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Measurement of Sound Speed Using a Frequency Generator-assisted Resonance Tube for STEM-based Learning

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Abstract

This study investigates the measurement of the speed of sound in air using a resonance tube assisted by a smartphone-based frequency generator, designed to support STEM-based learning. The experiment follows a quantitative approach, with the length of the air column as the independent variable and the speed of sound as the dependent variable. Control frequencies of 495 Hz, 755 Hz, 1010 Hz, 1270 Hz, and 1530 Hz were generated via a mobile application. Resonance points were identified by observing the peak sound intensity using a digital sound level meter, which indicated the formation of standing waves. The results showed a strong linear relationship between wavelength (λ) and wave period (T), with regression equations $\lambda = 347.62T + 0.0098$ (open pipe) and $\lambda = 361.59T - 0.0176$ (closed pipe), each with a correlation coefficient of $R = 0.99$. At room temperature (24.4°C), the measured speed of sound was (347.6 ± 0.2) m/s for the open pipe and (361.6 ± 0.1) m/s for the closed pipe. These results demonstrate that low-cost, smartphone-assisted setups can produce accurate, reliable data. This method enhances student engagement and understanding of acoustic phenomena, providing an accessible and effective model for implementing hands-on STEM-based learning in physics education.

Keywords: *Resonance tube, Sound speed, STEM*

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INTRODUCTION

Natural science is a field of study that explores natural phenomena to generate scientific knowledge in the form of facts, concepts, principles, laws, and theories (Lukum, 2013). Furthermore, natural science is one of the scientific fields concerned with how to systematically learn about nature, so that science is more than only theories and facts about nature, but also a process of discovery with natural features. However, science studies are considered difficult because of the complex conceptual framework, so students are hesitant to enjoy science studies. The application of learning media in the learning process is a form of giving direct experience to students. Learning media helps students obtain information by optimizing the work of all senses in the learning process (Kustijono, 2011).

One effective way to overcome these challenges is by integrating learning media and experimental activities into the classroom. Experiments provide students with the opportunity to develop cognitive, psychomotor, and scientific inquiry skills through hands-on experiences (Rahmawati & Budiningarti, 2018). This approach is particularly crucial for abstract topics such as wave phenomena, including sound waves, which are difficult to visualize directly. Practicum activities related to sound waves can help students understand concepts such as vibration, frequency, and wave propagation more effectively (Lutfiyah et al., 2018).

In the Indonesian national curriculum, the topic of sound is introduced through Basic Competency (KD) 3.11, which states that students are expected to "*analyze the concepts of vibration, waves, and sound in everyday life, including the human auditory system and the sonar system in animals.*" In parallel, Basic Competency 4.11 requires students to "*present experimental results about vibration, waves, and sound*" (Permendikbud, 2018). These competencies emphasize not only conceptual understanding but also the application of scientific inquiry skills through hands-on activities. Therefore, there is a strong curricular mandate to design learning experiences that integrate both theoretical analysis and practical experimentation. This makes sound wave experiments, such as measuring the speed of sound using resonance tubes particularly relevant in science classrooms. Embedding such experiments within a STEM framework can further enhance student engagement, technological literacy, and real world scientific thinking.

Sound waves are longitudinal waves that occur as a result of density and stretching in a gas medium. A acquiring wave is produced when an object, such as a tuning fork, vibrates and causes a disruption in the density of the medium. Sound propagates quickly in the gas medium due to interference with the density of the medium induced by the vibrating tuning fork (Tipler, 1991). Temperature impacts the speed of sound in a gas medium, and the elastic characteristics of objects affect it in a solid media. The first criteria for the existence of sound is that there must be a source of sound, which, like with all waves, is a vibrating object. Second, energy is transported from the source to the medium in the form of longitudinal sound waves, and third, sound is perceived by the receiving ear or instrument. As a result, sound is a longitudinal wave that requires a medium to propagate (Astuti, 2016).

