloscope versus relying on possibly faulty equipment.

The equation linking f and $T, \frac{m}{L}, L$ comes from a definition of the frequency of sound produced by an oscillating string, but can be applied for the induced resonance of a wire as well.

1.3 Methodology

Firstly, the mass per unit length of the wire will be measured using a ruler and sensitive weighing scale to find a exact reference value to assess the results of the investigation.

The experiment will be conducted on a table, with the wire clamped down at one end and attached to 100g, 50g, or 20g weights hanging over the end of the table at the other end, running over a pulley to reduce friction as much as possible. The wire will be stretched over two wedges to anchor the wire down, in between which it will oscillate during the experiment. An alternating current (AC) signal generator will be connected to the wire at either end, and an oscilloscope will be connected to the signal generator output if necessary, from which the frequency f of the current can be read to corroborate the value displayed by the signal generator. A horseshoe-style magnet will be placed in between the two wedges with the wire running in between the poles to induce the oscillation.

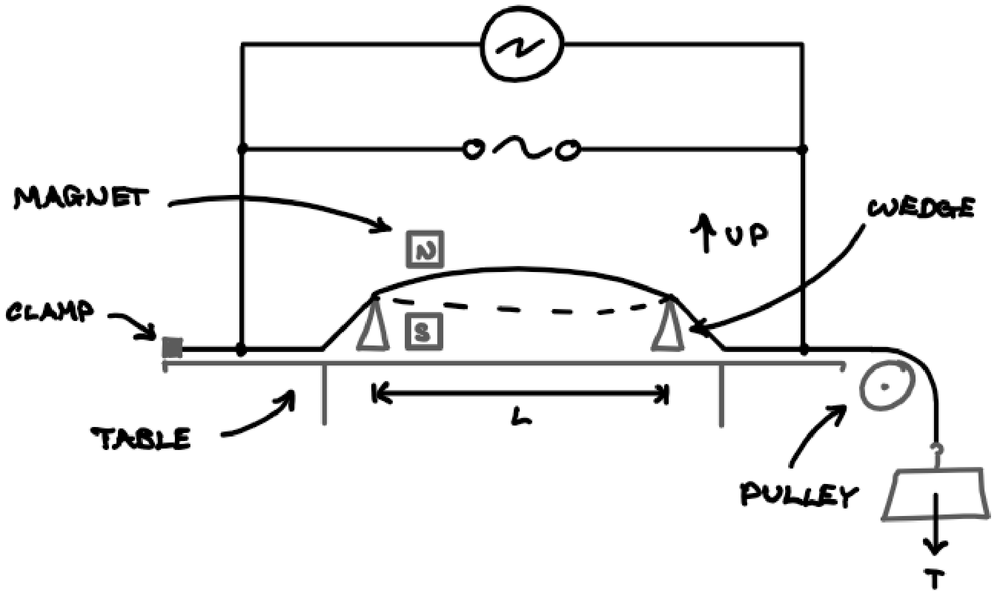


Figure 1 - Diagram Showing Setup for Experiment

The experiment will be conducted with a constant length L as the control variable, and varied tension T as the independent variable. Mass will be added to one end of the wire in constant increments to increase tension, and the frequency – the dependent variable – will be adjusted from the signal generator until the wire oscillates at the first harmonic. Judgement as to whether the wire is at the first harmonic or not will be made by eye, as to when the displacement of the oscillating wire is greatest. Mass will be added to the wire until the tension overcomes the wire's tensile strength and it snaps.

The data will be recorded in Microsoft Excel to simplify calculations, and from there graphs will be plotted to find mass per unit length.

1.4 Limitations

There are, of course, limitations to this method. The biggest is the measurement of the first harmonic: it is not possible to use instrumentation to measure this, and so it must be done by eye, which is inherently imprecise. It is therefore likely that the exact position of the first harmonic will be unknown.

There is also an issue with the signal generator and the question of the accuracy of the displayed frequency: it is entirely possible that this value is wrong, and so it may be necessary to use an oscilloscope to corroborate the reported frequency.

The oscilloscope itself is not infallible however, since it may be hard to read and imprecise, with the displayed image slightly shifting about.

There are also intrinsic inaccuracies in instruments such as the ruler and masses, which also feed the uncertainty of the final values.

There also may be a small amount of wasted energy at the ends of the wire, with the wedges deforming as the wire oscillates, skewing results; compared to the other limitations, however, this seems negligible.

1.5 Risk Assessment

It is important to account for the risks of the experiment before starting the practical element of the investigation.

The most obvious risk is that of the electricity, with the possibility of fault or mishandling of equipment such as the signal generator leading to electric shock. This can be mitigated by following correct procedure for the safe handling of such equipment, such as ensuring the casing is earthed and not allowing overheating, and following instructions for use.

Another risk is that of the snapping of the wire if tension is too great. If the wire snaps, the elastic potential energy given to it by the tension will cause it to rebound back, possible striking an eye. This is exacerbated by the oscillations putting additional strain on the wire. For this reason, it is prudent to wear eye protection and wear sleeves down to protect yourself.

Another, perhaps overlooked, risk is that of the masses falling and striking a toe or foot. With the mass planned to exceed half a kilogramme, it is possible that, on the wire snapping, the masses may fall from the edge of the table and hit a foot or a toe – this has the potential to be somewhat painful. It is therefore necessary to ensure the area below the masses is clear.

