

A NOVEL APPROACH TO MEASURING ACOUSTIC PROPERTIES OF METAL RODS USING SOUND BEAT INTERFERENCE

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Abstract

A novel and simplified method is proposed for measuring the propagation speed of mechanical waves in a metal rod and determining the fundamental frequencies of its standing wave modes. This technique leverages the phenomenon of sound beats, eliminating the need for specialized and costly laboratory equipment. In the experimental setup, a metal rod is securely clamped at its midpoint to function as a mechanical resonator. When one end is percussively struck, a standing wave of longitudinal deformation is excited. A vibrating speaker (4) connected to an audio frequency generator (3) introduces a variable-frequency reference tone, while a piezoelectric sound pickup (1) attached to the rod and connected to an oscilloscope (2) detects the resulting vibrations. Resonance is identified by systematically adjusting the generator frequency until a low-frequency beat signal (typically ≤ 1 Hz) is observed on the oscilloscope, indicating that the external source frequency precisely matches the natural frequency of the rod. At this point, the speed of the acoustic wave within the metal can be accurately calculated using the rod length and the measured resonant frequency. This propagation speed, in turn, enables the calculation of Young's modulus, an important material property. Overall, the method's key benefits lie in its simplicity, accessibility, and high precision in determining the speed of sound.

Keywords: Mechanical waves; Speed of sound in metal; Standing waves

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Introduction

The study of mechanical waves is fundamental to understanding a wide range of physical phenomena, from sound propagation to the behavior of elastic materials. Determining the speed of sound in metals is a classic experiment, but it often requires complex setups involving mechanical generators and sensitive receivers to excite and detect standing waves.

The physics of mechanical waves is central to understanding wave processes and resonators. Traditional laboratory experiments determine the speed of sound in metals by exciting standing waves in a metal bar using mechanical generators. An oscillation receiver placed at the opposite end detects the resonance frequency, which corresponds to the formation of a standing acoustic wave. In this work, we propose a simpler method of determining the frequency of a standing wave by using beats generated from sound waves in air. This approach requires almost no additional equipment and can be implemented quickly and at negligible cost in any physics laboratory.

This paper presents a novel approach that significantly simplifies conventional methods. By exploiting the phenomenon of sound beats, we introduce a technique that requires minimal equipment and setup time. The core principle involves inducing a standing wave in a metal bar and generating audible beats through interference with a variable-frequency sound source. This method provides a practical and accessible alternative to traditional approaches, rendering it suitable for both educational and research purposes (Amiri *et al.*, 2014; Daru *et al.*, 2017; Liu *et al.*, 2022; Yu *et al.*, 2022; Jiang *et al.*, 2023; Yang *et al.*, 2024).

Sound beats and mechanical resonators

Sound beats are periodic fluctuations in loudness that occur when two waves of slightly different frequencies interfere. This phenomenon is described by the following trigonometric expression:

$$y(t) = A \sin(2\pi\nu_1 t) + A \sin(2\pi\nu_2 t) \Rightarrow$$

$$y(t) = 2A \cos\left(2\pi\left(\frac{\nu_1 - \nu_2}{2}\right)t\right) \sin\left(2\pi\left(\frac{\nu_1 + \nu_2}{2}\right)t\right),$$

where:

A: The amplitude of the waves.

ν_1 and ν_2 : The frequencies of the two sound sources.

The resulting signal has a high frequency, equal to the average of the two source frequencies;

however, its amplitude is modulated at a much lower beat frequency, equal to the difference between the source frequencies ($\nu_{beat} = |\nu_1 - \nu_2|$). Beats become audible when the frequency difference is extremely small, typically ≤ 1 Hz.

Mechanical Resonators and Sound Speed

In this study, a metal rod is used as a mechanical resonator. When struck at one end, it generates a standing wave of longitudinal deformations. In this setup, the wavelength (λ) of the standing wave is twice the length of the rod (2ℓ). The speed of sound (ϑ) in the rod is calculated using the following formula:

$$\vartheta = \lambda \cdot \nu = 2\ell \cdot \nu,$$

where:

ϑ : The speed of sound in the metal.

ℓ : The length of the rod.

ν : The frequency of the standing wave, which is determined by matching it to a variable-frequency external sound source to create beats.

By adjusting the source frequency until clear beats are generated by the rod's oscillations, the natural frequency of the rod and thus the speed of sound in the metal can be precisely determined.

Figure 1 shows the dependence of the total sound intensity on time.

