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Analysis of the influence of amplitude, frequency, angle of propagation, and air pressure on the characteristics of sound waves

Winda Setya*, Ilman Azmi, Ikmal Konit Istiqomah, Dinaldhi Muhammad Aditya, Muhammad Minan Chusni, Ea Cahya Septia Mahen, Pina Pitriana, Ade Yeti Nuryantini, Seni Susanti

Program Studi Pendidikan Fisika, UIN Sunan Gunung Djati, Bandung, Indonesia
*Corresponding Author. E-mail: suratwindasetya@uinsgd.ac.id

Abstract: This study offers a comprehensive approach that has not been widely explored, integrating PhET interactive simulations and the Phyphox sensor application to analyze the simultaneous influence of four physical parameters amplitude, frequency, dispersion angle, and pressure on the characteristics of sound waves. The integration of PhET interactive simulations and the Phyphox application enables real-time visualization and experimental data measurement through smartphone sensors. Furthermore, this research contributes new insights by exploring the dispersion angle in the context of wave direction and intensity, a topic rarely discussed in digital media-based acoustic studies. The method used is a quantitative experiment with amplitude variations from 1 to 10 and frequencies of 400 Hz, 500 Hz, and 600 Hz, measured at distances of 1 cm, 3.25 cm, and 5.5 cm. The study also includes observations of reflection and interference patterns of waves at propagation angles of 18°, 45°, and 90°, as well as an analysis of the effect of air pressure on sound intensity, with pressure varied from 0.0 atm to 1.0 atm. The results show that sound wave intensity increases with higher amplitude and frequency, in accordance with the theory that intensity is proportional to the square of the amplitude. The propagation angle influences the reflection and interference patterns, resulting in varied energy distribution. Additionally, air pressure significantly affects sound intensity, emphasizing the crucial role of the medium in sound wave propagation.

Keywords: Sound Waves, Amplitude, Frequency, Air Pressure, Interference Patterns

INTRODUCTION

A wave is a propagating vibration. Waves occur due to the presence of a vibration source and can carry energy as they propagate. Waves can be classified based on the direction of propagation and the medium through which they travel. Sound waves are waves that propagate in a longitudinal direction, consisting only of compressions and rarefactions, and require a mechanical medium to travel (Muhtar, 2022). Sound is a longitudinal wave formed within a medium, whether the medium is solid, liquid, or gas (Mulyaningsih, 2024).

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Although longitudinal mechanical waves have a wide frequency range, only certain frequencies can be detected by the human auditory system—those capable of producing the sensation of sound in the ears and brain. Sound can be heard due to the vibration of an object that acts as the sound source. These vibrations cause the surrounding air to vibrate, and the disturbance then propagates through the air medium until it reaches the eardrum. Sound waves are essentially periodic variations in air pressure along their path of propagation (Putri et al., 2024).

Sound waves occur when an object vibrates and the resulting vibrations affect the surrounding medium, creating regions of compression and rarefaction within the medium (Bosia et al., 2022). In this process, energy can transfer from one place to another or from one object to another, enabling longitudinal waves to travel through a medium (Machado, 2021). The displacement of molecules from their equilibrium position results in compressions and rarefactions. The maximum displacement or the greatest distance from the equilibrium point is referred to as the amplitude (Rismawan et al., 2023). In terms of molecular displacement, sound waves occur along a horizontal axis and take the form of compressions or rarefactions, which can be observed through pressure variations (Qowiyyah, 2022). The pressure of the medium increases during compressions, while it decreases during rarefactions (Li et al., 2021).

Sound waves possess fundamental properties common to all types of waves, such as interference, diffraction, refraction, and resonance (Rijal, 2024). Interference is a key wave characteristic that occurs when two or more sound waves meet and overlap in the same region, resulting in a new wave pattern (Siregar, 2022). Diffraction occurs when the direction of sound wave propagation changes as it passes around the edge or through an opening of a barrier, allowing it to spread into shadowed regions. The extent of diffraction largely depends on the relationship between the wavelength of the sound and the size of the obstacle. If the wavelength is larger than the obstacle, the diffraction effect becomes more pronounced (Kho, 2024). Resonance occurs when two objects share the same frequency. Additionally, when two waves with maximum amplitude meet and reinforce each other, they produce a loud humming sound (Widiansyah, 2021). The speed of sound wave propagation is influenced by its amplitude and frequency. However, since the speed of sound cannot be observed with the naked eye, simulations are needed to visualize it (Amelia et al., 2023). Sound can also be reflected, following the law of reflection, which states that the angle of incidence is equal to the angle of reflection. When sound is reflected, the following conditions apply: (1) the angle of incidence, the angle of reflection, and the normal line lie in the same plane; (2) the angle of incidence equals the angle of reflection (Afifah et al., 2025).

