Speed of sound experiments

This page presents an undergraduate project for measuring the speed of sound in air as a function of air temperature. The measurement is implemented in two versions. The simplicity of the basic experiment in dry air is used for a detailed analysis of systematic errors: the measured values are corrected with an additive constant and optimized to match the expected parabolic dependence of the speed of sound on temperature. In the second version the measurement is performed in air saturated with water vapour. The difference between the two data sets is used to determine the saturation vapour pressure of water as a function of temperature. The project demonstrates how systematic errors are identified and corrected, and how one simple experiment can connect acoustics with thermodynamics.[1]

Attribution: this resource was created by Harold Foppele.

Subject classification: this is a physics resource.

Type classification: this is a quiz resource.

Type classification: this resource is a learning project.

From speed of sound to vapour pressure

Introduction

The speed of sound in air is a classic undergraduate experiment, typically performed using a resonance tube with a tuning fork or speaker/microphone setup. This project extends the basic experiment by:

- Performing precise measurements in dry air to analyse and correct systematic errors (primarily end correction).[1]
- Repeating measurements in humid (saturated) air at 100% relative humidity.[1]
- Deriving the saturation vapour pressure of water from the observed increase in sound speed.[1]

The goal is pedagogical: to teach systematic error analysis, data fitting, and interdisciplinary connections between wave physics (acoustics) and thermodynamics (ideal gas law and vapour pressure).[1]

FA-18 Hornet breaking sound barrier (7 July 1999)

Theory

The speed of sound in an ideal gas is given by $c = \sqrt{\frac{\gamma RT}{M}}$ where γ is the adiabatic index (C_p/C_v), R is the universal gas constant, T is the absolute temperature in kelvin, and M is the average molar mass.

$c \approx 331 + 0.6t$ m/s where t is temperature in °C. More accurately, plotting c^2 vs T produces a straight line: $c^2 = \frac{\gamma R}{M} T$[1]

Moist air

In moist air the effective molar mass decreases because water vapour ($M_{H_2O} = 18.02$ g/mol) is lighter than dry air. At saturation the mole fraction of water vapour is $x = \frac{p_v(T)}{P}$ where $p_v(T)$ is the saturation vapour pressure and P is total pressure. The mixture molar mass becomes $M_{mix} = (1-x)M_{dry} + xM_{H_2O}$ and the adiabatic index is approximately $\gamma_{mix} \approx \frac{(1-x)C_{p,dry} + xC_{p,H_2O}}{(1-x)C_{v,dry} + xC_{v,H_2O}}$ The reduction in M_{mix} dominates, causing c to increase. The resulting increase allows solving for $p_v(T)$.[1]

Materials

- Resonance tube (glass or PVC, length 0.8–1.2 m, inner diameter 3–5 cm)
- Loudspeaker or tuning fork (~400–1000 Hz)
- Microphone or sound sensor
- Digital thermometer with wet-bulb and dry-bulb
- Ruler/metre scale
- Distilled water
- Air bubbler or pump
- Frequency generator or app

Procedure

1. Assemble the resonance tube vertically.
2. Measure atmospheric pressure and temperature.
3. Perform dry air measurements at different temperatures.
4. Calculate and correct for end correction.
5. Saturate the air and repeat measurements.
6. Derive vapour pressure from Δc.
7. Analyse data and compare with literature.[1]

Graphs and plots

1. c^2 versus T for dry air (straight line after end correction)

$c^2 = \frac{\gamma R}{M} T$ (linear)

Explanation: This graph is meant to show the theoretical linear relationship between the square of the speed of sound (c^2) and absolute temperature (T in Kelvin) for dry air.[1]

M

a straight line through the origin with slope = γR/M ≈ 401.9 m² s⁻² K⁻¹ for dry air.