2. PRELIMINARY EXPERIMENT

A preliminary experiment was conducted to find any issues in the pre-planned experimental process.

2.1 Adjustments Made

I started with length L at 0.2m and mass m at 50g, with no oscilloscope. I found that the wire oscillated too much, meaning that it was jumping off the wedge at one end, disturbing the pattern of oscillation, and so the frequency at the first harmonic changed as the wire jumped between different positions. The reported frequency from the signal generator display also seemed implausible.

To correct these issues, I adjusted the experiment, adding an oscilloscope to read the frequency of the signal generator, and increased the mass to 500g in an attempt to put enough tension on the wire to prevent it jumping out of position. After this, the oscillations became so small that they were impossible to see, so I increased the length of the wire to 0.5m.

After this, an adjustment had to be made to the position of the magnet, since the wire would hit the magnet on oscillating – it was moved closer to one of the wedges, where displacement of the wire from centre is lesser, to avoid this. I also laid a ruler underneath the central maxima of the wire to more accurately judge when the wire had the greatest displacement from the centre, and therefore it was easier to assess when the wire was resonating at the first harmonic.

3. DATA COLLECTION

3.1 Preparation

The mass per unit length was taken before the experiment to act as a reference for later comparison.

$\frac{m}{L} = 0.000960 \ \pm 0.00000480 \ kg * m^{-1}$

This was found by weighing a 1m length of the wire on a sensitive electronic scale. For the uncertainty, the limiting factor here is the resolution of the ruler, so it is calculated as follows, where u_L = absolute uncertainty for length, $u_{m/L}$ = absolute uncertainty for the mass per unit length, and L = the length, 1 metre, used to measure the mass per unit length.

$$u_L = 0.005 \ m$$

Since this is half the resolution of the ruler, as is standard for analogue equipment, and so,

$$\%u_L = \frac{u_L}{L} * 100$$

$$\%u_L = \frac{0.005}{1.00} * 100 = 5.00\%$$

From here we can calculate the uncertainty for mass per unit length,

$$u_{m/L} = \frac{\%u_L}{100} * \frac{m}{L}$$

$$u_{m/L} = 0.005 * 0.000960 \ kg * m^{-1}$$

$$u_{m/L} = 0.00000480 \ kg * m^{-1}$$

3.2.1 Varying Tension for Frequency – Data

The experiment was laid out such that $L = 0.490 \pm 0.005 \ m$.

As mass was added in 20g intervals from 500g, tension increased, according to the relationship $T = mg$, where m = total mass and $g = 9.81 \ m * s^{-1}$ (gravitational field strength).

When reading from the oscilloscope, the following equation was used to find the frequency for each level of tension:

$$f_{oscil} = \frac{1}{\frac{n_{grids}}{n_{peaks}} * \frac{tDiv}{1000}}$$

Where n_{grids} = number of grids from first to last peak, n_{peaks} = number of peaks being counted, $tDiv$ = oscilloscope time division per grid square in milliseconds.

The following data were thus collected.

Firstly, for the frequency measured from the signal generator display:

Mass /g	**Tension /N**	**Frequency /Hz** (sig. gen. display)
500	**4.91**	**72.4**
520	**5.10**	**73.7**
540	**5.30**	**75.1**
560	**5.49**	**76.5**
580	**5.69**	**77.7**
600	**5.89**	**79.3**
620	**6.08**	**80.7**
640	**6.28**	**81.8**
660	**6.48**	**83.2**
680	**6.67**	**84.5**
700	**6.87**	**85.7**
720	**7.06**	**86.7**
740	**7.26**	**87.8**
760	**7.46**	**89.6**

Secondly, for the data measured simultaneously from the oscilloscope display:

Tension /N	n_{peaks}	$tDiv$ /ms	n_{grids}	Calculated Time Period /s	**Frequency /Hz** (oscilloscope)
4.91	3.00	10.0	4.10	0.0137	**73.2**
5.10	3.00	10.0	4.00	0.0133	**75.0**
5.30	3.00	10.0	3.95	0.0132	**75.9**
5.49	3.00	10.0	3.90	0.0130	**76.9**
5.69	3.00	10.0	3.80	0.0127	**78.9**
5.89	3.00	10.0	3.75	0.0125	**80.0**
6.08	3.00	10.0	3.65	0.0122	**82.2**
6.28	3.00	10.0	3.60	0.0120	**83.3**
6.48	4.00	10.0	4.65	0.0116	**86.0**
6.67	4.00	10.0	4.60	0.0115	**87.0**
6.87	4.00	10.0	4.55	0.0114	**87.9**
7.06	4.00	10.0	4.50	0.0113	**88.9**
7.26	4.00	10.0	4.35	0.0109	**92.0**
7.46	4.00	10.0	4.30	0.0108	**93.0**

In order to obtain a linear graph, it is necessary to find the square of the frequency, in accordance with the original equation.