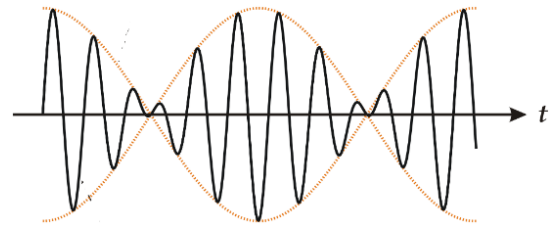


Figure 1. Sound beats As the frequency difference decreases, the period of oscillations in total sound intensity increases

The beat phenomenon is widely used in music, for example, when tuning instruments with a tuning fork, a source of sound with a fixed frequency.

Various acoustic resonators can produce sound at characteristic frequencies. The simplest is a metal bar fixed at its midpoint. When one end is struck, a standing wave of longitudinal deformations forms, with a wavelength equal to twice the bar length (Sadhal, 2012; Danilov and Uryupin, 2023; Guo *et al.*, 2023; Su *et al.*, 2024)

In practice, a tuning fork is also a resonator: although bent at its midpoint unlike a linear bar, it generates transverse waves upon impact rather than longitudinal waves.

Comparison of Sound Speed Measurement Methods

The proposed resonant method is effective and illustrative but differs from more widely used industrial approaches.

Our Method (Resonant Approach)

This method determines the natural frequency of a rod to calculate the speed of sound.

Advantages: Highly visual, easy to implement, and requires inexpensive equipment. It is ideal for educational purposes as it allows direct observation of wave phenomena.

Disadvantages: Less accurate for materials with nonuniform structures, more sensitive to external factors, and unsuitable for short pulses due to dispersion effects.

Ultrasound Pulse Method (Impulse Method)

This is the most common industrial method. It involves sending a short ultrasound pulse into a material and measuring the time it takes to travel a specific distance.

Advantages: Provides high accuracy and speed, with potential for automation. Useful in quality control and defect detection.

Disadvantages: Requires specialized equipment and calibration. Less suitable for teaching, as the wave process is not directly observed.

Interferometry Method

This method uses laser technology to measure the surface displacements of a material caused by a passing sound wave.

Advantages: Offers extremely high accuracy and contactless measurement, and enables investigation of wave propagation on small scales.

Disadvantages: Equipment is expensive and complex, making it impractical for routine industrial or educational use.

In summary, the resonant method provides a reliable, accessible demonstration of fundamental wave phenomena, whereas the more complex industrial techniques are reserved for high-precision measurements in research and quality-control applications.

Description of the Device for Measuring the Speed of Sound in Metal.

The general setup is shown in Figure 2.

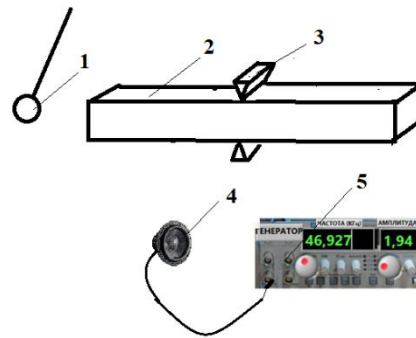


Figure 2. Schematic of the experimental setup for measuring the standing - wave frequency in a metal rod

1. percussion instrument; 2. rod; 3. rod clamp; 4. loudspeaker; 5. sound generator.

Note: 4 and 5 can be replaced by a personal computer (PC) running a variable-frequency sound generator program.

Note: We recommend recording the beats with a high-quality audio recorder (specify sampling rate). Recording allows the beat frequency to be determined with greater precision during offline analysis.

Materials and Methods

A metal rod is clamped at its midpoint, a vibrating speaker (4 Ω , 25 W) is attached to one end, and a piezodriver (sound pickup) is attached to the other. The text correctly states that the goal is to induce sound beats with a frequency of approximately 1 Hz by adjusting the generator frequency. The method for determining the natural frequency of the rod (v_{bar}) using the beat frequency (v_{beat}) and generator frequency (v_g) is correctly presented: $v_{\text{bar}} = v_g \pm 2v_{\text{beat}}$.

For the convenience of our experiment, we replaced items 4 and 3 (Figure 3) with a sound pickup (a piezodriver) and a vibrating speaker (specified as 4 Ω and 25 W).

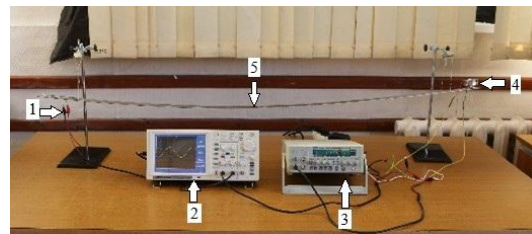


Figure 3. Experimental Equipment Diagram.