To address the needs of 21st-century education, STEM-based learning (Science, Technology, Engineering, and Mathematics) has been widely promoted as an interdisciplinary approach that emphasizes problem solving, critical thinking, and real-world applications. Through the integration of engineering design processes, students are encouraged to engage in designing, building, testing, and optimizing tools or systems that represent scientific phenomena (Beers, 2011). In the context of sound wave experiments, STEM learning can foster scientific reasoning, inquiry skills, and technological literacy. For example, when students are asked to construct and operate a resonance tube to measure the speed of sound, they apply engineering principles while deepening their understanding of wave physics. However, effective STEM integration requires more than simply including engineering elements; it must be supported by coherent instructional design and teacher understanding of STEM pedagogy (Roehrig et al., 2012). Furthermore, STEM activities promote student-centered, collaborative learning environments that align with future educational demands (Bybee, 2013).

This study introduces a conceptual framework that enables students to explore the concept of sound wave resonance through hands-on experiments using resonance tubes. One such tool is the Kundt's tube, originally developed by August Kundt to determine the speed of sound in air (Sakamoto et al., 2006). The experimental setup typically includes an acrylic tube, an adjustable piston, a speaker, and an audio frequency generator (AFG), which allows the formation of standing waves that make resonance phenomena observable. Gabunilas et al., (2022) developed an improvised Kundt's tube using a PVC pipe and two smartphones—one to generate sound and the other to detect it—successfully creating longitudinal standing waves and measuring the speed of sound with only a 3.76% deviation from the theoretical value. Similarly, Hellesund (2019) demonstrated that a simple setup using a smartphone and a cardboard tube could measure the speed of sound with a deviation of less than 3%, validating the method's reliability for educational use. These studies show that low-cost and easily accessible tools can effectively substitute traditional laboratory equipment, making them especially valuable in schools with limited resources. However, there is still a gap in STEM education regarding the integration of such tools into formal curricula. Many schools, particularly in developing countries, continue to rely on theory-based instruction due to the lack of laboratory access. Despite the potential of these technologies to enhance inquiry-based and experiential learning—key components of effective STEM education—they are not yet widely adopted in classroom practice or teacher training programs. Bridging this gap requires curriculum reform, increased awareness, and professional development to empower educators to implement innovative, low-cost experiments in everyday teaching.

In era revolution industry, smartphones have grown increasingly with sensors; microphones, cameras, accelerometers, thermometers, proximity sensors, and so on. Smartphones, which have become commonplace in society, can provide cost-effective alternatives to costly laboratory equipment in science education (Hellesund, 2019). Several studies have investigated the use of smartphones in experimental tools for educational purposes (Klein et al., 2014; Kuhn et al., 2014; Kuhn & Vogt, 2013; Vogt et al., 2014). So, a frequency generator can be developed using Bluetooth to increase the flexibility of the device. The use of Bluetooth is intended so that the designed frequency generator can be controlled wirelessly (Prabowo & Sucahyo, 2018). Beyond replacing traditional equipment, smartphones support active learning through real-time data collection, visualization, and analysis—making them highly compatible with STEM-based learning approaches (Haleem et al., 2022; Wu et al., 2023). In physics experiments, for example, smartphones have been used to measure acceleration, sound intensity, light levels, and even magnetic fields (González et al., 2015). These applications not only promote hands-on inquiry but also align well with STEM education principles by integrating science concepts with technology and engineering tools, and fostering mathematical analysis of experimental data. Therefore, the use of smartphones in physics experiments exemplifies an innovative and practical way to implement STEM education, especially in schools with limited laboratory infrastructure.

