Testing the Speed of Sound in Various Gases Using a Ruben's Tube

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Abstract

In this experiment we used Heinrich Ruben's standing wave tube to calculate the speed of sound in various mediums. We found that with our tube our results matched fairly well with the expected speeds of sounds in both air and propane. By taking measurements of intensity at various points along the tube, our data agrees with the theory of standing wave tubes. We were also able to observe standing waves in the Ruben's tube when we played resonant frequencies through the tube.

Science

Invented by German physicist Heinrich Rubens, the Rubens' Tube visually shows the relationship between sound waves and sound pressure. It is composed of a tube that is constructed to be airtight besides holes drilled at regular intervals across the length of the top of the tube. There exists a gas line and one end of the tube is fitted with a diaphragm. When the gas is pumped into the tube it is forced out of the holes. At this point the gas is ignited creating individual flames at each of the holes. When a frequency is played across the diaphragm, the resultant pressure in the tube causes the flames to vary in height.

The cause of the distinct waves that form, are from the sound waves from the source lined up right next to the tube. The sound will cause vibrations in the gas forcing the gas to flow out of the holes at varying volumes. Based on Bernoulli's principle (which can be summarized as: *static pressure + dynamic pressure = total pressure*), the gas flow is proportional to the pressure difference between the inside and outside of the tube. Manipulating Newton's 2nd law gives the equation below for incompressible fluids. This is visually demonstrated in Figure 1.

$$\frac{v^2}{2} + gz + \frac{p}{\rho} = constant \qquad \textbf{(Equation 1)}$$

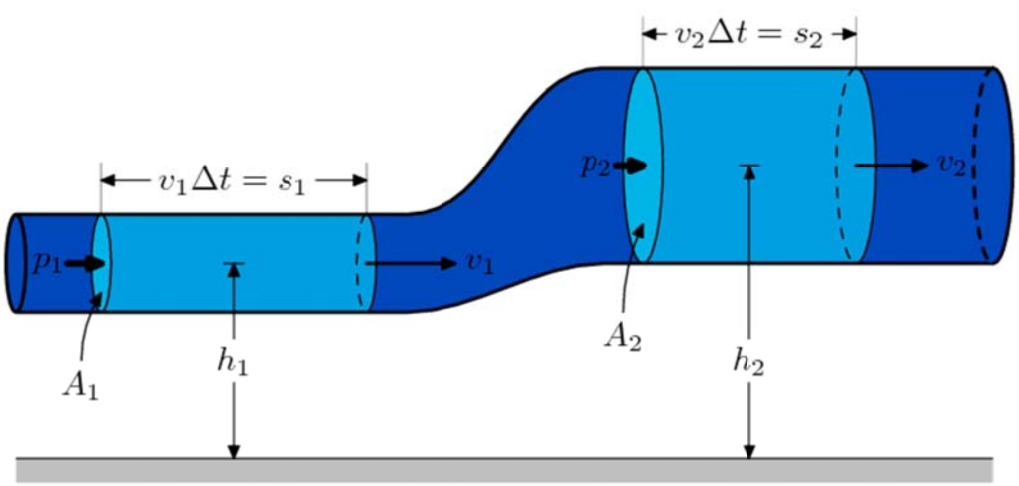

Figure 1. A diagram illustrating fluid dynamics from a continuum mechanics perspective

When the speaker is turned on, the standing wave inside of the tube will create nodes and anti-nodes. Oscillating pressure due to the sound waves will let less gas escape creating the nodes (minima) while the points with steady pressure will create the anti-nodes (maxima) of the wave. At the nodes, the gas hardly moves creating smaller flames while the antinodes experiences maximum displacement and the gas creates higher flames. This is demonstrated in Figure 2.