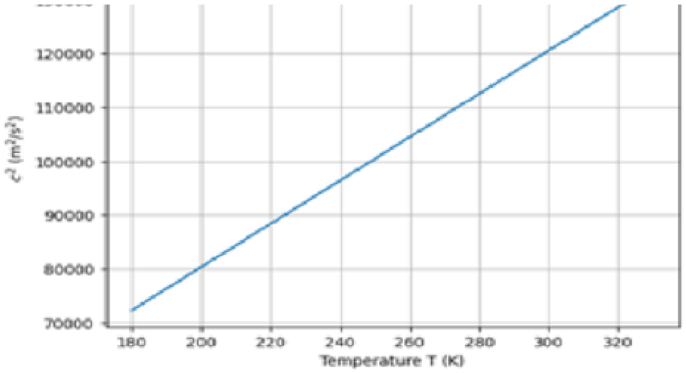
This linearization is much better than plotting c vs T (which is slightly curved). In the experiment, students measure apparent c values, apply an end correction, and use least-squares fitting to make the data fall on this straight line.[1]

2. c versus T for dry and humid air

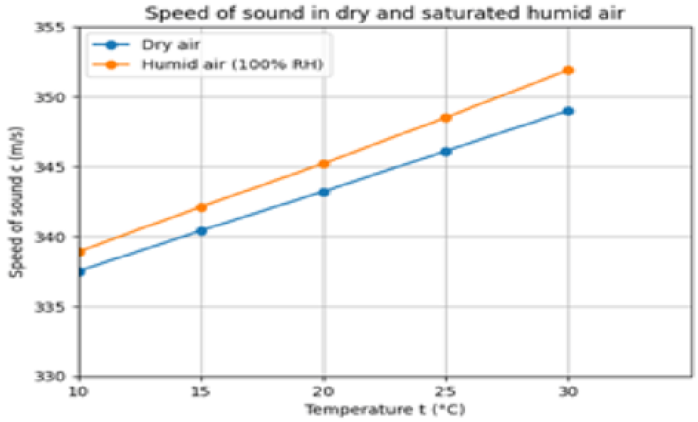
This graph compares the measured speed of sound in dry air (blue) and in air fully saturated with water vapour (orange) across a typical laboratory temperature range (10–30 °C).[1]

The speed increases approximately linearly with temperature in both cases, following the relation $c \approx 331 + 0.6t$ (where t is temperature in °C).

The key observation is that the speed of sound is consistently higher in humid air by 1–3 m/s in this range. This increase occurs because water vapour ($M_{H_2O} = 18$ g/mol) has a lower molar mass than dry air ($M_{dry} \approx 29$ g/mol), reducing the effective molar mass M in the ideal gas formula $c = \sqrt{\frac{\gamma RT}{M}}$. The change in the adiabatic index γ is smaller and has a lesser effect.



c² versus absolute temperature T for dry air (theoretical relationship). The plot shows the expected linear relationship between the square of the speed of sound and absolute temperature after applying the end correction.



Data points from resonance tube measurements at 10–30 °C

Speed of sound versus temperature in dry air and saturated humid air (100% relative humidity)

The difference $\Delta c = c_{\text{humid}} - c_{\text{dry}}$ increases with temperature because the saturation vapour pressure (and thus the mole fraction of water vapour) rises rapidly with temperature. This measured $\Delta c(T)$ is later used to calculate the saturation vapour pressure $p_v(T)$.[1]

3. Δc versus T (increasing with temperature)

This graph shows the measured increase in the speed of sound $\Delta c = c_{\text{humid}} - c_{\text{dry}}$ when the air in the resonance tube is fully saturated with water vapour (100% relative humidity) compared to dry air.[1]

The difference Δc is positive and increases with temperature because the saturation vapour pressure $p_v(T)$ rises rapidly (exponentially) with temperature. This leads to a higher mole fraction $x = \frac{p_v(T)}{P}$ of water vapour (lower molar mass) in the gas mixture at higher temperatures.

the reduction in the effective molar mass M_{mix}, causing a larger increase in c at higher T.