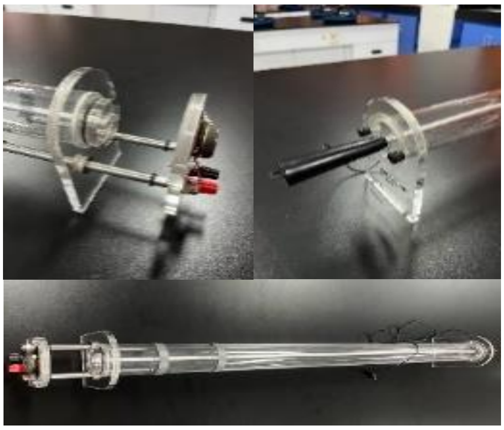
The rationale for using a resonance tube in this research stems from the fact that many students are unfamiliar with the tool and its practical applications in measuring wave properties.Throug the construction and operation of the resonance tube, students are actively engaged in STEM-based learning that integrates science (understanding sound waves), technology (using digital tools such as smartphones and sound sensors), engineering designing and optimizing the resonance tube system), and mathematics (analyzing wave equations and data). This practicum is expected to not only enhance students' conceptual understanding but also foster critical thinking, creativity, and problem-solving skills in line with 21st-century competencies. Ultimately, students can apply multiple wave principles such as frequency, period, wave speed, and resonance in real life contexts through hands on experiment. The findings of this study can enhance the quality of learning sound wave concepts by integrating contextual approaches that connect physics with health applications, such as the use of sound waves in medical diagnostics. The developed self-assessment instrument encourages students to reflect on their understanding independently while supporting inquiry-based and project-based learning. Consequently, students gain not only theoretical knowledge but also the ability to apply concepts in real-life contexts, fostering deeper and more meaningful learning. The formulation of the problems that will be discussed in this research includes:

1. What is the method to determine the speed of sound utilizing a resonance tube assisted by a frequency generator?
2. How can the resonance tube experiment be effectively integrated into STEM education?

METHOD

Materials

Several equipment are required for this research, such as resonance tubes, sound level meters, microphones, frequency generator applications, and Bluetooth speakers. These materials are shown in Pictures 1–5.



Picture 1. Resonance tube

Picture 2. Sound level meter

Picture 3. Micropone

Picture 4. Frequency generator assisted

Picture 5. Bluetooth speaker

Variable

This experiment contains three kinds of variables: independent, dependent, and control. These variables are detailed in Table 1.

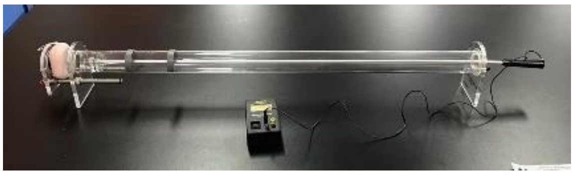
Table 1. Experiment parameters

Parameter	Details
Independent	Air column length (λ)
Dependent	Fast Sound Propagation (v)
Control	Frequency (495 Hz, 755 Hz, 1010 Hz, 1270 Hz, and 1530 Hz)

Procedure

The experimental settings, as shown in Picture 6, were carried out in several steps. For the open organ pipe configuration, the resonance tube was prepared by keeping the pipe open and connecting the microphone to a sound level meter. The Bluetooth speaker was paired with a smartphone running a frequency generator application. The initial frequency was set to 495 Hz as the first test value.

The microphone was then slowly moved along the tube while listening for the loudest sound, which was confirmed by observing the peak decibel reading on the sound level meter. The position at which the loudest sound occurred was recorded by reading the scale on the tube. This procedure was repeated to locate the second resonance point.



Picture 6. Laboratory settings

These procedures were repeated 15 times with different frequencies (495 Hz, 755 Hz, 1010 Hz, 1270 Hz, 1530 Hz), and each frequency was repeated three times to acquire five types of data. The resonance tube was then reassembled by closing one end of the pipe using the provided ring. The same procedure was applied to the closed organ pipe, with three repetitions per frequency, yielding an additional 15 sets of data.

Before data collection, both the frequency generator software and sound level meter application were calibrated against standard laboratory-grade instruments. Frequency Generator Calibration: The smartphone-based generator was matched against a bench-type function generator. Frequencies were tested at 495 Hz, 755 Hz, 1010 Hz, 1270 Hz, and 1530 Hz using an oscilloscope connected to an external speaker output. The average deviation was within ±5 Hz, which was taken as the standard error for frequency control. Sound Level Meter Calibration: The mobile sound level meter was compared against a Class 2 professional SPL meter (Sound Pressure Level meter) in a quiet room. A calibration tone of 1000 Hz at 85 dB was played through the speaker. The mobile SPL app consistently recorded ±1.5 dB from the standard, which was deemed acceptable for educational purposes. To minimize random errors and improve measurement reliability, the average value of the air column length (ΔL) was calculated from the three repetitions for each frequency. These averaged values were then used to determine the wavelength and calculate the speed of sound in air.