The study conducted by Rejeki (2024) examined the influence of amplitude and frequency on the speed of sound waves in air and water mediums using PhET simulations. The results showed that amplitude and frequency are directly proportional to the speed of sound wave propagation, and due to the higher particle density in water, sound waves travel faster in water compared to air. Amplitude determines the loudness of the sound; the greater the amplitude, the louder the sound and the higher the energy, since energy is proportional to the square of the amplitude. Meanwhile, frequency affects the pitch; a high frequency produces a sharp sound, while a low frequency produces a deep sound. In some cases, high frequencies also carry greater energy. Thus, amplitude and frequency play important roles in determining the characteristics and energy of sound waves.

The study conducted by Maulana (2020) found that changes in temperature and pressure affect the amplitude of ultrasonic waves in a liquid medium, which is directly related to the amount of acoustic energy transmitted (Maulana, 2020). Additionally, frequency is known to influence the perception of pitch and is closely related to the vibration pattern of the sound source. Frequency is one of the main physical parameters affecting human perception of pitch. This frequency is closely associated with the periodic vibration pattern produced by the sound source, where the higher the vibration frequency, the higher the pitch perceived by the human auditory system.

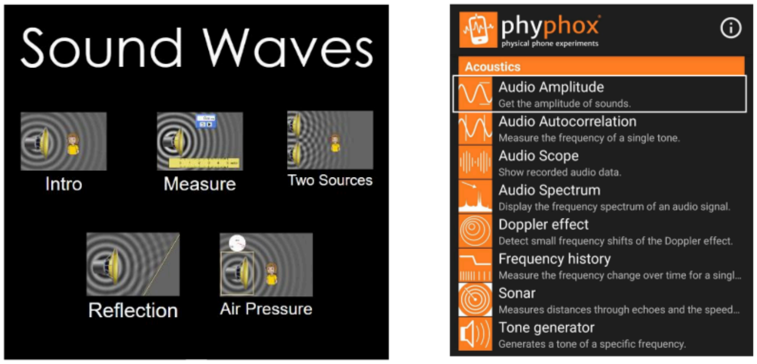
Finally, the study conducted by Fitri (2023) demonstrated that air pressure is closely related to the speed of sound propagation, as pressure affects the particle density within the air medium, thereby influencing how longitudinal waves travel (Fitri, 2023). On the other hand, the wave spreading angle can also alter the direction and intensity of sound wave energy received at different spatial points, although this aspect has not been extensively explored experimentally. Based on theoretical understanding and supported by these findings, an initial hypothesis was formulated that amplitude, frequency, spreading angle, and air pressure simultaneously influence the characteristics of sound waves, including their intensity, propagation speed, and direction of spreading. A review of several other articles suggests that amplitude is believed to play a role in determining the magnitude of sound intensity perceived by the listener.

This study utilized the PhET Simulation platform developed by the University of Colorado to conduct experiments. This simulation media comprises educational materials in physics, chemistry, and biology, and is designed interactively to enable users to learn virtually (Kurniawan et al., 2023). The simulation supports the learning of physics concepts through detailed and interactive visualizations (Ledjab et al., 2024). Besides PhET, another platform that can be employed in this research is Phyphox. Phyphox is an application developed by RWTH Aachen University that allows users to conduct physics experiments using built-in smartphone sensors, such as microphones, accelerometers, magnetometers, gyroscopes, and light sensors (Imtinan & Kuswanto, 2023).

This study aims to examine the simultaneous influence of four physical parameters (amplitude, frequency, dispersion angle, and air pressure) on the characteristics of sound waves, which has not been comprehensively addressed in previous research. It also integrates two digital platforms PhET interactive simulations and the Phyphox application which enable real-time visualization of wave patterns and experimental data measurement using smartphone sensors. Moreover, the dispersion angle, which has rarely been explored, is analyzed in the context of wave propagation direction and intensity, thereby providing a new contribution to digital media-based acoustic studies.