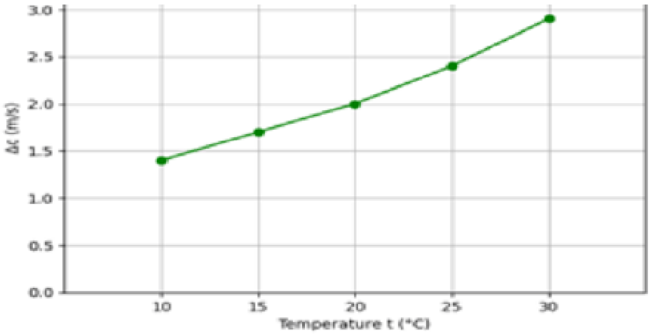
These $\Delta c(T)$ values are used in the next step to solve numerically for the saturation vapour pressure $p_v(T)$, which is then compared to literature values from the Antoine equation.[1]

4. $p_v(T)$ experimental vs Antoine equation

$p_v(T)$ (hPa) This graph presents the saturation vapour pressure of water $p_v(T)$ calculated from the measured speed difference $\Delta c = c_{\text{humid}} - c_{\text{dry}}$ using the mixture model for moist air.[1]

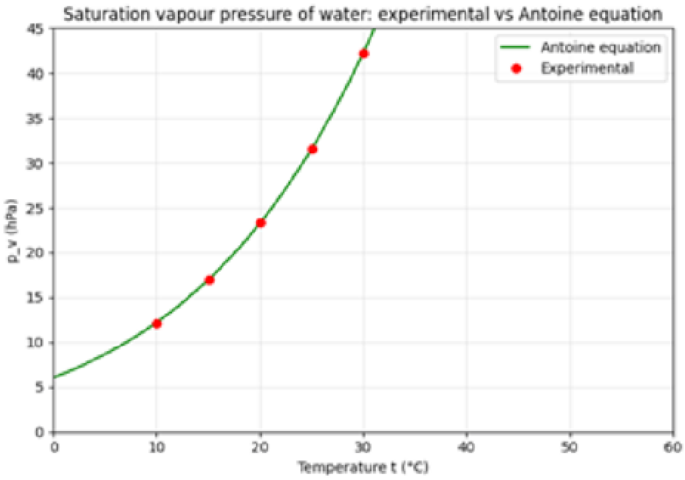
The red points are the experimental values obtained by solving $\left(\frac{c_{\text{humid}}}{c_{\text{dry}}}\right)^2 \approx \frac{\gamma_{\text{mix}}}{\gamma_{\text{dry}}} \cdot \frac{M_{\text{dry}}}{M_{\text{mix}}}$ numerically for the mole fraction x, followed by $p_v(T) = x \cdot P$ (where P is atmospheric pressure).

The green curve is the standard literature values from the Antoine equation. The close agreement between experimental points and the Antoine curve demonstrates the success of the method: a simple acoustic measurement in a resonance tube can accurately determine thermodynamic properties like saturation vapour pressure without specialised equipment.[1]



Increase in speed of sound $\Delta c = c_{\text{humid}} - c_{\text{dry}}$ due to saturation humidity (100% relative humidity) versus temperature t (°C).

Increase in speed of sound $\Delta c = c_{\text{humid}} - c_{\text{dry}}$ due to saturation humidity (100% relative humidity) versus temperature t (°C). Example data from resonance tube measurements.



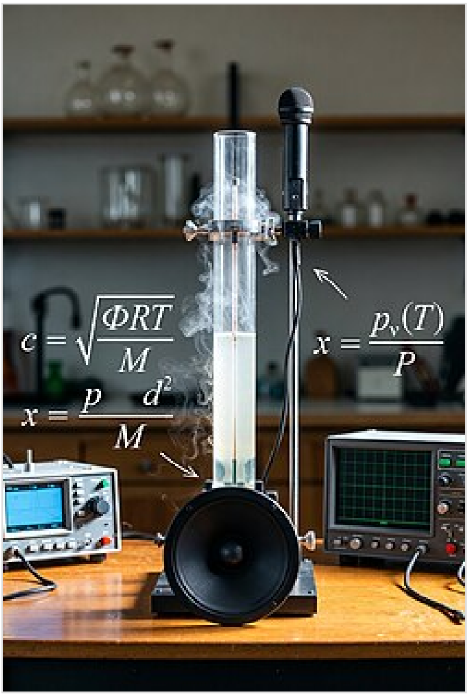
Saturation vapour pressure of water: experimental values derived from speed difference measurements (red points) versus the Antoine equation (green curve).