Frequency Squared /Hz² (sig. gen. display)	**Frequency Squared /Hz²** (oscilloscope)
5240	5350
5430	5630
5640	5770
5850	5920
6040	6230
6290	6400
6510	6760
6690	6940
6920	7400
7140	7560
7340	7730
7520	7900
7710	8460
8030	8650

3.2.2 Varying Tension for Frequency – Uncertainties

It is first necessary to find the uncertainty for each value to plot error bars on the graph. There are several initial uncertainties to account for here:

$u_{mass} = 1\%$

This uncertainty is as standard with mass blocks.

$u_{f,signal\ generator} = 0.01\ Hz$

This uncertainty corresponds to the resolution of the signal generator display, as is standard for digital displays.

$u_{n\ of\ grids,oscilloscope} = 0.025$

This uncertainty is derived from half of the resolution of the grids on the oscilloscope display, as is standard for analogue equipment.

From these, the following can be calculated:

$$\%u_{tension} = \%u_{mass}$$

$$\%u_{f,signal\ generator} = \frac{u_{f,signal\ generator}}{f_{signal\ generator}} * 100$$

$$\%u_{f^2,signal\ generator} = 2 * \%u_{f,signal\ generator}$$

$$\%u_{f,oscilloscope} = \frac{u_{n\ of\ grids,oscilloscope}}{n_{grids}} * 100$$

$$\%u_{f^2,oscilloscope} = 2 * \%u_{f,oscilloscope}$$

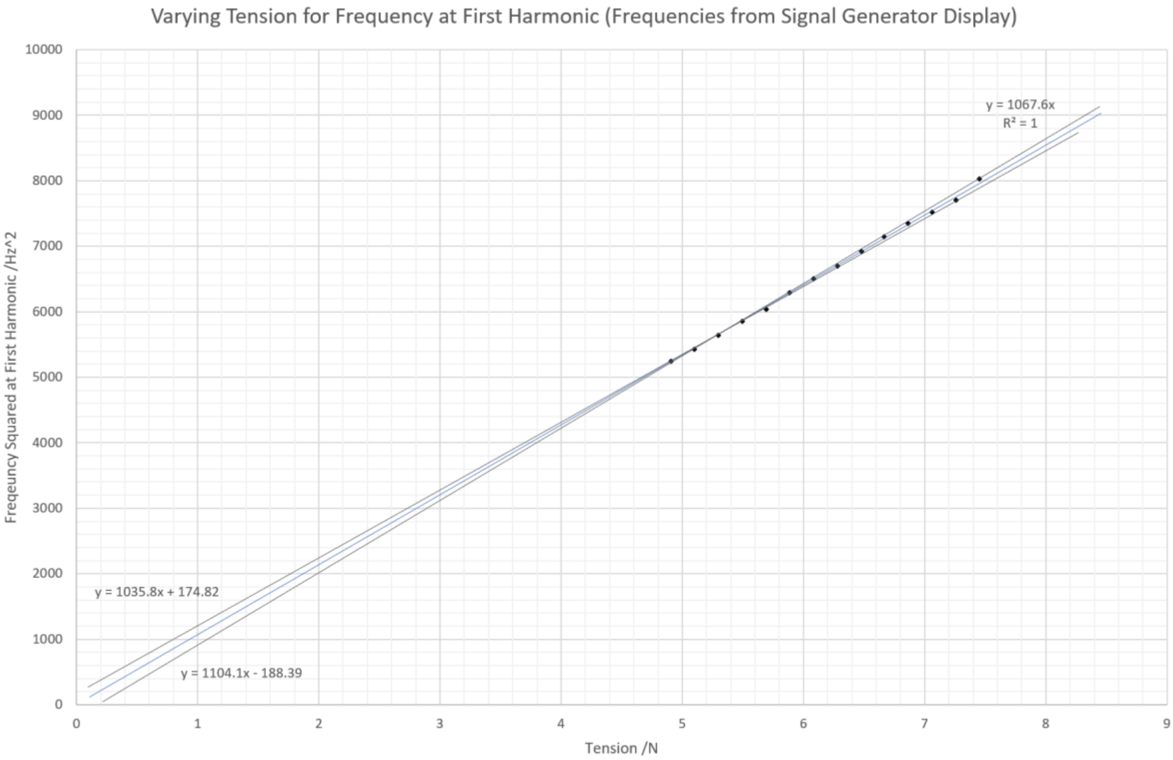
Where $u_{tension}$ = uncertainty of tension, $u_{f^2,signal\ generator}$ = uncertainty of the frequency squared from the signal generator display, $u_{f^2,oscilloscope}$ = uncertainty of the frequency squared from the oscilloscope, and $f_{signal\ generator}$ = uncertainty of the frequency displayed by the signal generator.

Therefore, the uncertainties are as follows. See Table 2 in the Appendix for the full table of data. Note that the order is the same as in the previous table (i.e. row 1 corresponds to 500g, row 2 corresponds to 520g, etc.).