Analytical Method

The equations are based on the derived data from equation 1 (Tipler, 1991) for an open organ pipe with the tube end correction (ΔL) set to zero and the tube resonance assumed to be ideal.

Meanwhile, the equation is determined for a closed organ pipe with tube end correction (ΔL) set to zero and tube resonance set to ideal as,

$$L_{n+1} - L_n = \frac{1}{2}\lambda_0$$
$$\lambda = 2\,\Delta L$$

Therefore, in determining the wavelength in the air column of open and closed organo pipes represented by the formulas in this equation.

$$\Delta L = L_2 - l_1$$
$$\lambda = 2\,\Delta L$$

then, using linear regression, calculated the speed of sound in air.

Analysis of Experimental Error nd Uncertainty

To ensure the validity of the experimental results, error and uncertainty analysis were conducted. The uncertainty in the slope (a) of the linear regression line y = ax + b

Repeated or multiple measurements were conducted three times for each frequency to improve accuracy and to assess the reliability of the experimental data. Repetition allows estimation of absolute uncertainty, which reflects the precision of the measurement tools. A smaller absolute uncertainty indicates a more precise measurement. The precision of the measurements is calculated using:

$$Precision = \frac{S_a}{v}\ x\ 100\%$$

Measurement accuracy is affected by relative uncertainty. The following equation yields the relative uncertainty. (Djonoputro, 1984)

$$v_{relative} = \left|\frac{v_{experiment-}v_{theory}}{v_{theory}}\right|\ x\ 100\%$$

These reliability procedures ensure that the experimental setup, although simple and low cost produces results that are both precise and consistent, reinforcing the suitability of this approach for STEM-based physics education.

RESULT AND DISCUSSION

In this research, data were collected once to measure the length of the column, which was then followed by measuring the speed of sound. frequency generator software as a sound source as well as a resonance tube that works as a tube to measure the length of the column used in this practicum. Frequency generator software is installed and can be accessed via a smartphone. The frequency can be set using the Frequency Generator program by calculating the amount based on the standard audio generator in the laboratory during the optimization process. The standard error frequency generator software is ± 5 Hz because the smallest frequency in the application is 20 Hz with a minimum increment of 5 Hz. After the determination of the frequency, the next step is to determine the wavelength of sound when resonance occurs.

The location of the resonance can be determined directly through the window of the sound level meter and the loud sound produced by the resonance by moving the piston attached to the mic. The advantage of using the Frequency Generator software in this practicum is that it may be utilized to identify resonance phenomena with simple practicum instruments. Furthermore, the n-resonance data can be retrieved simply by moving the piston until the next resonance is detected.

The column length measurement results derived are provided in Tables 3 and 4 for open organ pipes and closed organ pipes, respectively. First, data on air column length is collected using five different frequencies with three repetitions at each frequency on both open and closed organ pipes to acquire more accurate measurement results (Rismaningsih et al., 2021). The column length for the first and second resonances is then determined by sliding the piston on the resonance tube. The measurement of the length of the column on the piston has an accuracy of 0.1 cm or the equivalent of 0.001 m. The length of the air column (ΔL) is the difference from the average length of the air column in the 1st and 2nd resonances.

The column length measurements of an open organ pipe are shown in Table 2. The standard error for the average length of the column in the 1st ($\overline{x_{L1}}$) and 2nd ($\overline{x_{L2}}$) resonances are 0.07 respectively, with a percentage error of 7%. Repetition of column lengths is conducted three times to acquire a more reliable analysis. Calculation of the length of the air column (ΔL), the length of the air column (ΔL) for a frequency of 495 Hz is 34.7 ± 0.1 cm, for a frequency of 755

Hz is 23.8 ± 0.1 cm, for a frequency of 1010 Hz is 18.5 ± 0.1 cm, for a frequency of 1270 Hz is 14.5 ± 0.1 cm, and 11.6 ± 0.1 cm for a frequency of 1530 Hz in an open organ pipe.