Saturation vapour pressure of water: experimental values derived from speed difference measurements (red points) versus the Antoine equation (green curve).

Minor deviations are attributable to approximations in γ_{mix}, incomplete saturation, or small measurement uncertainties.

Dry air measurements and systematic error analysis

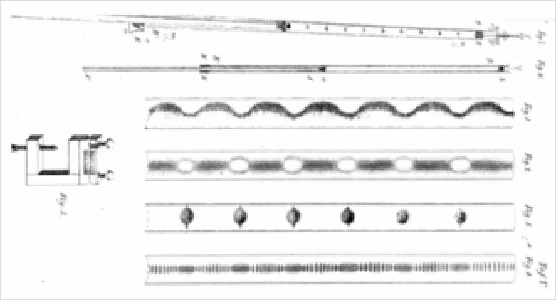
Resonance frequencies f_n are measured at several temperatures. The apparent speed of sound is calculated from $f_n = \frac{nc}{4(L+e)}$ (closed tube, odd harmonics) where e is the end correction (~0.3–0.6 × radius). Without correction, data deviate systematically from theory. An additive constant Δc (or fitted e) is introduced. Least-squares optimisation aligns $c^2(T)$ with the theoretical straight line to find the best-fit end correction.[1]



Resonance tube setup for determining saturation vapour pressure via sound speed

Humid air measurements and vapour pressure derivation

The experiment is repeated with saturated air at the same temperatures. The increase $\Delta c(T) = c_{humid} - c_{dry}$ is measured. Using the ratio $\left(\frac{c_{humid}}{c_{dry}}\right)^2 \approx \frac{\gamma_{mix}}{\gamma_{dry}} \cdot \frac{M_{dry}}{M_{mix}}$ one solves numerically for x, then $p_v(T) = xP$ Results are compared with literature values (Antoine equation) and show good agreement after corrections.[1]



Kundt's tube setup for measuring speed of sound

Results

Example data[1]

Temperature (°C)	c_{dry} (m/s)	c_{humid} (m/s)	Δc (m/s)	Measured p_v (hPa)	Literature p_v (hPa)
10	337.5	338.9	1.4	12.1	12.3
15	340.4	342.1	1.7	17.0	17.0
20	343.2	345.2	2.0	23.3	23.4
25	346.1	348.5	2.4	31.6	31.7
30	349.0	351.9	2.9	42.3	42.4

Discussion

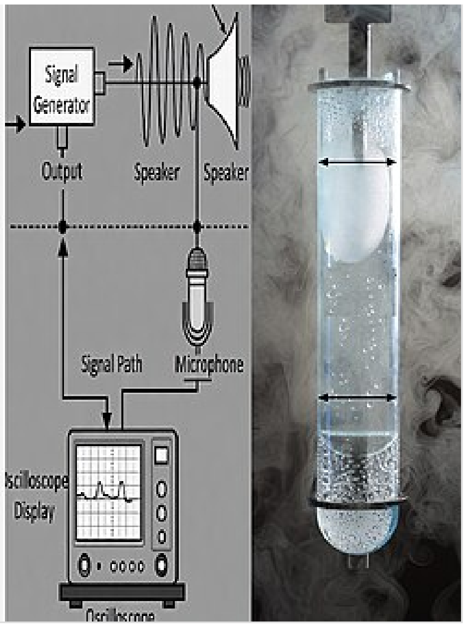
The project illustrates how a single low-cost setup can:

- Teach detailed error analysis (random vs. systematic, end correction as additive offset).
- Link acoustics to thermodynamics via humidity effects.
- Provide quantitative results for vapour pressure without specialised equipment.[1]

- End correction variation with frequency and temperature
- Temperature gradients in the tube
- Incomplete saturation
- Ideal gas assumption
- Measurement precision (±0.1 °C, ±0.5 Hz)[1]

Sound speed in water

The speed of sound in liquid water is significantly higher than in air (typically 1480–1700 m/s compared to ~340 m/s in air at room temperature). It depends strongly on both temperature and pressure.[2]

