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IMPLEMENTATION OF THE RESONANCE METHOD TO MEASURE THE SPEED OF SOUND USING PVC PIPES AND SMARTPHONE

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Abstract. The objective of this study is to replace the conventional approach that involved using water and vertically-held pipes in the measurement of sound speed. In this new method, the sound source is generated by an Android application called Tone Generator, utilizing a smartphone. The study investigates frequency variations in the range of 500 Hz to 1000 Hz with interval of 100 Hz. By graphing the length of the organ pipe against the harmonic number (*n*), where *n* is odd number, we observed a linear relationship. From this linear relationship, the speed of sound in the experimental setup was calculated. The speed of sound was determined to be 346 m/s with a standard deviation of 2 m/s, which is in close agreement with the reference speed of sound at 25 degrees Celsius. This innovative approach offers a convenient and accurate way to measure the speed of sound, making use of readily available smartphone applications and simplifying the experimental setup compared to traditional methods.

Keywords: resonance, pvc pipe, smartphone, speed of sound.

INTRODUCTION

The speed of sound, a fundamental physical constant, holds paramount importance in various scientific, technological, and everyday contexts. Knowing the speed of sound in different materials and conditions is essential for a multitude of reasons, ranging from advancing our understanding of the natural world toenabling countless technological innovations.

Beyond scientific and technological applications, knowing the speed of sound has numerous practical implications in everyday life. For instance, it is critical in the design and maintenance of acoustic spaces, such as concert halls and recording studios, where sound quality and clarity are of paramount importance. In the oil and gas industry, the speed of sound is employed to measure and monitor fluid flow rates in pipelines, ensuring the safe and efficient transport of resources. Even in the realm of sports, understanding the speed of sound is relevant, particularly in activities like shooting sports and archery, where sound propagation influences the timing of shots.

In this context, it becomes evident that the speed of sound is far more than a theoretical concept; it is a real-world parameter with vast implications across a diverse range of fields. The ability to measure and understand sound speed is not only of academic interest but also crucial for technological advancement, safety, and innovation.

The determination of the speed of sound in various media is a foundational experiment in physics, often introduced at the secondary education level and revisited in more advanced studies. Brian E. Martin, presents a novel variation on the classic methods used to measure the speed of sound (Martin, 2001). Utilizing a combination of low-cost digital electronics, mobile computing, and sophisticated data analysis techniques, this research aims to refine the accuracy of speed of sound measurements and make the process more accessible for educational purposes. The measurement of the speed of sound in various gas mixtures has also been conducted by Parolin and Pezzi (2013) using smartphones.

In traditional academic settings, the conventional method for measuring the speed of sound often involves the use of an open-ended, vertically positioned organ pipe submerged in water. In this method, a tuning fork is struck to generate sound at a specific frequency, and it is then brought near the mouth of the organ pipe, which is raised and lowered to achieve a state of resonance. However, this approach presents certain challenges. As the sound produced by the tuning fork travels through the air column within the pipe, it gradually weakens and dissipates, making it increasingly difficult to determine the precise resonant condition accurately. This reduction in sound intensity poses a significant obstacle in obtaining precise and reliable measurements of the speed of sound using the traditional approach.

The substitution of traditional tuning forks with alternative sound sources has been explored in various studies. In 2005, da Silva and colleagues ventured into this avenue by introducing a novel approach, employing computer-generated sound as the acoustic stimulus (da Silva et al., 2005). However, the method still retained the utilization of a water-submerged pipe. From their research, da Silva and the research team successfully determined the speed of sound, yielding values that closely matched established data for the speed of sound at a temperature of 296 Kelvin. This innovative utilization of computer-generated sound sources not only modernizes the experimental setup but also reaffirms the accuracy and reliability of sound speed measurements under specific temperature conditions.

In 2015, Yavuz harnessed the capabilities of smartphones to produce specific frequency sounds (Yavuz, 2015). However, the traditional setup still involved the use of a water-filled container and an organ pipe that needed to be raised and lowered to achieve resonance, with the smartphone being brought near the open end of the organ pipe. From this research, Yavuz successfully determined the speed of sound at a temperature of 23 degrees Celsius. Remarkably, the value obtained closely aligned with established data for the speed of sound at the same temperature. This innovative use of smartphones in acoustic experiments high-lights the potential for simplifying and enhancing sound-related measurements and investigations.