1. sound pickup (piezodriver); 2. oscilloscope; 3. audio frequency generator; 4. vibrating speaker (4 Ω , 25 W); 5. rod

Experimental Data

We determined the natural frequency of the rod using a sound pickup (piezodriver) connected to an oscilloscope and by observing beats produced at the opposite end of the rod. The measured natural beat frequency was approximately 1700 Hz. Subsequently, we attached a vibrating speaker to one end of the rod. This speaker was connected to an audio frequency generator operating in the range of 1200–3500 Hz. A sound pickup (piezodriver) was connected to the other end of the rod and, in turn, to the oscilloscope's second channel. By setting the generator to the rod's natural frequency and observing the oscilloscope trace, we detected the standing wave. Using the rod length together with the measured standing-wave frequency, we calculated the speed of sound in the rod and thereby determined the Young's modulus.

The frequency of vibrations of the bar is determined according to the formula:

$$v_{\text{bar}} = v_g \pm 2v_{\text{beat}}$$

The plus sign corresponds to the case when the frequency search begins at lower frequencies, whereas the minus sign applies when the search begins at higher frequencies.

Calculations and Analysis

The speed of sound in metal is determined by the following formulas:

$$\begin{aligned} \vartheta &= 2\ell_{\text{beat}} \cdot v_{\text{beat}}, \\ \vartheta &= 2 \cdot 1.4 \text{ m} \cdot 1725 \frac{1}{\text{s}} = 4830 \frac{\text{m}}{\text{s}}, \end{aligned}$$

where: $\ell_{\text{beat}} = 1.4 \text{ m}$ and $v_{\text{beat}} = 1725 \frac{1}{\text{s}} (\text{Hz})$.

With the experimentally determined density $\rho = 2213.5 \text{ kg/m}^3$, we calculate Young's modulus (E).

The density of the rod is determined by the formula:

$$\rho = \frac{m}{V},$$

where m is the mass and V is the volume of the rod.

The formula for Young's modulus is

$$E = \rho \vartheta^2,$$

where the experimental density of the rod is $\rho = 2213.5 \text{ kg/m}^3$. Substituting the numerical values yields:

$$\begin{aligned} E &= \left(4830^2 \frac{\text{m}^2}{\text{s}^2}\right) \cdot \left(2213.5 \frac{\text{kg}}{\text{m}^3}\right), \\ E &\approx 51.6 \text{ GPa} \end{aligned}$$

Repeatability and Measurement Uncertainty

Table 1 presents several sound speed measurements using $\vartheta = 2\ell_{\text{beat}} \cdot v_{\text{beat}}$

As shown in Table 1, the calculated Young's modulus values vary substantially depending on the measured frequency. Therefore, the resonant method is most reliable when the fundamental natural frequency (1725 Hz) is correctly identified; at that point, the calculated speed and Young's modulus are most trustworthy, whereas measurements at other frequencies exhibit lower repeatability due to measurement uncertainty.

Calculation of Deviation

The average theoretical value, based on the range of 4920–5180 m/s, is $(4920+5180)/2 = 5050 \text{ m/s}$.

The experimental value is 4830 m/s.

Thus, the deviation is calculated using the formula:

$$\begin{aligned} \text{Deviation}(\%) &= \frac{|\text{Experimental Value} - \text{Average Theoretical Value}|}{\text{Average Theoretical Value}} \times 100\% \\ &= \frac{|4830 - 5050|}{5050} \times 100\% \\ &\approx 4.36\%. \end{aligned}$$

Table 1. Repeatable and Uncertain Measurements

Number of Measurements	ℓ - Rod Length, m	v - Rod Frequency, (Hz = $\frac{1}{\text{s}}$)	Rod Sound Speed, $\vartheta = 2\ell \cdot v$, m/s	Young's modulus, GPa
1	1.4	1427	3995.6	35.33
2	1.4	1711	4790.8	50.84
3	1.4	1725	4830.0	51.64
4	1.4	2006	5616.8	69.85
5	1.4	2291	6414.8	91.07
6	1.4	2881	8866.8	144.1
7	1.4	3497	9791.6	212.0

A deeper analysis of the calculated Young's modulus values reveals a significant discrepancy between the experimental results and expected theoretical values for aluminum. The wide range of computed Young's moduli (35.34 GPa to 212.22 GPa) demonstrates that the method's accuracy depends strongly on correctly identifying the fundamental resonant frequency.