Tension Uncertainty / %	Frequency Uncertainty / % (sig. gen. display)	**Frequency Squared Uncertainty / %** (sig. gen. display)	Frequency Uncertainty / % (oscilloscope)	**Frequency Squared Uncertainty / %** (oscilloscope)
1.00	0.0138	**0.0276**	0.610	**1.21**
1.00	0.0136	**0.0271**	0.625	**1.25**
1.00	0.0133	**0.0266**	0.633	**1.27**
1.00	0.0131	**0.0261**	0.641	**1.28**
1.00	0.0129	**0.0257**	0.658	**1.32**
1.00	0.0126	**0.0252**	0.667	**1.33**
1.00	0.0124	**0.0248**	0.685	**1.37**
1.00	0.0122	**0.0244**	0.694	**1.39**
1.00	0.0120	**0.0240**	0.538	**1.08**
1.00	0.0118	**0.0237**	0.543	**1.09**
1.00	0.0117	**0.0233**	0.549	**1.10**
1.00	0.0115	**0.0231**	0.556	**1.11**
1.00	0.0114	**0.0227**	0.575	**1.15**
1.00	0.0112	**0.0223**	0.581	**1.16**

3.2.3 Varying Tension for Frequency – Graphs

With this data, the graph for the relationship between tension and the square of frequency (according to the signal generator display), can be drawn thus:

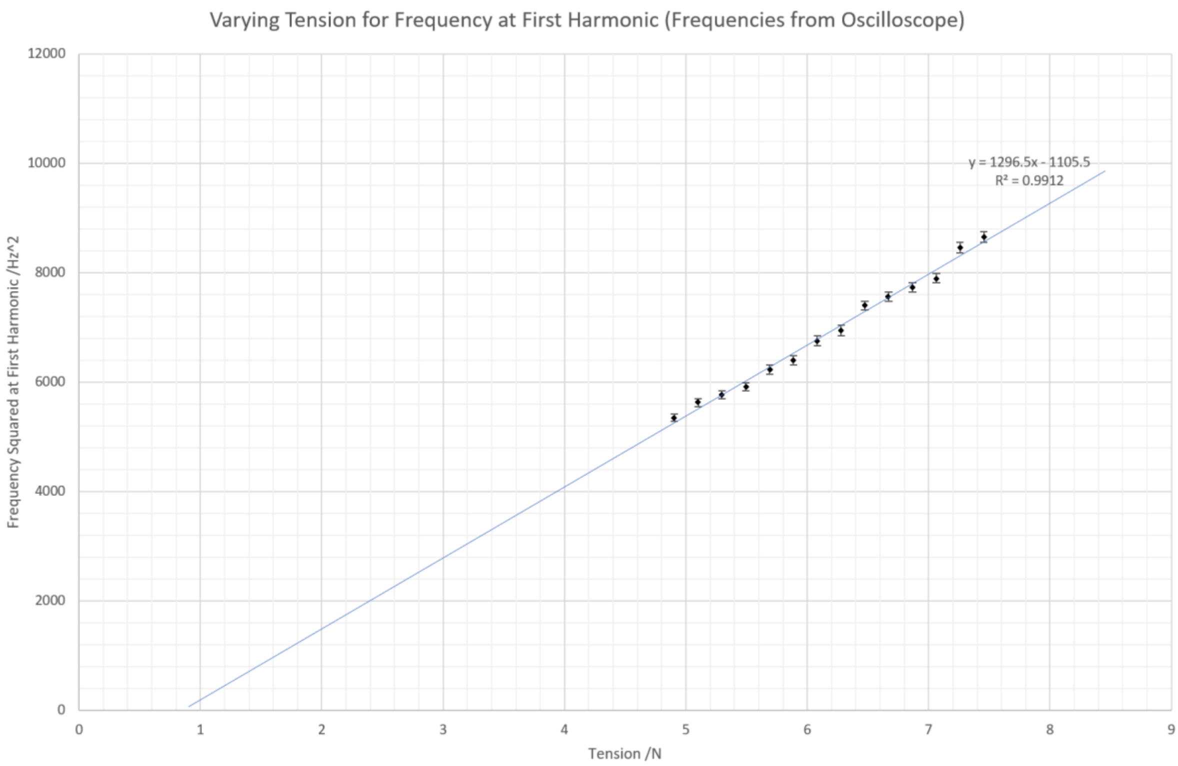


The data forms a line with equation $f^2 = 1070T$, accounting for a rounding of 3 significant figures as throughout the investigation, with gradient 1070. The line crosses through the origin as expected, verifying the validity of the data.

While the error bars here are too small to be visible, the maximum gradient line $f^2 = 1100T - 188$ has been formed from the points $T = 4.91$ and $T = 7.46$, which are the points which looked best suited to form the maximum gradient, plus or minus their uncertainties.

The minimum gradient line $f^2 = 1040T + 175$ has been formed from the points $T = 4.905$ and $T = 7.26$, which, similar to the process for the maximum gradient line, are the points which looked best suited to form the minimum gradient, plus or minus their uncertainties.

For the frequencies from the oscilloscope:



Immediately, the less precise and less accurate nature of the data can be seen. The graph is imprecise, as the points do not fit the straight line well; the graph is also inaccurate, displaying undesirable behaviour by not intersecting the origin, as would be expected. Additionally, the size of the uncertainties shows the ambiguity of this result, further framing it as the less suitable data set to use for analysis, and the uncertainties themselves seem to be incorrect, since the line of best fit misses several of the error bars. For this reason, maximum and minimum graphs have not been drawn, since this graph will not be used for further calculation – the graph taking frequencies from the signal generator is much more desirable.