In 2019, Hellesund introduced an alternative method for measuring the speed of sound, still utilizing a smartphone but departing from the traditional water-dipped pipe setup (Hellesund, 2019). Instead, Hellesund employed cardboard tubes of specific dimensions, where the smartphone was used to generate sinusoidal sound waves with frequencies ranging from 50 Hz to 3000 Hz in proximity to the cardboard tube's mouth. The resulting sound was recorded using the same smartphone and subsequently analyzed to identify its resonant frequencies. From the outcomes of this experimental approach, Hellesund successfully derived the speed of sound, with results falling within a 3% tolerance range in comparison to theoretical values. This innovative methodology not only simplifies the experimental setup but also offers a reliable and practical means of determining the speed of sound using readily available smartphone technology.

METHOD

The experiment method harnesses the principles of resonance within an organ pipe theory (Halliday et al., 2018). Unlike traditional setups, our approach positions the pipe horizontally. Within this pipe, a smaller diameter pipe is strategically placed, functioning akin to a piston. This "piston" pipe can be advanced or retracted, allowing for adjustments in the length of the air column inside the main pipe.

Figure 1. Equipment setup

The arrangement of the equipment used is shown in Figure 1. The experiment involved the use of the following equipment: a 130 cm long 5/4-inch PVC pipe serving as the organ pipe and a 1/2-inch PVC pipe used as a sort of piston positioned inside the 5/4-inch pipe. The 1/2-inch pipe was equipped with a ruler scale for measure the length of air colum (Figure 2). This adjustable 1/2-inch pipe acted as a piston and could be moved to vary the length of the air column within the 5/4-inch pipe. The essence of this method lies in its simplicity and precision. By activating a sound source of a known frequency and adjusting the inner pipe’s position, it becomes possible to observe resonances, that is points where the sound is notably amplified. As the length of the air column is adjusted by the inner piston pipe, the resonance conditions change, providing valuable data points for various frequencies.

Figure 2. A pipe with a smaller diameter, functions like a piston with a scale.

Figure 3. A Bluetooth speaker to produce sound at frequencies controlled by the Tone Generator app.

A Bluetooth speaker is mounted at the open end of the pipe with a stand (Figure 3). To generate sound at specific frequencies, a smartphone running an Android application called Tone Generator was used. This application produced sinusoidal sound waves. The sound from the smartphone was transmitted to the Bluetooth speaker. Resonance, characterized by the most intense sound, and during this state, the scale on the piston pipe was read and recorded. The room temperature during the experiment was recorded at 25 degrees Celsius.

RESULTS AND DISCUSSION

Table 1 presents the measurements of the air column lengths (in centimeters) where resonance occurs for sound frequencies ranging from 500 Hz to 1000 Hz in 100 Hz interval. There is a discernible trend in the data: as the frequency increases, the length of the air column required for resonance decreases. This is consistent across multiple resonance modes represented by the varying values of *n* (odd number). The data indicates that for higher resonance modes (larger values of *n*) and for specific frequency, the air column length increases, which is an expected behavior. For high values of *n* and low frequencies, such as 500Hz and 600Hz, resonance conditions were not achieved due to the limited length of the organ pipe, which is only 130 cm.

Table 1. Air column lengths at resonance for various sound frequencies and resonance mode *n*

n	*l* (cm)					
	500Hz	600Hz	700Hz	800Hz	900Hz	1000Hz
1	15.7	13.0	10.7	9.0	8.0	7.0
3	50.5	41.5	35.5	30.5	27.5	24.0
5	85.0	70.5	60.0	52.5	46.5	41.5
7	119.0	99.5	84.5	74.0	66,0	59.0
9			110.0	96.0	85.0	76.5
11				117.5	104.5	93.5
13						111.0

The pattern of decreasing air column length with increasing frequency is consistently observed for all modes, which reinforces the validity of the measurements. Figure 4 presents a graph of the resonant air column length, *L*, plotted against the order of resonance, *n*, for all the sound frequencies used. The results depict a linear relationship, consistent with theoretical expectations. The equation of the graph's line was derived using the linear regression method for each frequency. The slope of the line is $v/4f$, therefore, by using the slope values from each equation for each frequency, the speed of sound v can be calculated, the results of which are presented in Table 2.