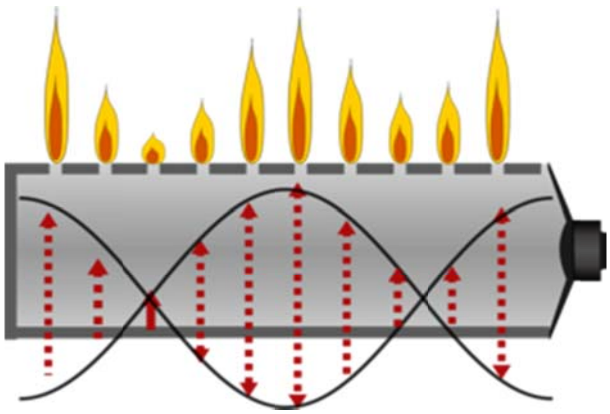

Figure 2. Diagram illustrating how waves generated by a speaker through a propane medium will affect flame heights

The amount of nodes and anti-nodes present throughout the wave features of the tube depend on the frequency harmonics of the the wave. For the open-closed tube profile used for this experiment, the equation used to calculate the nth-harmonic in empty air is:

$$f_n = nv/\square L \qquad \textbf{(Equation 2)}$$

Here, L is the length of the tube (175.5 cm), n is the harmonic, and v is the speed of sound in various mediums. We chose to use air ($v = 343\ m/s$) and propane ($v = 258\ m/s$).

With each change in harmonic, the number of nodes and anti-nodes will increase by $(n+1)/2$. Figure 3 below shows the displacement of air and pressure variation in the tube with the first, third and fifth harmonic.

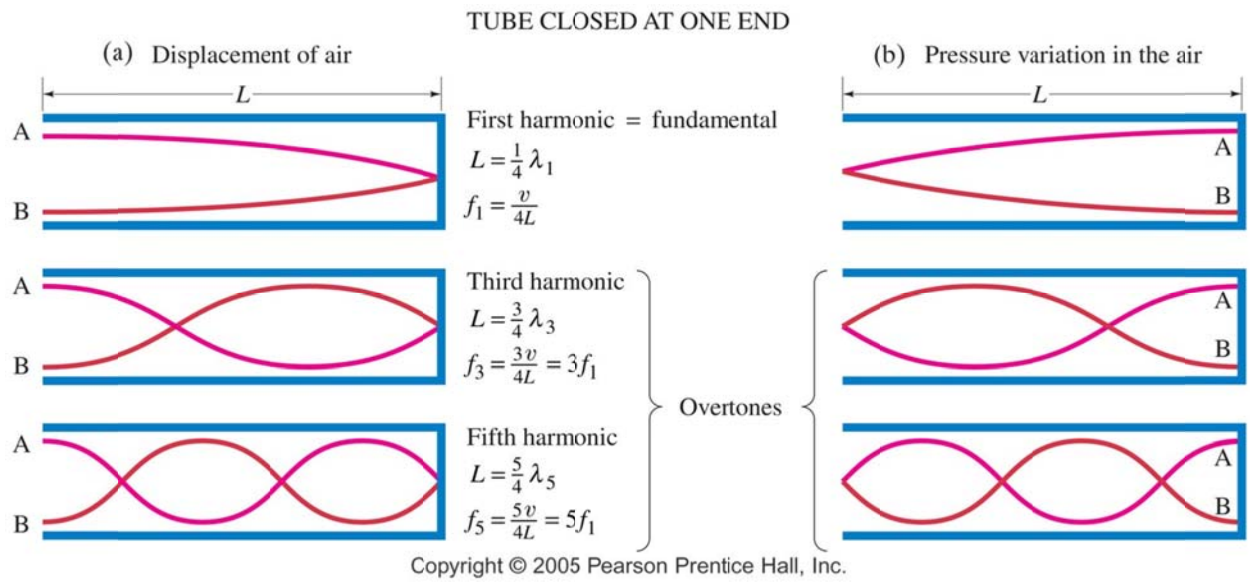

Figure 3. Diagram illustrating various harmonics created in a tube closed at one end.

Procedure

Apparatus

We began our Ruben's tube with a metal tube of length 175.5 cm and a circumference of 5.9 cm. We constructed our Ruben's tube by measuring out a distance of 22.75 cm from each end of the tube. We then proceeded to drill seventy holes in a line each a distance of 2 cm from the next with the width of each hole being 0.3175 cm round.

After this we drilled two holes at 120° from the line of seventy holes roughly 46 cm away from each end. These holes were 1.27 cm round. From this point we closed one end of the tube with a metal cap and soldered it shut. We then took two barb adapters and placed them in the 1.27 cm holes. These too were soldered to ensure a tight seal.