4. DATA ANALYSIS

4.1 Comparison between the Signal Generator Display and the Oscilloscope for Frequency

When observing the graphs, it is clear that the signal generator display gives a more accurate and more precise value for frequency, and so these are the values that should be trusted as reliable enough to find mass per unit length. It seems that the digital process used by the signal generator to find frequency is better than the analogue process of reading the oscilloscope display, despite the measures I took to maximise the accuracy of the oscilloscope values, such as reading the distance between the peaks of multiple waves.

However, that is not to say that the use of the oscilloscope added no value to the investigation. It served to corroborate the signal generator display to some extent, ensuring that there was not a catastrophic error.

It also served to demonstrate the limits of the oscilloscope as a measuring device, proving that digital solutions are often more accurate and more precise.

4.2.1 Finding m/L for Varying Tension for Frequency

The graph shows the following relationship between the square of the frequency and tension:

$$f^2 = 1070T$$

It is also possible to derive an equation for mass per unit length m/L from the equation relating frequency, tension, mass, and length.

$$f = \frac{\sqrt{\frac{T}{m/L}}}{2L}$$

$$f^2 = \frac{T}{m/L} * \frac{1}{4L^2}$$

$$(f^2)(4L^2) = \frac{T}{m/L}$$

$$m/L = \frac{T}{(f^2)(4L^2)}$$

Since $f^2 = 1070T$ and $L = 0.490$,

$$m/L = \frac{T}{(1070T)(4)(0.490)^2}$$

From here, T can be cancelled out, so,

$$m/L = \frac{1}{(1070)(4)(0.240)}$$

$$\frac{m}{L} = 0.000980\ kg * m^{-1}$$

4.2.2 Uncertainty

With u = final absolute uncertainty, and u_L = absolute uncertainty for length, $u_{m,max}$ = uncertainty of gradient to maximum, $u_{m,min}$ = uncertainty of gradient to minimum,

$$\%u_{m,min} = \frac{1070 - 1040}{1070} * 100\%$$

$$\%u_{m,min} = 2.98\%$$

$$\%u_{m,max} = \frac{1100 - 1070}{1070} * 100\%$$

$$\%u_{m,max} = 3.42\%$$

The uncertainty of the gradient to the maximum slope is greater, so that will be used for the total uncertainty u. For this calculation, recall that $\%u_L = 5.00\%$,

$$\%u = 2(\%u_L) + \%u_{m,max}$$

$$\%u = 2(5.00) + 3.42\%$$

$$\%u = 13.4\%$$

$$u = \frac{13.4}{100} * 0.000980\ kg * m^{-1}$$

$$u = \pm 0.000131\ kg * m^{-1}$$

4.2.3 Final Calculated Value for m/L

$$m/L_{calc} = 0.000980\ \pm 0.000131\ kg * m^{-1}$$

And again, for easier reference, the measured value for mass per unit length:

$$m/L_{measured} = 0.000960\ \pm 0.00000480\ kg * m^{-1}$$

5. EVALUATION

5.1 Conclusion

In accordance with the aim, the investigation was a success. An accurate value for mass per unit length was found, with the measured value falling within the uncertainty for the calculated value. It has proved the usefulness of this equation and verified this method, proving that theory of resonance can be applied practically to find usable data.

There are some limitations to this, however. The most important is that of the uncertainty, which leaves open a broad range of values – if I did not have the measured value available, I would still be left with a relatively vague idea of the mass per unit length, not precise beyond two significant figures.

This limitation is not the fault of the theory, but the fault of the way the experiment was conducted. More precise equipment could have been used to reduce the uncertainty with respect to frequency, using dedicated digital instruments, designed to measure frequency, but also with respect to the length of the wire, using more precise equipment to find the distance between the wedges. If the investigation was conducted thus, the error of the gradient of the relationship between frequency squared and tension would have been lower, alongside a lower error for length, leaving a lesser uncertainty for the final calculated value of mass per unit length.

However, the manual method for judging when the first harmonic is achieved did not prove to be as problematic as first predicted, since it was insignificant comparted to other uncertainties. This could, however, still be improved, perhaps using a slow motion camera to better judge this.

5.2 Possible Extension

Other methods to find mass per unit length could be evaluated to improve this calculated value – looking into other methods involving the equation linking frequency, tension, wire mass, and wire length would be useful. While I also took data with constant tension and varying length during this investigation, analysis of this data was not within the scope of this investigation: these data and graphs are available in the Appendix in Tables 3 and 4, and Figures 1, 2, 3, and 4. A full analysis of this would be very useful to understanding the theoretical and practical elements of electricity and magnetism.

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APPENDIX

Table 1 – Varying tension for frequency: data collection

			Oscilloscope Data							
T Mass /g	T	f sig gen	n waves	Time div	n grids	T per	f oscil		f^2 sig gen	f^2 oscil
500	4.905	72.4	3	10	4.1	0.013667	73.17073		5241.76	5353.956
520	5.1012	73.7	3	10	4	0.013333	75		5431.69	5625
540	5.2974	75.1	3	10	3.95	0.013167	75.94937		5640.01	5768.306
560	5.4936	76.5	3	10	3.9	0.013	76.92308		5852.25	5917.16
580	5.6898	77.7	3	10	3.8	0.012667	78.94737		6037.29	6232.687
600	5.886	79.3	3	10	3.75	0.0125	80		6288.49	6400
620	6.0822	80.7	3	10	3.65	0.012167	82.19178		6512.49	6755.489
640	6.2784	81.8	3	10	3.6	0.012	83.33333		6691.24	6944.444
660	6.4746	83.2	4	10	4.65	0.011625	86.02151		6922.24	7399.699
680	6.6708	84.5	4	10	4.6	0.0115	86.95652		7140.25	7561.437
700	6.867	85.7	4	10	4.55	0.011375	87.91209		7344.49	7728.535
720	7.0632	86.7	4	10	4.5	0.01125	88.88889		7516.89	7901.235
740	7.2594	87.8	4	10	4.35	0.010875	91.95402		7708.84	8455.542
760	7.4556	89.6	4	10	4.3	0.01075	93.02326		8028.16	8653.326