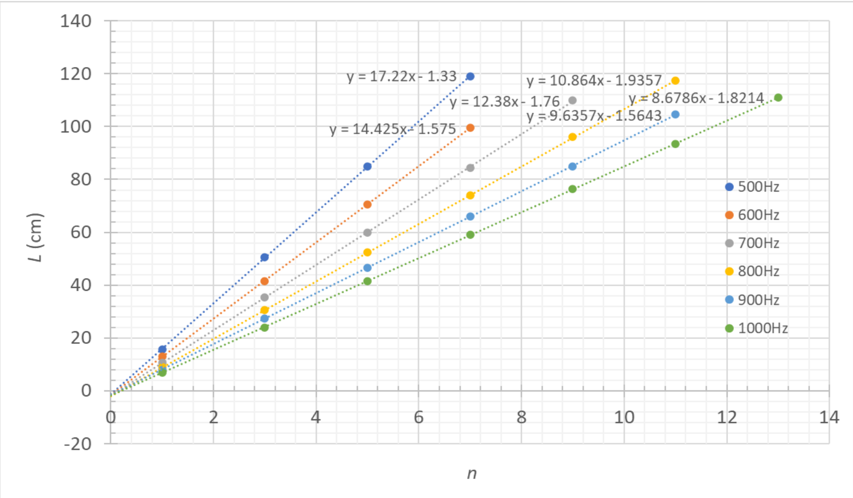

Figure 4. Resonant Air Column Length *L* versus Order of Resonance *n* for Various Sound Frequencies

Table 2. Linear Equations of the Graph for Each Frequency Obtained by Linear Regression and speed of sound calculated from the equations

f (Hz)	Equation	*v* (m/s)
500	$y = 17.22x - 1.33$	344.40
600	$y = 14.42x - 1.58$	346.06
700	$y = 12.38x - 1.76$	346.64
800	$y = 10.86x - 1.94$	347.65
900	$y = 9.36x - 1.56$	347.04
1000	$y = 8.68x - 1.82$	347.20

In the presented data, the mean value of the speed of sound was calculated to be approximately 346 m/s. The standard deviation, a measure of the spread of the sound speed values, was approximately 2 m/s. This low standard deviation indicates a high level of precision in the measurements, suggesting that the experimental setup and procedures were able to produce consistent results. According to the data in the CRC Handbook of Chemistry and Physics, the speed of sound in air at a temperature of 25 degrees Celsius is 346.3 m/s (Haynes, 2014). This value is very close to that obtained from this study, indicating a high level of accuracy.

In theory, if the relationship between the length of the air column (L) and the mode number (n) is direct and linear, where $v/4f$ is the slope, this implies that there is a zero intercept, meaning the line passes through the origin. This would suggest that the length of the air column is directly proportional to the mode number with no additional length offset. However, the experimental result $L_n = (v/4f)n - A$, includes an intercept term, A, which indicates that when the mode number n is zero, the length of the air column (L) does not start at zero but at a negative value ($-A$). The intercept A could represent a systematic error or an adjustment in the experimental setup. For example, it could correspond to an additional length that was not accounted for in the theoretical model, such as the end correction at the open end of the pipe due to the diameter of the pipe not being negligible compared to the wavelength of the sound.

In acoustics, especially when dealing with resonant air columns, the end correction accounts for the fact that the antinode of the standing wave is not exactly at the open end of the tube but a small distance outside it. This distance is often added to the physical length of the tube when calculating resonant frequencies. The study conducted by Michael C. LoPresto (2005) aimed to determine the end correction factor for a quarter-wave resonant tube, which is essential for accurate physical and acoustical measurements. The research involved an empirical approach to measure the resonant frequencies of a tube with one closed end and one open end. Upon conducting the experiments and analyzing the resonant frequencies, LoPresto found that the end correction was consistently around 0.37 times the diameter of the tube (0.37D), very similar to the model proposed by Boelkes (2011), which is 0.33D, where D represents the diameter of the pipe. Meanwhile, Kasper et al. (2015) employed an end correction of 0.61R, where R represents the radius of the resonant pipe. This can be considered similar to the findings of LoPresto and Boelkes, given that the radius is half of the diameter.

Utilizing the equation provided by LoPresto, which is $L = v/4f - eD$, where eD represents the end correction, the results of this research suggest that the linear regression line equation obtained can be used to estimate the end correction. After averaging the intercept values (A), and subsequently calculating the 'e' value as in LoPresto's equation, a value of 0.52 was derived from this research, with the PVC pipe's (resonant pipe's) diameter being 3.175 cm. This discrepancy could likely be due to several factors, among them systematic errors, imprecise positioning of the Bluetooth speaker, or other factors that may require further exploration.

CONCLUSION

From this study, a sound speed value of 346 m/s was obtained with a standard deviation of 2 m/s, or an uncertainty of about 0.6%, indicating precise results. The sound speed value is consistent with the data for the speed of sound in dry air at a temperature of 25 degrees Celsius, which was the temperature during the experiment, meaning the research results are also accurate.

From this research, it can also be concluded that this innovative method presents not just a new way to measure the speed of sound in air but does so with a design that promises precision and reproducibility. The incorporation of the adjustable ”piston” within the organ pipe offers a degree of control and flexibility previously unexplored in such experiments, marking a significant leap forward in acoustic research.

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