We then sealed one end with a flexible diaphragm (a rubber balloon) and secured the seal with electrical tape. Our next step in construction was taking a gas tube and cutting it into three sections. Two hoses stemmed from each barb and a third to the gas source. All three hoses were connected by a t-connector. Our basic experimental experiment can be found in *Figure 4*.

We finished our construction by creating a wooden base stand for the tube. We cut two semi circles the diameter of the tube and then screwed them into a base.

After the construction came the assembly. We mounted a computer speaker onto a base where we were able to position the speaker directly in front of the diaphragm end of the tube. The speaker was connected to a 50W Audio Power Amp and a wave function generator.

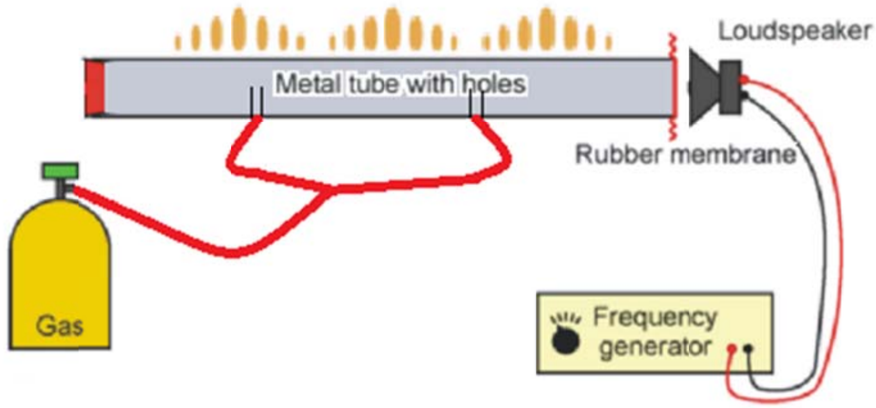

Figure 4. A visual representation of our experimental apparatus

Testing

With our goal to figure out the speed of sound in air and propane we had to set our function generator to appropriate settings. In both situations we had to calculate expected frequencies for specific harmonics. Knowing the length of the tube and the rough speeds of sound in our mediums we were able to find our theoretical frequencies.

We began our testing with air and started our testing with higher harmonics. Using a microphone and a multimeter we looked for points along the tube of highest magnitude. It was important that we kept the x and z variables the same as we scanned the y for the maximums. Once we found our peak we altered the driving frequency. While doing this we were looking for the greatest amplitude at our found maximum. Once we found the frequency that produced the greatest value we knew that we had found our resonant frequency. From here we were able to use *Equation 2* and compare our value of the speed of sound in air the theoretical velocity.

Testing with propane was slightly more complicated, but was based upon the same idea. We calculated several harmonics and still completed a frequency scan. However with the propane we decided to ignite the tube. This meant that we were no longer able to use a microphone. Instead, we were physically able to see the maximums that the tube was producing. Using the calculated harmonics as a stepping point we were able to get close to the predicted frequency and then look for a maximum height in the flames of the tube. We were able to use Equation 2 and compare our found values with the theoretical speed of sound in propane.

Results & Analysis

From the voltage output from the microphone scanning across the length of the Ruben's tube, plots of relative air density (represented by voltage) vs. distance on the tube were ascertained. When waves generated in the tube concentrated air at certain points, the volume (and thus voltage output) also increased. This translated to where the highest points on the flames would be if the tube was filled with propane and lit. Below are various harmonics that were found by adjusting frequency of the tone until a wave pattern appeared.

In the first few harmonics, defined sinusoidal patterns were difficult to find. This was likely due to the a number of errors, such as imperfectly drilled holes, human error in holding the microphone to the holes and vibrational errors the diaphragm might have introduced. It was also difficult to locate as there were a limited number of anti-nodes to survey and find the maximums. However, these errors seemed to lessen as higher harmonics were reached, with the 11^{th} and 13^{th} harmonics producing extremely sinusoidal patterns.