Table 2. Measurement of column length on open organ pipes

	f (Hz)	L₁ (cm)	$\overline{x_{L1}}$ (cm)	L₂ (cm)	$\overline{x_{L2}}$ (cm)	ΔL (cm)
		23.0 ± 0.1		57.6 ± 0.1		
1	495 ± 5	22.8 ± 0.1	22.9 ± 0.07	57.8 ± 0.1	57.7 ± 0.07	34.7 ± 0.1
		23.0 ± 0.1		57.6 ± 0.1		
		11.2 ± 0.1		34.8 ± 0.1		
2	755 ± 5	11.2 ± 0.1	11.1 ± 0.07	35.0 ± 0.1	34.9 ± 0.07	23.8 ± 0.1
		11.0 ± 0.1		35.0 ± 0.1		
		6.0 ± 0.1		24.8 ± 0.1		
3	1010 ± 5	6.2 ± 0.1	6.1 ± 0.07	24.6 ± 0.1	24.7 ± 0.07	18.5 ± 0.1
		6.2 ± 0.1		24.6 ± 0.1		
		4.0 ± 0.1		18.8 ± 0.1		
4	1270 ± 5	4.2 ± 0.1	4.1 ± 0.07	18.6 ± 0.1	18.7 ± 0.07	14.5 ± 0.1
		4.2 ± 0.1		18.6 ± 0.1		
		3.0 ± 0.1		14.6 ± 0.1		
5	1530 ± 5	3.0 ± 0.1	3.1 ± 0.07	14.8 ± 0.1	14.7 ± 0.07	11.6 ± 0.1
		3.2 ± 0.1		14.6 ± 0.1		

The standard error for the average length of the column in the 1st ($\overline{x_{L1}}$) and 2nd ($\overline{x_{L2}}$) resonances are 0.07 respectively, with a 7% error rate in the closed organ pipe as shown in Table 3. Repetition of the length of the column was carried out three times to obtain more accurate results. Analysis of the length of the air column (ΔL), the length of the air column (ΔL) for a frequency of 495 Hz is 35.1 ± 0.1 cm, for a frequency of 755 Hz is 22.7 ± 0.001 cm, for a frequency of 1010 Hz is 17.6 ± 0.1 cm, for a frequency of 1270 Hz is 13.9 ± 0.1 cm, and 11.2 ± 0.1 cm for a frequency of 1530 Hz.

Table 3. Measurement of column length in closed organ pipes

	f (Hz)	L₁ (cm)	$\overline{x_{L1}}$ (cm)	L₂ (cm)	$\overline{x_{L2}}$ (cm)	ΔL (cm)
		16.6 ± 0.1		51.6 ± 0.1		
1	495 ± 5	16.4 ± 0.1	16.5 ± 0.07	51.6 ± 0.1	51.7 ± 0.07	35.1 ± 0.1
		16.6 ± 0.1		51.8 ± 0.1		
		9.8 ± 0.1		32.4 ± 0.1		
2	755 ± 5	10.0 ± 0.1	9.9 ± 0.07	32.6 ± 0.1	32.5 ± 0.07	22.7 ± 0.1
		9.8 ± 0.1		32.6 ± 0.1		
		6.0 ± 0.1		23.6 ± 0.1		
3	1010 ± 5	6.2 ± 0.1	6.1 ± 0.07	23.6 ± 0.1	23.7 ± 0.07	17.6 ± 0.1
		6.0 ± 0.1		23.8 ± 0.1		
		4.2 ± 0.1		18.0 ± 0.1		
4	1270 ± 5	4.0 ± 0.1	4.1 ± 0.07	18.0 ± 0.1	18.0 ± 0.1	13.9 ± 0.1
		4.2 ± 0.1		18.0 ± 0.1		
		3.0 ± 0.1		14.4 ± 0.1		
5	1530 ± 5	3.2 ± 0.1	3.1 ± 0.07	14.2 ± 0.1	14.3 ± 0.07	11.2 ± 0.1
		3.2 ± 0.1		14.4 ± 0.1		

Data analysis and processing were performed using Microsoft Excel to determine the period, the difference in the air column, the wavelength, and the speed of sound in the air. To assist data processing, column length and frequency are converted to periods and meters. The period is then measured using the formula,

$$T = \frac{1}{f}$$

Period value data (T), column length (L), and wavelength (λ) as shown in Table 4 and Table 5 for open organ pipes and closed organ pipes, respectively. The results of calculating the wavelength (λ), table 4 shows the observed wavelength (λ) for a frequency of 495 Hz is 0.695 ± 0.001 m, for a frequency of 755 Hz is 0.476 ± 0.001 m, for a frequency of 1010 Hz is 0.371 ± 0.001 m, for a frequency of 1270 Hz is 0.291 ± 0.001 m, and 0.232 ± 0.001 m for a frequency of 1530 Hz in an open organ pipe.