METHOD

This study employs a quantitative approach with an experimental design to analyze the effects of amplitude, frequency, dispersion angle, and air pressure on the characteristics of sound waves using PhET simulations (Eka, 2023). The quantitative approach in this research refers to the use of numerical data generated from experiments to measure, analyze, and test the relationships among variables involved in the physical phenomenon of sound waves (Widyastuti et al., 2024). Through this approach, the study aims to produce data that can be statistically analyzed to identify patterns or trends that may exist in changes to sound wave characteristics. PhET simulations were chosen for their ability to provide a clear visual representation of the interactions between these physical factors, allowing researchers to directly manipulate variables and observe the outcomes in a controlled and interactive environment. This approach offers an opportunity to explore complex acoustic phenomena, measure the mathematical relationships among these variables, and obtain data that can be used to deepen understanding of the behavior of sound waves under various physical conditions.



(a) (b)

Figure 1. Application Interface. (a) *Sound Wave* experiment on PhET Simulation and (b) *Audio Amplitude Experiment* on the Phyphox application

The experiment begins by opening the "Sound" simulation on the PhET website, which is designed to test various factors that affect the characteristics of sound waves. In this experiment, the Phyphox application is used to help measure the amplitude of the produced sound. The use of Phyphox in the sound wave experiment aims to measure audio amplitude. The PhET simulation is run on a Lenovo Yoga Slim 7i Carbon 13ITL5 laptop, and Phyphox is operated on a Samsung S23 Ultra mobile phone.

In the Sound simulation on PhET Interactive Simulations, the amplitude setting refers to the displacement amplitude of particles in the medium, which is visualized through the vibration of particles around their equilibrium position; the greater the amplitude, the greater the particle displacement. Although it does not directly represent pressure amplitude, this particle displacement is closely related to pressure variations in longitudinal waves, so an increase in displacement amplitude also reflects an increase in pressure amplitude.

First, the experiment analyzes the effect of amplitude and frequency on the intensity of sound waves, conducted at three frequency levels: 600 Hz, 500 Hz, and 400 Hz. The selection of these frequencies is based on the range commonly found in various acoustic phenomena in the surrounding environment, particularly in the context of sound waves used by many organisms for communication and navigation. These frequencies are low enough to allow the waves to travel moderate to long distances without significant absorption, yet remain within a range that is easy to measure and analyze in the simulation. Each frequency is tested with three amplitude categories maximum (1000), medium (550), and minimum (100) to observe changes in the shape and intensity of the resulting sound waves.

Next, the experiment continues by observing the effect of sound waves produced by two adjacent sound sources, focusing on the listener's position relative to the left speaker at distances of 1 cm, center at 3.25 cm, and right at 5.5 cm. Three frequency variations 1000 Hz, 500 Hz, and 250 Hz are tested with three amplitude categories (maximum, medium, and minimum) to observe changes in the characteristics of sound waves at different positions, as illustrated in Figure 2.

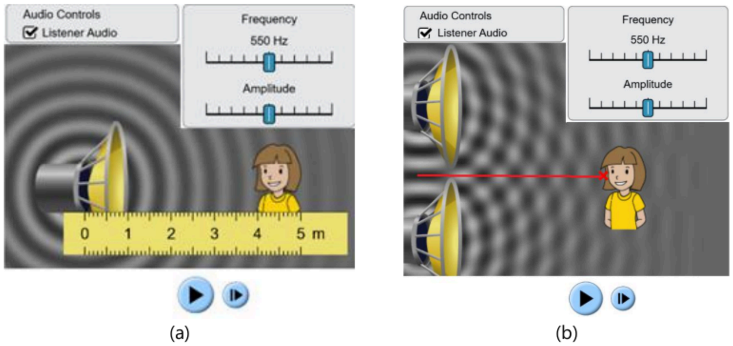


Figure 2. PhET Simulation Experiment Display. (a) Measure single sound, and (b) Measure double sound

Sound measurements were conducted using the Phyphox application through the Audio Amplitude Experiment feature. In this application, sound amplitude is displayed in decibels (dB). The measurements were taken using the microphone sensor, which functions to capture the intensity of the produced sound. Higher decibel values indicate greater sound amplitude, meaning the sound is stronger or louder. Phyphox also provides a real-time visual display, making it easier for users to observe and analyze changes in noise levels or sound intensity during the experiment. The interface of the Audio Amplitude Experiment in Phyphox is shown in Figure 3.