The Young's modulus values closest to the standard range for aluminum alloys (69-72 GPa) originate from measurements at the higher frequencies (2006 Hz, 2291 Hz, 2881 Hz, and 3497 Hz). However, the measurement at 1725 Hz is identified as the fundamental natural frequency and thus is considered the most reliable. The Young's modulus obtained at 1725 Hz, 51.6 GPa, is lower than typical values for aluminum alloys; this discrepancy is attributed to the measured sample density ($2213.5 \text{ kg}\cdot\text{m}^{-3}$), which differs from standard aluminum densities, rather than to an inherent flaw in the resonant method.

This analysis underscores two key conclusions about the experiment.

The Method's Strength: The resonant technique is reliable for characterizing a specific sample; when the fundamental resonant frequency is identified precisely, the approach yields a consistent and reproducible Young's modulus for that sample.

The Method's Limitation: Low repeatability at higher frequencies indicates that correctly identifying resonant frequencies becomes more difficult as frequency increases, a difficulty that is likely caused by dispersion and other external factors that contribute to measurement uncertainty.

Consequently, the broad range of calculated Young's moduli should not be interpreted as a failure of the method; rather, it illustrates the method's sensitivity and highlights the essential requirement of correctly determining the fundamental resonant frequency. Overall, the analysis confirms that the resonant method is a valuable pedagogical tool for teaching the scientific process of data collection, analysis, and error evaluation.

Standing waves in the rod

In our experiment, a standing wave is generated in a metallic rod using a resonant method. Thus, the observed motion is not a single traveling wave but a persistent wave pattern that is repeatedly reflected at the rod ends. At a specific frequency, the reflected waves interfere constructively with the incident waves, producing a stable standing-wave pattern.

Figure 4, which depicts a standing wave at 1725 Hz, illustrates the rod in a resonant state.

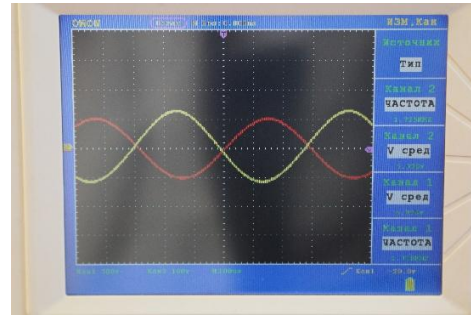


Figure 4. Standing Waves at a Frequency of 1725 Hz.

This frequency corresponds to one of the rod's natural frequencies. At resonance, the rod length equals an integer multiple of one-half wavelength, which permits the formation of the standing wave. By measuring the resonant frequency and the rod length, one can calculate the speed of sound in the metal using $v = \lambda \cdot \nu$, where v is the speed of sound, λ is the wavelength, and ν is the frequency.

In this experiment, the rod length corresponds to a specific number of half-wavelengths; therefore, measuring the rod length and the resonant frequency (1725 Hz) yields the speed of sound in the metal. The resonant method thus provides an elegant means to translate the physical phenomenon of standing waves into a measurable material property, namely the speed of sound (Abrahamyan *et al.*, 2022; Marques and Rodrigues, 2023; Perepelkin *et al.*, 2024; Vatulyan and Yurov, 2025).

Results and Discussion

The experimental setup is straightforward. A metal rod with a length of 1.4 m is fixed in a clamp at both ends with a rope to act as a resonator, and the rod is struck at one end to induce a standing wave. A vibrating speaker, connected to an audio-frequency generator, is used as a variable-frequency sound source. A separate sound pickup (a piezo driver) attached to the rod is used to detect the resulting vibrations. By adjusting the generator frequency, distinct sound beats are produced on the oscilloscope, indicating that the vibrating speaker frequency matches the natural frequency of the standing wave in the rod. The fundamental natural frequency of the rod was determined to be 1725 Hz,

which corresponds to a speed of sound of 4,830 m/s obtained using the formula $\vartheta = 2\ell v$. Using the measured experimental density value of $\rho = 2213.5 \text{ kg}\cdot\text{m}^{-3}$, Young's modulus (E) was calculated as:

$$E = \rho \vartheta^2 \approx 51.6 \text{ GPa}$$

Analysis of Discrepancies and Sources of Error

The calculated Young's modulus of 51.6 GPa is below the reference value for most aluminum alloys, which typically ranges from 69 GPa to 72 GPa. The discrepancy between the experimental results and the standard theoretical range was significant. The deviation in the speed of sound relative to the average theoretical value of 5,050 m/s was calculated to be 4.36%. However, for aluminum alloys, the calculated Young's modulus of 51.6 GPa exhibits a greater deviation of 23.9% relative to the standard theoretical values. This large deviation is primarily attributed to the inaccurate initial data, specifically the experimentally measured density of the material (2213.5 kg/m^3), which is lower than the standard value for aluminum (2900 kg/m^3). This low experimental density value is considered the reason for the calculated Young's modulus value being below the standard reference values.