Table 4. Rapid measurement of wavelength in air on open organ pipes

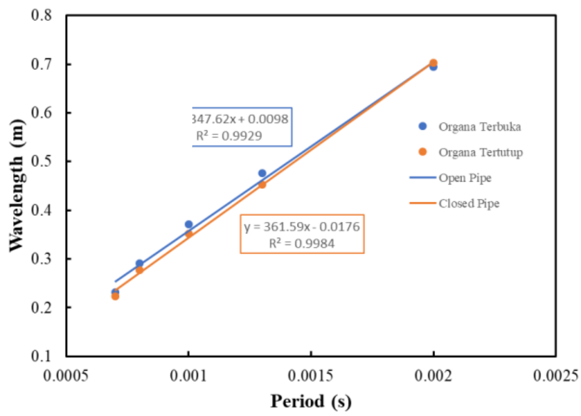
	f (Hz)	T(s)	ΔL (m)	λ(m)
1	495 ± 5	0.0020	0.347 ± 0.001	0.695 ± 0.001
2	755 ± 5	0.0013	0.238 ± 0.001	0 .476 ± 0.001
3	1010 ± 5	0.0010	0.185 ± 0.001	0.371 ± 0.001
4	1270 ±5	0.0008	0.145 ± 0.001	0.291 ± 0.001
5	1530 ± 5	0.0007	0.116 ± 0.001	0.232 ± 0.001

Meanwhile, the results of calculating the wavelength (λ) for closed organ pipes shown in Table 5. The measured wavelength (λ) for a frequency of 495 Hz is 0.703 ± 0.001 m, frequency of 755 Hz is 0.453 ± 0.001 m, frequency of 1010 Hz is 0.352 ± 0.001 m, frequency of 1270 Hz is 0.277 ± 0.001 m, and 0.224 ± 0.001 m is a frequency of 1530 Hz.

Table 5. Rapid measurement of wavelength in air on closed organ pipes

	f (Hz)	T(s)	ΔL (m)	λ(m)
1	495 ± 5	0.0020	0.351 ± 0.001	0.703 ± 0.001
2	755 ± 5	0.0013	0.227 ± 0.001	0.453 ± 0.001
3	1010 ± 5	0.0010	0.176 ± 0.001	0.352 ± 0.001
4	1270 ± 5	0.0008	0.139 ± 0.001	0.277 ± 0.001
5	1530 ± 5	0.0007	0.112 ± 0.001	0.224 ± 0.001

The data that has been obtained can be used to determine the relationship between wavelength (λ) and period (T). Data were analyzed by linear regression and processed into Microsoft Excel so that the graph plot is generated.



Picture 7. Relationship graph of wavelength (λ) and wave period (T)

The relationship between the wavelength (λ) and the wave period (T) used during the experiment shows a pretty good linear relationship because the value of R^2 approaches 1 e. v = 347.62T + 0.0098 with a coefficient of determination of 0.9929 in open organs and the equation v = 361.59T - 0.0176 with a coefficient of determination of 0.9984 shown in Picture 7.

The graph above shows that the bigger the period (the smaller the frequency), the longer the wavelength, or the longer the pipe, the lower the frequency of the sound produced. This means that theory about the relationship between frequency and pipe length can be proved directly, proving that the shorter the organ pipe, the higher the sound frequency produced (Tipler, 1991). As a result, the constructed experimental tools are capable of verifying the concept of open organ pipes as well as closed organ pipes.