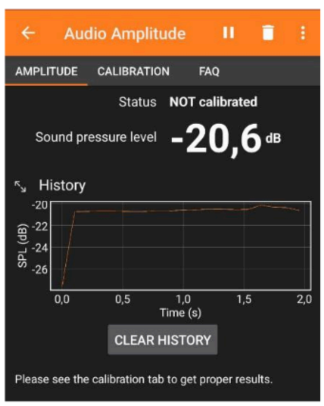
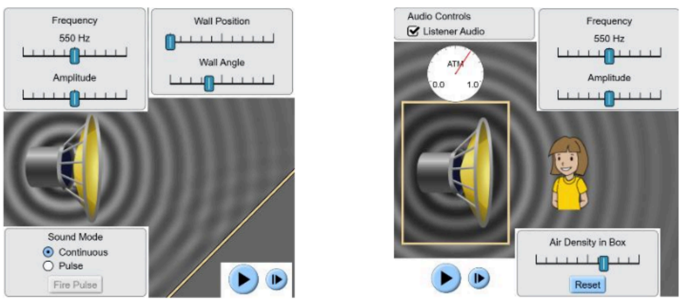


Figure 3. Interface of the Audio Amplitude Experiment in the Phyphox Application

Second, the experiment also analyzes the reflection and interference of sound waves caused by the dispersion angle. Observations were made on the effects of sound waves reflected at three different wall angles: 0°, 45°, and 90°, using a frequency of 500 Hz and three amplitude categories: maximum, medium, and minimum. The experimental setup is shown in Figure 4(a). The observations for maximum and minimum amplitude revealed differences in the patterns and characteristics of the sound waves produced at each of the three angles.

Third, the experiment analyzes the effect of air pressure on the intensity of sound waves by adjusting air pressure under different conditions, ranging from 0.0 atm to 1.0 atm, to observe changes in the speed and strength of the resulting sound waves. The pressure range from 0 to 1 atmosphere is used to demonstrate that the propagation of sound waves requires a medium. A pressure of 1 atm represents normal atmospheric conditions at the Earth's surface, which is ecologically relevant. In contrast, a pressure of 0 atm represents a vacuum in which sound cannot propagate although such conditions do not occur naturally on Earth, they are pedagogically important for understanding the fundamental concept of sound wave propagation. The experimental setup is shown in Figure 4(b). The results of all these experiments provide a deeper understanding of the factors that influence the characteristics of sound waves and their applications in the context of sound theory and technology.



(a) (b)

Figure 4. PhET Simulation Experiment Display. (a) Reflection, and (b) Air Pressure

The data obtained from this experiment were analyzed and presented in the form of graphs to facilitate understanding of the changes in sound wave characteristics influenced by variables such as amplitude, frequency, dispersion angle, and air pressure. Each graph illustrates the relationship between the tested variable and the observation results, such as the graph of sound intensity versus amplitude and the graph of sound intensity versus air pressure. The analysis was conducted by observing the trend of the graph's increase and comparing it with existing theories to determine whether the observations align with theoretical predictions (Muin, 2023). This approach makes it possible to evaluate the consistency between the experimental data and the fundamental principles of physics.

RESULTS AND DISCUSSION

The results of the experiment on the influence of amplitude and frequency on sound intensity at three different measurement distances are plotted in the relationship graphs presented in Figures 4, 5, and 6. Measurements were conducted at frequencies of 400 Hz, 500 Hz, and 600 Hz with amplitude variations ranging from 0.01 m to 0.10 m. The study by Pinochet et al. (2021) has empirically demonstrated that the intensity of a sound wave is directly proportional to the square of its amplitude.

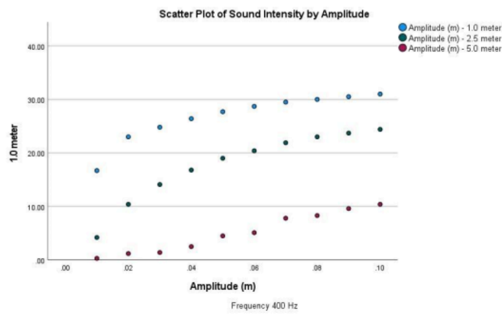


Figure 5. Graph of the Relationship Between Sound Intensity and Amplitude at a Frequency of 400 Hz

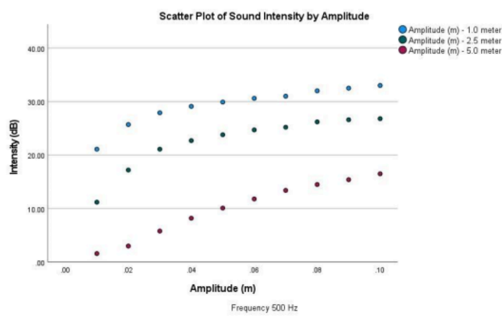


Figure 6. Graph of the Relationship Between Sound Intensity and Amplitude at a Frequency of 500 Hz