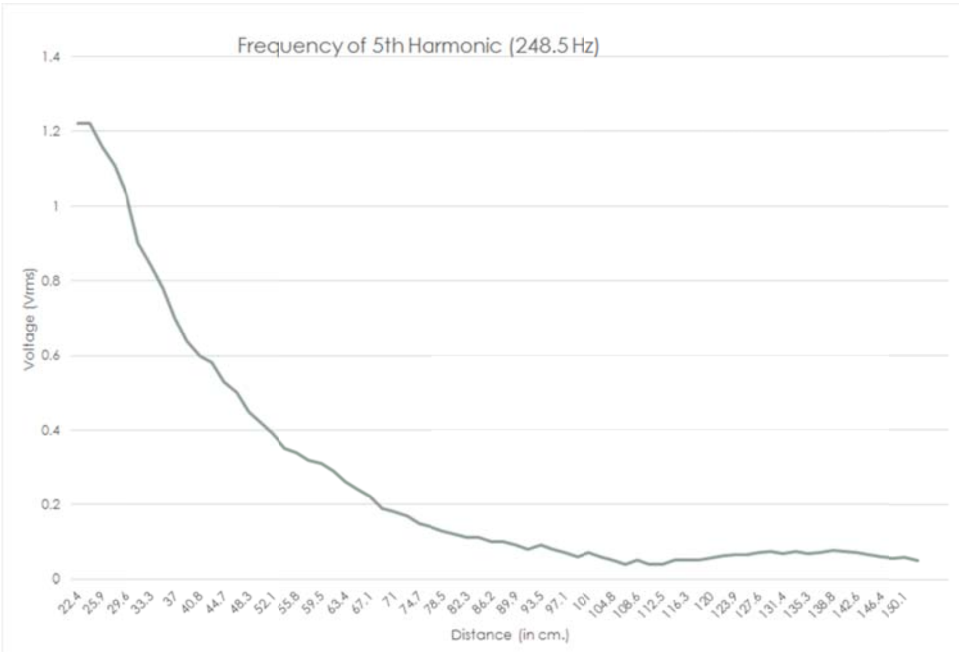

Figure 5. Voltage vs. distance graph of the 5th harmonic

The 5th harmonic was the first harmonic we were able to find values for. While it was not what we expected theoretically, we were able to find a nice maximum.

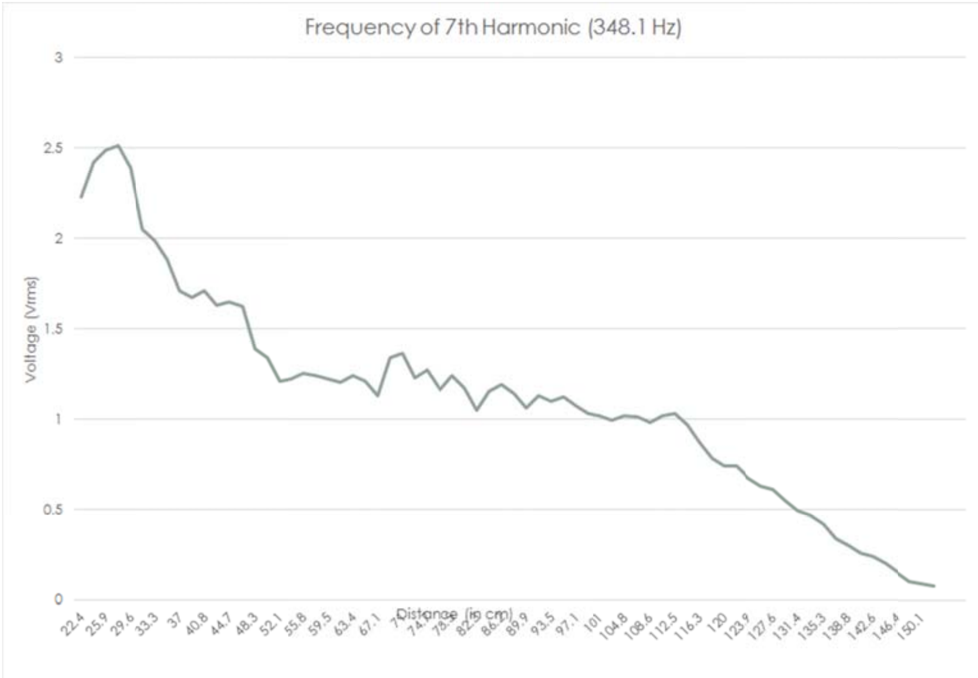

Figure 6. Voltage vs. distance (on tube) graph of the 7th harmonic

The 7th harmonic had slightly better data, but the second maximum that we predicted was not as clear as it should have been.