Then, analyze any errors or uncertainties. This uncertainty is estimated to yield a close-to-true error value. In the experimental results to calculate the speed of sound in air acquired from the gradient value in Picture 7, an open organ pipe at room temperature 24.4ºC, the gradient value a = 347.6 is obtained, so that the average value of the speed of sound is (347.6 ± 0.2) m/s, with relative error and absolute error of 0.6% and 0.1%, respectively. Meanwhile, the sound speed in the air with the closed organ pipe obtained a gradient value, a = 361.6, thus the average sound speed is (361.6 ± 0.1) m/s, with a relative error and absolute error of 4.7% and 0.2%. Theoretically, the speed of sound in the air medium at 0°C is 331 m/s. To calculate the relationship between wave speed and air temperature can be calculated using the formula (Serway & Jewett, 2017).

$$v = 331\sqrt{1 + \frac{T_c}{273}}$$

According to Formula 30, the sound speed at 24.4°C is 345.5 m/s. This suggests that the results of this research's measurements of the speed of sound in the air are quite accurate, with an accuracy value of 99.4% and 96.3% for open organ pipes and closed organ pipes, respectively. Many variables could contribute to experimental results that are incompatible with theory. The difference in fast values propagation of sound caused by the temperature difference inside the room and the state of the noisy room that resulted in the microphone is not valid inside capturing sound from the frequency generator software. Several previous studies have found that sound waves have a significant impact on temperature and humidity (Mahdi & Al-jumaily, 2012). The speed of sound increases as the temperature rises (Astuti, 2016; Young & Freedman, 2020).

This experiment involving the measurement of sound speed in air using both open and closed organ pipes provides a tangible example of the interdisciplinary nature of STEM (Science, Technology, Engineering, and Mathematics). The data collected such as the air column lengths, frequency values, wavelengths, and calculated speed of sound can be analyzed within the STEM framework to demonstrate the integration of these fields in scientific inquiry.

Science: Understanding Physical Phenomena

This experiment reinforces essential physics principles, particularly sound waves and resonance behavior in air columns. The alignment of resonance patterns in open and closed tubes with theoretical models confirms that resonance occurs when the column's natural frequency matches the source frequency. These outcomes offer a concrete application of wave propagation theory, enhancing students' conceptual grasp of acoustics (Serway & Jewett, 2017; Young & Freedman, 2020).

Technology: Tools for Precision and Measurement

This experiment utilizes smartphone-based frequency generators and sound meters, enabling low-cost and portable scientific measurement. Similar to Hellesund's (2019) study, which employed a smartphone and a cardboard tube to measure sound speed within 3% accuracy, the present experiment validates the use of simple mobile tools in physics education. This supports the integration of smartphones as effective alternatives to expensive laboratory equipment in classroom settings.

In line with this, the experiment can be developed into an interactive learning module, where students use their own mobile devices to explore resonance phenomena. For example, in a STEM classroom, students may record resonance frequencies using free mobile apps and a resonance tube, then analyze wave behavior directly. This method fosters both scientific inquiry and digital literacy, as highlighted in recent STEM education literature (Hellesund, 2019; Serway & Jewett, 2017). The success of this approach shows that even inexpensive tools can generate reliable data, enhancing the accessibility of physics learning across various educational contexts.

Engineering: Experimental Design and Problem Solving

Students can design their own experimental setups using smartphones, speakers, and resonance tubes. They control frequencies, identify resonance points, and calibrate their devices to optimize accuracy—mirroring authentic engineering processes. This hands-on activity promotes analytical thinking, iteration, and creative problem-solving (Mahdi & Al-jumaily, 2012; Rismaningsih et al., 2021).

Mathematics: Data Analysis and Calculation

Mathematical modeling is key to this experiment. Students apply relationships between frequency, wavelength, and period to determine the speed of sound. Through data plotting and regression analysis, they evaluate accuracy and calculate relative error. These practices enhance their quantitative reasoning and data interpretation skills (Young & Freedman, 2020).

This experimental design is well-suited for integration into STEM-based science instruction. Students may perform resonance measurements using smartphones, analyze the relationship between tube length and frequency, and compare empirical results with theoretical values. Such activities foster scientific inquiry, digital literacy, and interdisciplinary learning, making the resonance tube a viable instructional tool for physics education in resource-limited settings.