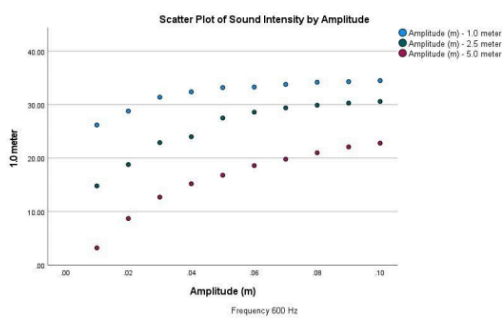


Figure 7. Graph of the Relationship Between Sound Intensity and Amplitude at a Frequency of 600 Hz

Sound intensity (dB) shows a clear positive trend with increasing amplitude for all measurement distances. The rate of dB increase appears steeper at low amplitudes and then slightly levels off at higher amplitudes, especially for the 1.0 m and 2.5 m distances. The 1.0 m distance consistently exhibits the highest dB values, followed by 2.5 m and then 5.0 m which shows the lowest dB values for each specific amplitude. A similar trend is observed at the frequency of 400 Hz, where sound intensity increases with amplitude for all distances. The absolute dB values at 500 Hz tend to be higher compared to 400 Hz for corresponding amplitudes and distances. The absolute dB values at 600 Hz generally produce higher dB levels than those at 400 Hz and 500 Hz for the same amplitude and distance. The leveling-off effect at high amplitudes is also evident. Overall, it is observed that increasing frequency consistently results in higher sound intensity (dB) at all amplitude levels and distances (Pinochet et al., 2021). Furthermore, attenuation of sound intensity due to distance is clearly seen, with stratification of intensity levels based on distance across all tests.

The results of the experiment on the effect of spreading angle on the reflection angle of sound waves are shown in Figure 8. Measurements were conducted at a frequency of 550 Hz with amplitude variations of 0.01 m, 0.05 m, and 0.10 m, and incidence angles of 90°, 45°, and 18°.

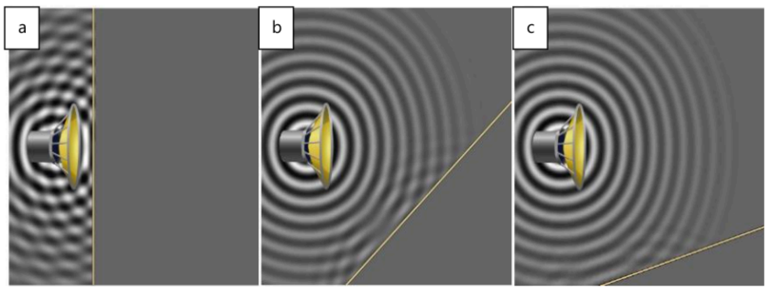


Figure 8. Reflection and Interference of Sound Waves Relative to Spreading Angle. (a) 90° Angle, (b) 45° Angle, (c) 18° Angle

Figure 8a shows waves appearing to radiate from the sound source and reflecting back from a vertical wall. The incident and reflected wavefronts are largely parallel, resulting in a clear superposition. Regions of constructive and destructive interference form a pattern resembling standing waves near the wall. When the wall is tilted, the incident waves strike the wall and reflect at an angle. The reflected waves interact clearly with the subsequent incident waves. The interference pattern is more complex compared to Figure 8b, with different regions of constructive and destructive interference forming an oblique pattern. A wall at a steeper angle produces distinct reflections and interference patterns. The areas of constructive and destructive interference differ from those in Figure 8c, illustrating how the angle of the reflecting surface determines the spatial distribution of the interference field (Zagubień & Wolniewicz, 2024).

The results of the experiment on the effect of air pressure on sound intensity are plotted in the graph presented in Figure 9. Measurements were conducted at a frequency of 550 Hz with amplitude variations of 0.01 m, 0.05 m, and 0.10 m, and air pressure ranging from 0.0 atm to 1.0 atm.