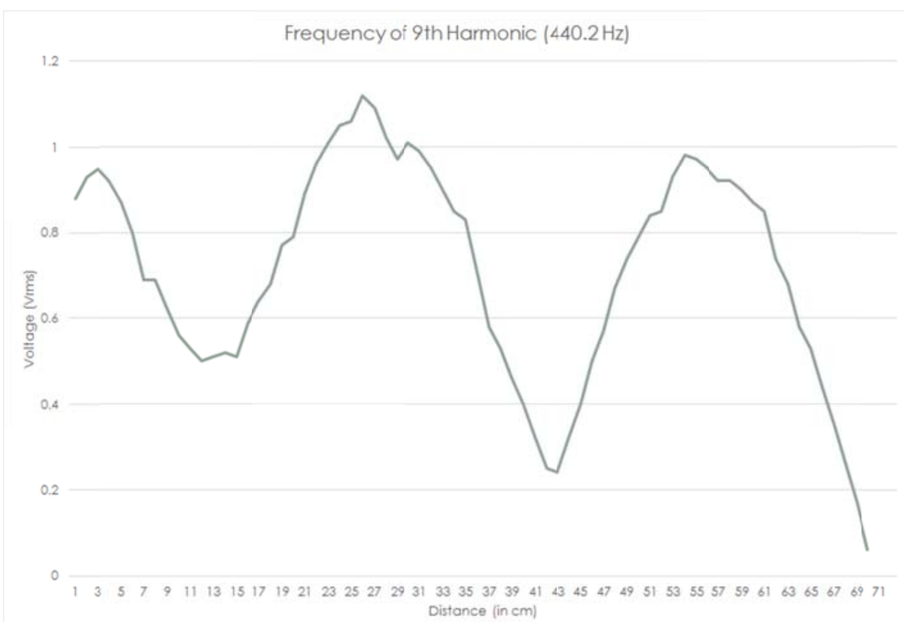

Figure 7. Voltage vs. distance (on tube) graph of the 9th harmonic

The 9th harmonic had the shape that we were expecting. There were clear peaks and valleys. However the peaks had lots of ridges. We believed that the real maximum was present, but were limited to our abilities to measure based on the location of the drilled holes. If we were able to scan the entire length of the tube then we might have been able to see smooth hills and valleys.