Table 2 – Varying tension for frequency: uncertainties

					Uncertainties					
Mass %	Mass n	f sig gen n	f sig gen %	f^2 sig gen %	**f^2 sig gen n**	n grids n	n grids %	f oscil %	f^2 oscil %	**f^2 oscil n**
1	5	0.01	0.01381215	0.027624309	1.448	0.025	0.6097561	0.6097561	1.219512195	65.2921
1	5.2	0.01	0.01356852	0.027137042	1.474	0.025	0.625	0.625	1.25	70.3125
1	5.4	0.01	0.01331558	0.026631158	1.502	0.025	0.63291139	0.63291139	1.265822785	73.0165
1	5.6	0.01	0.0130719	0.026143791	1.53	0.025	0.64102564	0.64102564	1.282051282	75.861
1	5.8	0.01	0.01287001	0.025740026	1.554	0.025	0.65789474	0.65789474	1.315789474	82.009
1	6	0.01	0.01261034	0.025220681	1.586	0.025	0.66666667	0.66666667	1.333333333	85.3333
1	6.2	0.01	0.01239157	0.024783147	1.614	0.025	0.68493151	0.68493151	1.369863014	92.5409
1	6.4	0.01	0.01222494	0.024449878	1.636	0.025	0.69444444	0.69444444	1.388888889	96.4506
1	6.6	0.01	0.01201923	0.024038462	1.664	0.025	0.53763441	0.53763441	1.075268817	79.5667
1	6.8	0.01	0.01183432	0.023668639	1.69	0.025	0.54347826	0.54347826	1.086956522	82.1895
1	7	0.01	0.01166861	0.023337223	1.714	0.025	0.54945055	0.54945055	1.098901099	84.929
1	7.2	0.01	0.01153403	0.023068051	1.734	0.025	0.55555556	0.55555556	1.111111111	87.7915
1	7.4	0.01	0.01138952	0.022779043	1.756	0.025	0.57471264	0.57471264	1.149425287	97.1901
1	7.6	0.01	0.01116071	0.022321429	1.792	0.025	0.58139535	0.58139535	1.162790698	100.62

Table 3 – Varying length for frequency: data collection

			Oscilloscope Data					*Linearised*		
L	f sig gen	n waves	Time div	n grids	T per	f oscil		ln L	ln f sig gen	ln f oscil
0.8	47.4	2	10	4.1	0.0205	48.7804878		-0.22314355	3.85862223	3.88733039
0.75	50.3	4	10	7.6	0.019	52.6315789		-0.28768207	3.91800508	3.9633163
0.7	53.8	5	10	9	0.018	55.5555556		-0.35667494	3.98527347	4.01738352
0.65	58	5	10	8.3	0.0166	60.2409639		-0.43078292	4.06044301	4.09835258
0.6	62.7	6	10	9.3	0.0155	64.516129		-0.51082562	4.13836145	4.16691526
0.55	68.4	6	10	8.5	0.01416667	70.5882353		-0.597837	4.22537282	4.25686349
0.5	75.7	7	10	9	0.01285714	77.7777778		-0.69314718	4.32677816	4.35385576
0.45	83.7	8	10	9.2	0.0115	86.9565217		-0.7985077	4.42723898	4.46540824
0.4	94.3	9	10	9.3	0.01033333	96.7741935		-0.91629073	4.54648119	4.57238036
0.35	107.8	11	10	9.9	0.009	111.111111		-1.04982212	4.68027766	4.7105307
0.3	123	12	10	9.2	0.00766667	130.434783		-1.2039728	4.81218436	4.87087335
0.25	149	15	10	9.4	0.00626667	159.574468		-1.38629436	5.00394631	5.0725107