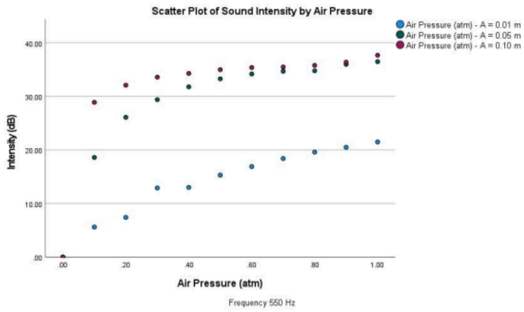


Figure 9. Graph of the Relationship Between Sound Intensity and Air Pressure

Figure 9 shows that for all three amplitude levels, the sound intensity is 0.0 dB at an air pressure of 0.0 atm. As air pressure increases, the sound intensity (dB) rises significantly (Pinochet et al., 2021). The most rapid increase occurs at low pressure levels, after which the rate of increase in dB becomes less steep, although the intensity continues to rise. Higher amplitudes consistently produce higher dB values at every air pressure above zero. This confirms that a medium is necessary for the propagation of sound waves, and the relationship between air pressure and sound intensity (dB) is nonlinear (Costa et al., 2023).

Analysis of the Influence of Amplitude and Frequency on Sound Wave Intensity

The research results show that the sound intensity increases along with the increase in amplitude. This finding aligns with the basic principle that the intensity (I) of a wave is proportional to the square of its amplitude (A). This means that doubling the amplitude results in an increase in intensity (power per unit area) by a factor of four. The decibel (dB) scale is logarithmic and is used to express the ratio between a certain amplitude value and a reference value. The general formula for calculating decibels is:

$$dB = 10log_{10}\frac{P}{P_0} \tag{1}$$

Where P is the power or sound intensity being measured, and P_0 is the reference power or intensity, which is usually the human hearing threshold of 10^{-12} watts per square meter ($watt/m^2$). Sound intensity measurements using the Phyphox application can show both positive and negative values. Positive values ($dB > 0$) indicate that the sound amplitude is greater than the reference value, meaning the sound is loud or strong, such as a car horn reaching around $100\ dB$. A zero value ($dB = 0$) means the sound amplitude is equal to the reference value. This does not mean there is no sound, but rather a very faint sound exactly at the threshold of human hearing. Negative values ($dB < 0$) indicate that the sound amplitude is less than the reference value, meaning the sound is very weak or almost inaudible, like a soft whisper in a very quiet room.

Consequently, although the actual sound energy increases significantly with amplitude, the perceived loudness (related to dB) increases more slowly (Zagubień & Wolniewicz, 2024). The "flattening" phenomenon observed in the dB versus Amplitude graphs (Figures 4, 5, 6) at higher amplitudes is a manifestation of logarithmic scaling (Fajarwati et al., 2023). For example, an increase in intensity from $10^{-6}\,W/m^2$ to $10^{-5}\,W/m^2$ (a tenfold increase) corresponds to a $10\,dB$. However, an increase from $10^{-3}\,W/m^2$ to $2\times10^{-3}\,W/m^2$ (a twofold increase) only corresponds to an increase of about $3\,dB$. This explains why large changes in amplitude at high intensity levels result in smaller dB increases compared to similar proportional changes at low intensity levels (Fajarwati et al., 2023). For instance, if the amplitude is doubled, the intensity increases fourfold, and the change in dB would be:

$$10log(4I_1/I_0) - 10log(I_1/I_0) = 10log(4) \approx 6\,dB \quad (2)$$

The experimental data also show that for a constant amplitude, higher frequencies generally produce higher sound intensities. This is consistent with the theoretical relationship:

$$I = \frac{1}{2}\rho v(\omega s_{max})^2 \quad (3)$$

where $\omega = 2\pi f$ is the angular frequency and s_{max} is the maximum displacement amplitude. If ρ and v is constant (e.g. in air), then $I \propto (\omega s)^2 = (2\pi f s)^2$, armeans that the intensity increases quadratically with frequency and amplitude. For a constant amplitude, the intensity is proportional to the square of the frequency. A higher frequency means more wave cycles passing a point per unit time. If the deviation per cycle (amplitude) is the same, then more cycles mean more energy delivered per unit time, resulting in higher power and intensity (Costa et al., 2023).

Relative value f^2 of each If the frequency value is against 400 Hz as a reference. At 400 Hz, the squared value of the frequency is 400^2=160000, which is normalized to 1.00. At 500 Hz, the squared value of the frequency is 500^2=250000, or about 1.56 times greater than 400 Hz. Meanwhile, for 600 Hz, 600^2=360000, or 2.25 times greater than 400 Hz. However, the PhET simulation results show that the intensity at 600 Hz actually increases more on a linear scale than 400 Hz.