The analysis confirms the reliability of the proposed method for determining the characteristics of the specific tested sample, rather than the averaged reference values, provided that the fundamental resonant frequency is correctly identified. Other sources of error include the limitations of the theoretical model, which do not account for the dispersion effect (where the sound speed depends on the frequency of short pulses).

Comparison with Reference Values

Our calculated Young's modulus of 51.6 GPa is below the reference values for most aluminum alloys (69-72 GPa). This discrepancy is explained by the low density determined during the experiment. We maintain that our approach calculating Young's modulus from experimental measurements is reliable because it characterizes the specific sample rather than relying on averaged reference values.

Assessment of Repeatability and Measurement Uncertainty

To assess the repeatability, a series of measurements was conducted across a wide range of frequencies (Table 1). The calculated Young's modulus values varied widely, from 35.33 GPa to 212.0 GPa, indicating that the method's accuracy is

highly dependent on the correct identification of the fundamental resonant frequency.

Only the sound speed of 4830 m/s, corresponding to the fundamental natural frequency of the rod (1725 Hz), was within a reasonable range, close to the theoretical value, indicating the reliability of the method when applied to the fundamental frequency. The significant scatter of the other obtained values underscores the presence of uncertainty related to the difficulty of precisely determining the higher resonant frequencies. This reinforces the importance of properly identifying the fundamental resonant frequency using this method.

Key Concepts:

Mechanical waves: Disturbances that travel through a medium, transferring energy without net particle movement; in this study, the focus is on sound waves in a metal rod.

Speed of sound: The distance travelled per unit time by a sound wave through a medium.

Standing waves: Waves that remain at fixed positions over time as a result of the interference of two waves traveling in opposite directions.

Young's modulus: A measure of a material's stiffness that relates stress (force per unit area) to the resulting strain (proportional deformation).

Beats: Periodic variations in amplitude that result from the superposition of two waves with slightly different frequencies.

Method Overview.

Create a standing wave in a metal rod: By striking the rod at its midpoint, a standing wave is produced.

Generate a variable-frequency sound: A loudspeaker produces a sound wave with an adjustable frequency.

Detect beats: By tuning the loudspeaker frequency, the frequencies of the rod's standing wave and the airborne sound can be made to interfere, producing audible beats.

Calculate the speed of sound: Using the rod length and the beat frequency, the speed of sound in the metal can be determined.

Determine Young's modulus: Once the sound speed is known, Young's modulus can be calculated from the relationship between sound speed, density, and elastic modulus.

Advantages of the method:

Simplicity: The method requires minimal equipment.

Accuracy: The method can provide precise measurements of the speed of sound under controlled experimental conditions.

In essence, this method offers a straightforward and effective way to measure the speed of sound in metals, which can then be used to calculate important material properties such as Young's modulus. The technique leverages the principles of wave mechanics and the phenomenon of beats to obtain accurate results when experimental conditions and sample properties are well controlled.

Possible Industrial or Educational Applications

Our model has several potential industrial and educational applications.

Industrial Applications: The method can be adapted for rapid, nondestructive material quality control; changes in sound speed may indicate internal defects, making the technique useful for defect detection in manufacturing

Educational Applications: The method is an excellent tool for visually demonstrating fundamental physical laws, such as the relationship among speed of sound, Young's modulus, and density. Moreover, the experiment enables students to observe wave phenomena such as standing waves, resonance, and beats, and the analysis of discrepancies between experimental and theoretical results provides a practical exercise in data analysis and critical thinking.

Conclusions

This study successfully demonstrated the feasibility of a simple, accessible method to measure the speed of sound in a metal rod and to calculate its Young's modulus. By exploiting the principle of sound beats, the method enabled precise determination of the rod's natural frequency, a key parameter for computing sound speed. Its primary strength lies in simplicity and low cost, which render the method an excellent pedagogical tool.

However, a thorough analysis of the experimental data revealed significant limitations and sources of error. The calculated Young's modulus exhibited a considerable deviation of 23.9% from standard theoretical values for aluminum alloys; this discrepancy was primarily attributable to the nonstandard density of the experimental sample. This finding underscored that, although the method reliably characterized a specific specimen, its results may not coincide with averaged theoretical values. Given this limitation, critical data analysis is essential when comparing experimental outcomes with established norms. Overall, the study contributes to a deeper understanding of mechanical-wave propagation and

provides a solid foundation for future investigations in acoustics and materials science.

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