Table 4 – Varying length for frequency: uncertainties

					Uncertainties					
L n	L %	**ln L n**	f sig gen n	**f sig gen %**	**ln f sig gen n**	n grids n	n grids %	f oscil %	**f oscil n**	**ln f oscil n**
0.0005	0.0625	0.000625	0.05	0.105485232	0.00105485	0.025	0.6097561	0.6097561	0.297441999	0.0061
0.0005	0.06666667	0.00066667	0.05	0.099403579	0.00099404	0.025	0.32894737	0.32894737	0.173130194	0.00329
0.0005	0.07142857	0.00071429	0.05	0.092936803	0.00092937	0.025	0.27777778	0.27777778	0.154320988	0.00278
0.0005	0.07692308	0.00076923	0.05	0.086206897	0.00086207	0.025	0.30120482	0.30120482	0.181448686	0.00301
0.0005	0.08333333	0.00083333	0.05	0.079744817	0.00079745	0.025	0.2688172	0.2688172	0.173430454	0.00269
0.0005	0.09090909	0.00090909	0.05	0.073099415	0.00073099	0.025	0.29411765	0.29411765	0.207612457	0.00294
0.0005	0.1	0.001	0.05	0.066050198	0.0006605	0.025	0.27777778	0.27777778	0.216049383	0.00278
0.0005	0.11111111	0.00111111	0.05	0.059737157	0.00059737	0.025	0.27173913	0.27173913	0.236294896	0.00272
0.0005	0.125	0.00125	0.05	0.053022269	0.00053022	0.025	0.2688172	0.2688172	0.260145682	0.00269
0.0005	0.14285714	0.00142857	0.05	0.046382189	0.00046382	0.025	0.25252525	0.25252525	0.280583614	0.00253
0.0005	0.16666667	0.00166667	0.5	0.406504065	0.00406504	0.025	0.27173913	0.27173913	0.354442344	0.00272
0.0005	0.2	0.002	0.5	0.33557047	0.0033557	0.025	0.26595745	0.26595745	0.424400181	0.00266

Figure 1 – Varying length for frequency: graph using signal generator frequency

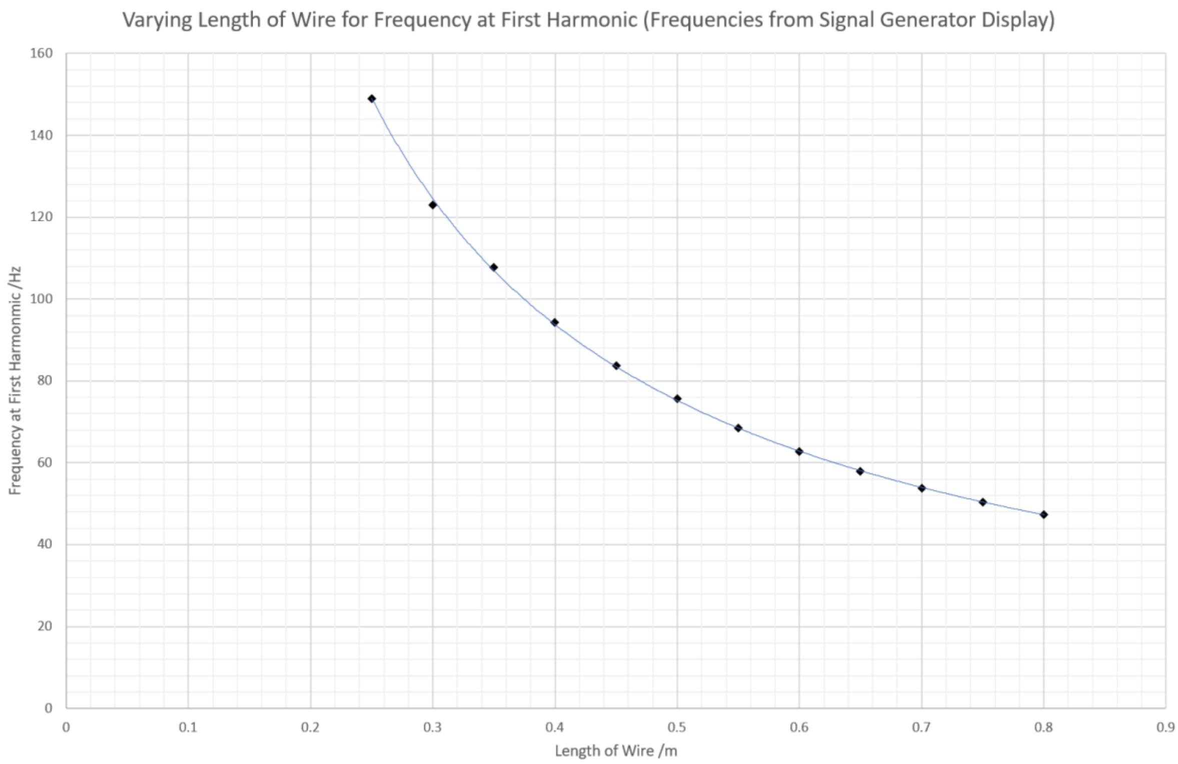

Figure 2 – Varying length for frequency: linearised graph using signal generator frequency