This considerable difference is likely due to several factors. First, although the amplitude is set as "maximum" in the simulation, the particle displacement (s) may not be exactly the same between frequencies. If the value of s at 600 Hz is slightly larger, so its square (s^2) will have a significant impact on the increase in intensity. Secondly, the way waves propagate in the simulation could be affected by the characteristics of the virtual medium, so waves at higher frequencies such as 600 Hz may experience smaller attenuation or a more focused propagation shape, resulting in greater intensity. Thirdly, it is possible that the representation of intensity in the PhET simulation is not completely linear with respect to f^2s^2 instead, it mixes aspects of visualization with audio perception. This can lead to discrepancies between purely mathematical theoretical predictions and visual or numerical results from simulations.

The increase in intensity at 600 hz is more likely to be a result of the prevailing laws of physics, rather than an artifact of the simulation. This is supported by several reasons, firstly consistency with physical theory. Theoretically, the intensity of a sound wave follows the relationship $I \propto f^2s^2$, where intensity is directly proportional to the square of amplitude and the square of frequency. Assuming the amplitude is fixed, an increase in frequency directly leads to an increase in intensity. In this case, the comparison between 600 hz and 400 hz predicts an increase of about 2.25 times, and the direction of the trend is reflected in the simulation results. The two patterns of intensity decrease with distance are reasonable. The data shows that the intensity decreases from near to far positions in a logical manner, following wave propagation principles such as the inverse square law of distance. This shows that the simulation represents the energy propagation process realistically, rather than randomly or erroneously. Third, the stability of values between observation points. The intensities recorded at the near, medium and far points remained consistent at each frequency. Although there were slight fluctuations, there were no noticeable anomalies that would normally indicate numerical noise or graphical errors in the simulation. Fourth, the impact of small amplitude differences on intensity. If there is a small difference in the amplitude of the source at a frequency of 600hz-for example, because the "maximal" visualization setting is not identical across frequencies-then the impact on intensity can be very large, as intensity depends on the square of the amplitude. This may explain why the increase in intensity is higher than the theoretical prediction of f^2 course.

Thus, it can be concluded that the increase in intensity at a frequency of 600 Hz is a logical consequence of the laws of physics, and is influenced by propagation efficiency and possibly small variations in source amplitude.

Analysis of Reflection and Interference of Waves Due to Angle of Propagation

Experimental data consistently show that the angle of incidence is equal to the angle of reflection for various amplithos and angles of incidence. Figure 8 clearly illustrates the wave interference phenomenon resulting from the superposition of incident and reflected sound waves. The incident sound wave travels from the left or right direction, while the reflected wave originating from the surface reflection travels from the opposite direction. When these two waves meet and interact, superposition occurs, which is the fusion of two waves that produces a new wave pattern called a standing wave. In these standing waves, two types of important points are formed, namely nodes and antinodies. Nodes(•) are points along the wave where the amplitude is always zero. This happens because the incident and reflected waves meet each other in opposite phases (180° phase difference), thus canceling each other out(minimum amplitude) a condition known as destructive interference. Destructive interference occurs when $\Delta s = (n + 1/2)\lambda$ where Δs denotes the difference in trajectory between the two waves, λ denotes the wavelength of the sound and n denotes an integer ($n = 1,2,3, \ldots$). In contrast, antinody points are those points where the amplitude of the waves reaches a maximum value. This point is formed when the two waves meet in the same phase, so their amplitudes amplify each other, resulting in constructive interference. Constructive interference occurs when $\Delta s = n\lambda$. The resulting standing wave pattern shows that the distance between two consecutive nodes or two consecutive antinodies is half a wavelength (λ).$\lambda/_2$).

Figure 8a shows clear constructive and destructive interference, forming a pattern that resembles a standing wave. This occurs because the incident and reflected waves travel in directly opposite directions, resulting in fixed points with maximum and minimum deviation. (Mahardhika & Darsono, 2024). Figure 8b and Figure 8c show how changing the angle of the reflecting surface changes the geometry of the interference pattern. The constructive and destructive interference regions are spatially redistributed based on the angle of reflection, creating a more complex pattern of skewed edges. This is because the difference in trajectory between the incident and reflected waves arriving at a particular point changes with the angle of reflectance.

Analysis of the Effect of Air Pressure on Sound Wave Intensity

Experimental results show that the sound intensity is zero at zero air pressure, regardless of the source amplitude. This confirms that sound, as a mechanical wave, requires a medium for propagation. Without air particles to oscillate and transfer energy, sound cannot propagate (Vishnu et al., 2023).