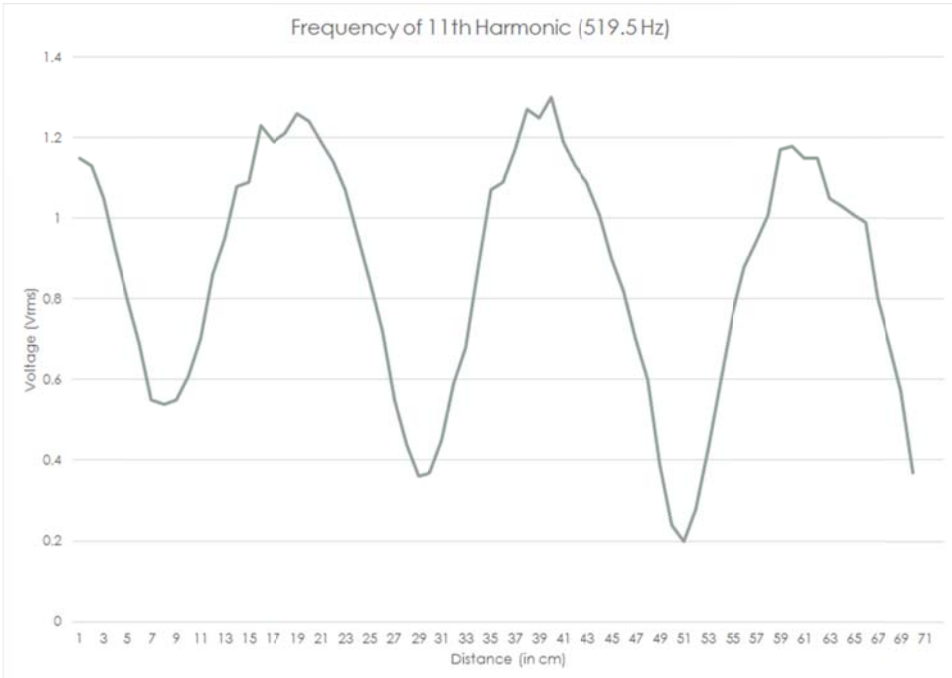

Figure 8. Voltage vs. distance (on tube) graph of the 11th harmonic

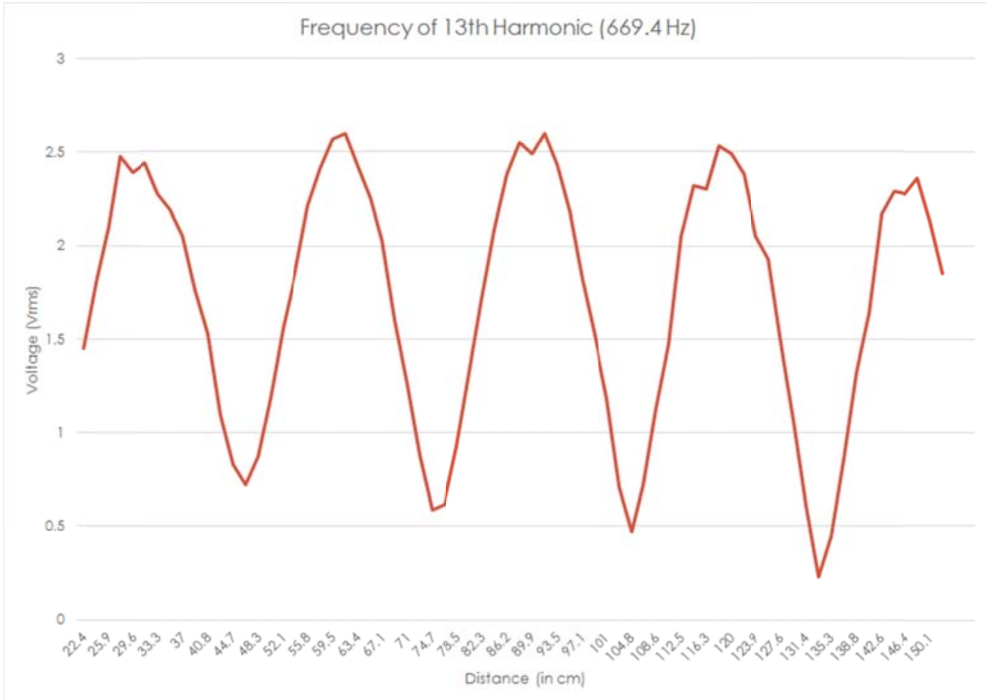

Figure 9. Voltage vs. distance (on tube) graph of the 13th harmonic

The 11th and 13th harmonics produced the best results. The 13th harmonic in particular was extremely smooth. In all of the harmonics that we measured we were able to achieve the predicted wavelengths. This assured us that we had found each of the predicted harmonic.

The results of this experiment were further backed by the values found for both the speed of sound in air and propane. By using Equation 2, the speed of sound at the various harmonics were determined. In air, the average speed was found to be 346.8 m/s, only 0.87% off from accepted values. In propane, the measured speed of sound was 260.5 m/s, only about 1% off from expected. Both these values were slightly higher than expected, which was theorized to be due to elevation above sea level, knowing that the air slightly less dense at higher altitudes. Plots of the speed of sound in different mediums for varying harmonics can be seen below.