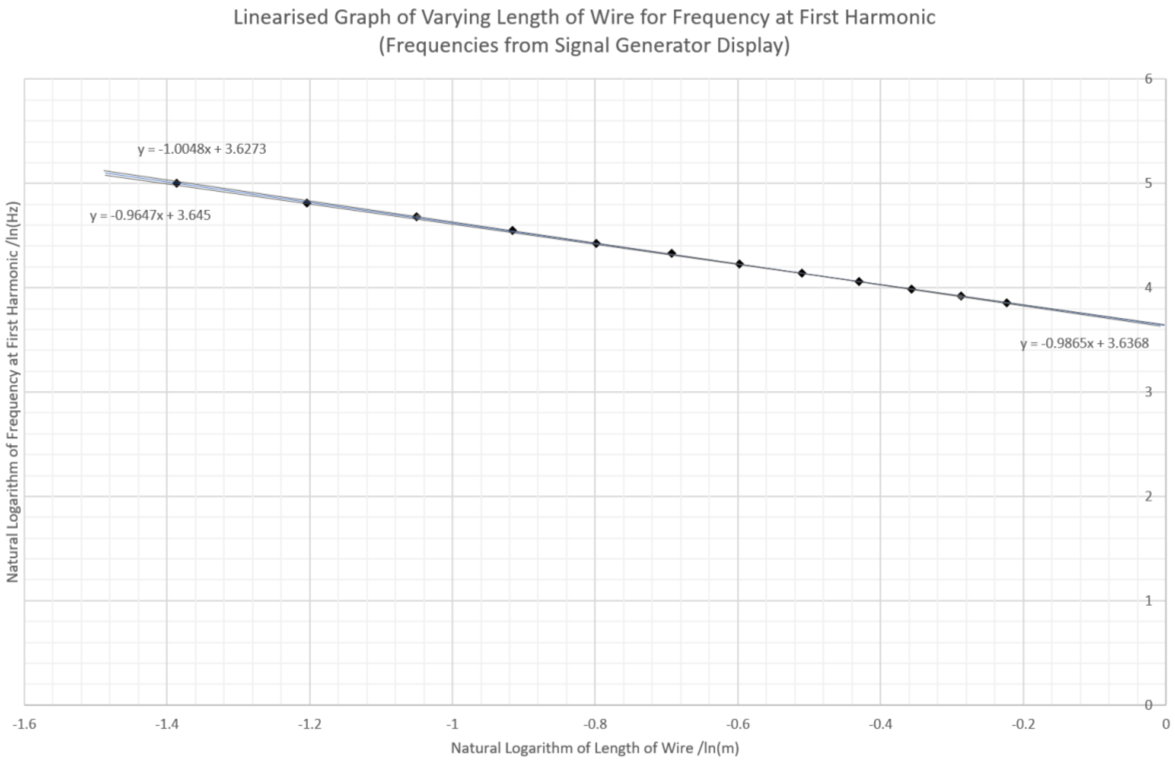

Figure 3 – Varying length for frequency: graph using oscilloscope frequency

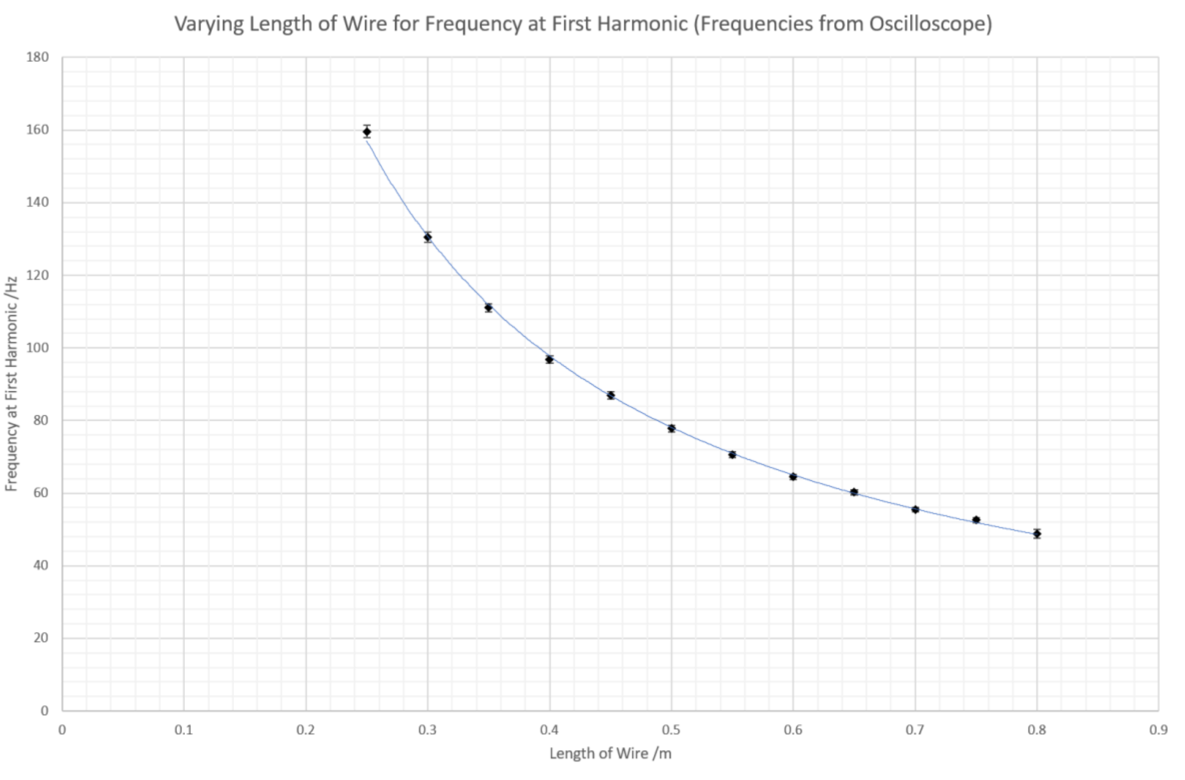

Figure 4 – Varying length for frequency: linearised graph using oscilloscope frequency