The findings of this study are in line with previous research that has employed STEM-based approaches in teaching sound and wave concepts. For instance, Astuti (2016) developed a sound speed measurement tool using Audacity software, demonstrating that simple, technology-supported tools can yield accurate results in physics experiments. Likewise, Prabowo & Sucahyo (2018) designed a mobile-based learning medium for the Melde's law experiment, highlighting the role of mobile applications in enhancing wave learning. Additionally, Hellesund (2019) and (Kuhn & Vogt, 2013) found that smartphones can be effectively used for acoustic experiments in educational contexts, serving as low-cost alternatives to conventional lab equipment. These studies support the outcomes of the current experiment, which incorporated smartphone-based frequency generators and resonance tubes within a STEM framework. This integration underscores the value of accessible, low-cost tools in fostering interdisciplinary learning and improving students' conceptual understanding.

This experiment exemplifies the interconnected nature of STEM disciplines. By integrating theoretical and practical aspects of science, technology, engineering, and mathematics, students can develop a deeper understanding of sound waves, resonance, and the physics behind sound propagation. The results obtained such as the calculated speed of sound are not only consistent with theoretical expectations but also emphasize the importance of STEM education in fostering critical thinking, problem-solving, and quantitative reasoning. The ability to analyze and calculate the speed of sound in different environments, while accounting for experimental uncertainties, underscores the value of an interdisciplinary approach to learning.

Moreover, this experiment could serve as a model for STEM-based curricula, where students are encouraged to design their experiments, collect data, and use technology to enhance their understanding of scientific concepts. The results align with established theories, further validating the role of STEM education in helping students connect theoretical knowledge with real-world applications (Astuti, 2016; Serway & Jewett, 2017). More details in Table 6.

Table 6. Laboratory + mobile application integration on STEM learning

STEM Component	Learning Activity	Description	Tools & Materials	Expected Outcome
Science	Concept Exploration on Sound and Resonance	Students learn the basic theory of sound waves, resonance, and	Textbook, teacher presentation, interactive	Students understand the relationship between

STEM Component	Learning Activity	Description	Tools & Materials	Expected Outcome
		standing waves through guided inquiry.	simulation (e.g., PhET)	frequency, wavelength, and speed of sound.
Technology	Using Mobile App to Visualize Sound Waves	Students use a sound frequency analyzer app (e.g., Spectroid, Phyphox) to visualize sound frequencies and identify resonant frequencies.	Smartphone with app installed	Students observe how different frequencies affect the resonance condition.
Engineering	Constructing a Resonance Tube Apparatus	Students design a simple resonance tube using PVC pipe, water, and a speaker connected to a frequency generator.	PVC pipe, beaker, water, ruler, speaker, frequency generator	Students construct a functioning resonance tube to detect resonant lengths.
Mathematics	Calculating the Speed of Sound	Students record frequency and length data at resonance, then calculate the speed of sound using $v = f \times \lambda$.	Calculator, worksheet, graphing tool (optional: spreadsheet app)	Students derive and analyze the speed of sound from their own experimental data.
Integration	Reflection and STEM Connection Discussion	Students reflect on how the activity connects science concepts, technology use, engineering design, and mathematical analysis.	Group discussion, reflection journal	Students articulate the interdisciplinary nature of the activity and its real-world relevance.

CONCLUSION

This study demonstrates an innovative approach to measuring the speed of sound in air using a simple, low-cost resonance tube enhanced with smartphone-based frequency generator software. The measured sound speeds—347.6 ± 0.2 m/s for an open organ pipe and 361.6 ± 0.1 m/s for a closed organ pipe at 24.4°C—show high levels of accuracy, with relative errors of 0.6% and 4.7%, and overall accuracies of 99.4% and 96.3%, respectively. These findings validate the effectiveness of this method for school-based science learning, offering a practical alternative to expensive laboratory equipment. The experiment not only enables quantitative analysis of resonance and wave principles but also integrates core aspects of STEM (Science, Technology, Engineering, and Mathematics), reinforcing conceptual understanding through hands-on experience. Although the setup does not capture qualitative data such as stationary wave visualizations, it remains a reliable and educationally valuable tool. Moreover, the use of digital technology simplifies the experimental process, fosters student engagement, and enhances comprehension of wave behavior, making this method an effective and accessible innovation for classroom and laboratory applications.

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