Table 1. Speed of Sound in Air

n	Predicted f (Hz)	Recorded f (Hz)	% error	V(F_n) (m/s)
5	244.3	248.5	1.7	348.89
7	342.02	348.1	1.7	349.09
9	439.74	440.2	0.1	343.36
11	537.46	519.5	3.4	331.54
13	635.18	669.4	5.1	361.48

Table 2. Speed of Sound in Propane

n	Predicted f (Hz)	Recorded f (Hz)	% error	V(F_n) (m/s)
7	257.26	265	3	265
9	330.76	349	5.5	272.2
11	404	412	1.9	262.86
13	477.7	484	1.3	261.36
15	551	550	0.18	257.4
17	624	616	1.3	254.4
19	698	690	1.1	254.61
21	771	767	0.5	256.945

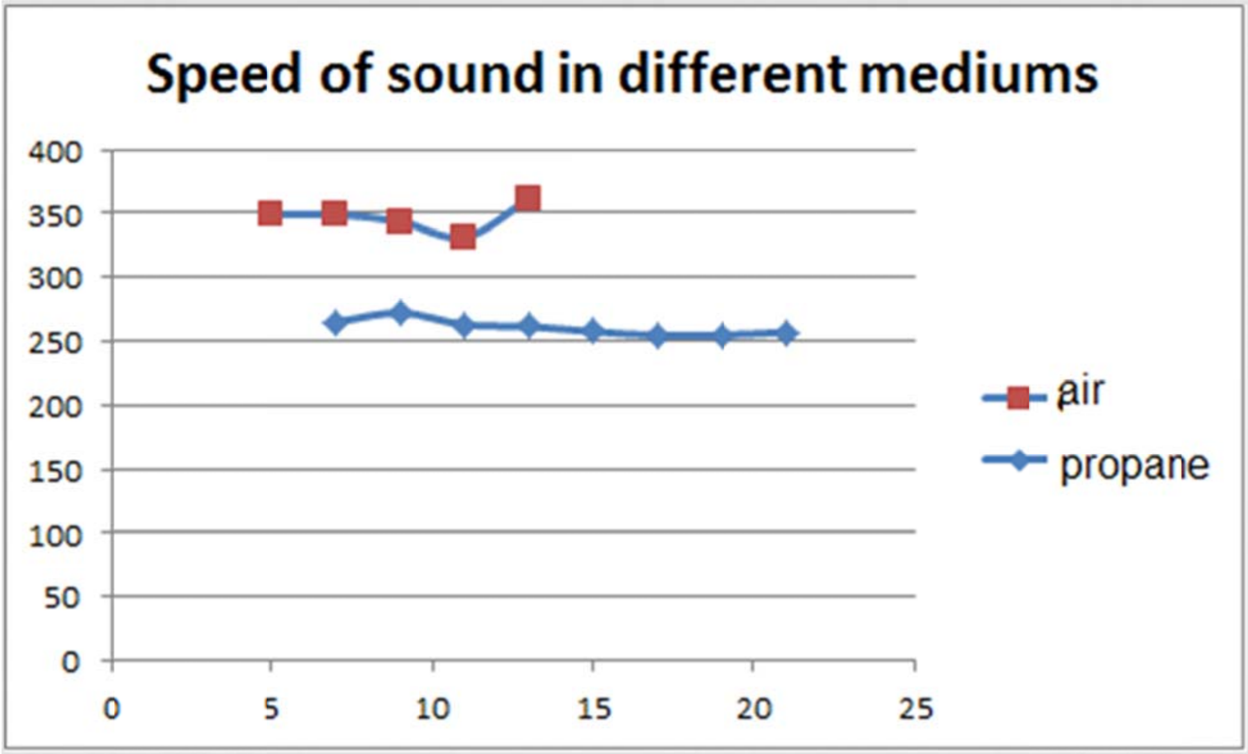

Figure 10. Plot of speed of sound (in m/s) against various harmonics (n-values)

Conclusion

The studied velocities of sound in various gases yielded results that aligned with our expectations. As expected, the speed of sound in air was much higher than that in propane. Our results of speed in air was more accurate than that of propane. However, the error window is only .13% difference between air and propane. This could be due to the fact that propane and air tests were done on different days in different environments.

Due to the data we collected and with limited error in our results, the Ruben's tube construction and testing was deemed a success. If we had more time we would have continued to gather data from other harmonics. We also would have liked to have tested other gases.

Acknowledgments

We would like to thank our professor, Steven Errede, for his guidance in the creation the of Ruben's tube, suggestions throughout the project, planning, execution and for putting himself in front of us in the case that something were to go wrong in the testing phase of our project.