The sound intensity (I) is related to the pressure amplitude of the sound wave (Δp_{sound}), the density of the medium (ρ), and the speed of sound in the medium (v) through the equation:

$$I = \frac{(\Delta p_{sound})^2}{2\rho v} \quad (4)$$

The term ρv is the characteristic acoustic impedance (Z) of the medium. Air pressure is directly related to air density (ρ) assuming constant temperature, through the ideal gas law. As air pressure increases, density increases, resulting in higher acoustic impedance.

The graph in Figure 9 shows that as air pressure increases from zero, sound intensity also rises significantly. This indicates a more efficient energy transfer from the sound source to the medium and through the medium. At very low pressure, the medium is sparse, leading to poor energy transfer. As pressure increases, the medium becomes denser, allowing for better coupling and more effective propagation of sound energy. Sound is a vibration of particles; more particles mean the transfer of vibrational energy is more efficient (Costa et al., 2023). Acoustic impedance represents the medium's resistance to acoustic flow. The data shows intensity increases with pressure, indicating the medium's improved capacity to carry sound energy. A study by Vishnu et al. (2023) on underwater noise emissions, although in a different medium, underscores the importance of the medium's properties in sound generation and propagation.

The observed non-linear increase in dB with rising air pressure (Figure 9) can be attributed to fundamental physics and the logarithmic nature of the dB scale. Even the presence of a small amount of medium initially allows sound propagation, leading to a large relative increase from zero intensity. As pressure (and density) continues to increase, the absolute intensity keeps rising, but the dB increment becomes smaller for equivalent linear changes in pressure, especially if the relationship between pressure and actual intensity itself is non-linear (Pinochet et al., 2021). Research on sound propagation under various atmospheric conditions often considers the effects of pressure, temperature, and humidity on absorption and speed, which in turn influence intensity over distance.

Implications of Research Based on PhET Simulations

Simulation using PhET allows controlled manipulation of variables and visualization of concepts that are difficult to observe directly in traditional laboratories. The effectiveness of PhET in enhancing conceptual understanding has been documented in various studies (Nuryantini et al., 2021). However, PhET simulations are idealizations of real-world conditions. The simulations may not account for all factors affecting sound propagation, such as air turbulence, complex reflections from uneven surfaces, or the full spectrum of atmospheric absorption effects. The representation of wave interactions and medium properties may be simplified. For example, the exact algorithm by which the "amplitude" setting in PhET translates to physical displacement or pressure amplitude, and how "air pressure" affects density and sound speed, might involve underlying assumptions not fully transparent to users. Additionally, the simulation may not include all relevant variables that can influence sound characteristics in real-world scenarios, such as humidity and temperature gradients (Nuryantini et al., 2021).

Advantages of the simulation include its ability to isolate variables and demonstrate core principles. However, this control comes at the cost of potentially oversimplifying the rich acoustic complexities of the real world. PhET aims to effectively teach fundamental concepts by simplifying reality and removing distracting variables (Mahardhika & Darsono, 2024). For example, in reflection simulations, the walls are likely perfect reflectors, and the medium is perfectly homogeneous. In reality, surfaces absorb and scatter sound, and the air exhibits micro variations. This means that although the simulation accurately demonstrates the principles of reflection and interference, precise quantitative results may differ from physical experiments due to real-world imperfections. Findings from the simulation should be understood as illustrations of fundamental concepts, and caution is necessary when directly extrapolating quantitative results to specific and complex real-world applications without further validation (Nuryantini et al., 2021). This research could be expanded by comparing simulation results with physical experiments or more advanced computational acoustic models to assess the degree of idealization within PhET.

CONCLUSION

The research findings show that sound intensity increases non-linearly on the decibel scale with rising amplitude and frequency. Greater amplitude produces higher wave energy, while higher frequency accelerates the rate of energy transfer. In terms of geometry, the angle of reflection is proven to be equal to the angle of incidence, in accordance with the law of reflection, while the dispersion angle influences complex interference patterns resulting from the superposition of incident and reflected waves. An increase in air pressure also leads to a non-linear rise in sound intensity, reinforcing the crucial role of the medium in sound propagation.

The PhET simulation has proven effective in visualizing fundamental acoustic principles but has limitations due to the idealization of physical conditions. Therefore, direct physical experiments, such as using a pressurized chamber to validate the effect of pressure on sound intensity, are recommended to improve the accuracy of results. Furthermore, future studies should consider other environmental variables such as temperature and humidity, as these factors can affect the speed and intensity of sound wave propagation, yet were not covered in this simulation. A combination of simulations, physical experiments, and advanced computational modeling will offer a more comprehensive understanding of acoustic phenomena under real-world conditions.

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