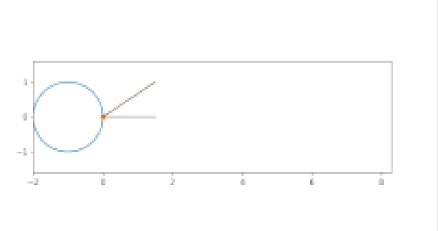


Schematic speed of sound test device

The SOFAR Channel

The **SOFAR channel** (Sound Fixing And Ranging) is a natural acoustic waveguide in the ocean formed by a minimum in sound speed at intermediate depths.[3][4]

Formation and ray paths



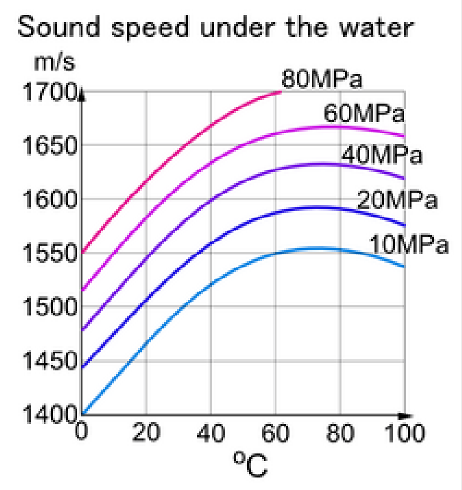
Sine cosine unit circle

Sound speed in seawater is influenced by three main factors:

- Temperature (dominant in upper layers)
- Salinity
- Pressure (increases with depth)

Typical vertical profile:

- Surface layer: warm water → high sound speed (~1530 m/s)
- Thermocline: rapid cooling → sound speed decreases sharply
- Minimum sound speed layer: ~800–1200 m depth (~1480 m/s)
- Deep water (>1200 m): increasing pressure → sound speed rises again[5]



Sound speed under water

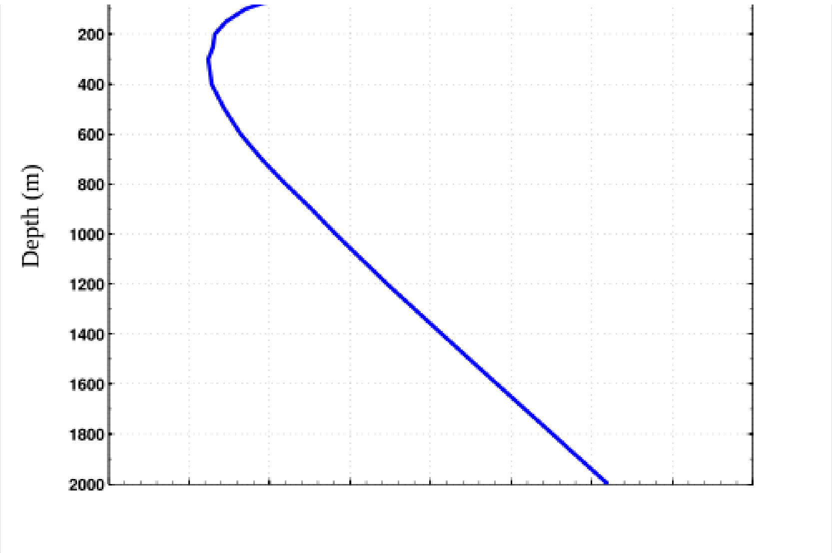
Refraction and Snell's Law

Sound rays bend according to **Snell's law**: $\frac{\sin\theta_1}{c_1} = \frac{\sin\theta_2}{c_2}$ When sound enters a region of lower speed, it bends toward the normal (like light in glass). Rays that enter the SOFAR channel at shallow angles are repeatedly refracted back toward the channel axis, trapping the sound energy.[5]

Frequency dependence

- Low-frequency sounds (< 100 Hz) travel the farthest (up to 3000–5000 km) because they suffer less absorption.
- Higher frequencies attenuate much faster due to viscous and thermal losses.

100 Hz.



Typical sound speed profile in the ocean showing the SOFAR channel.

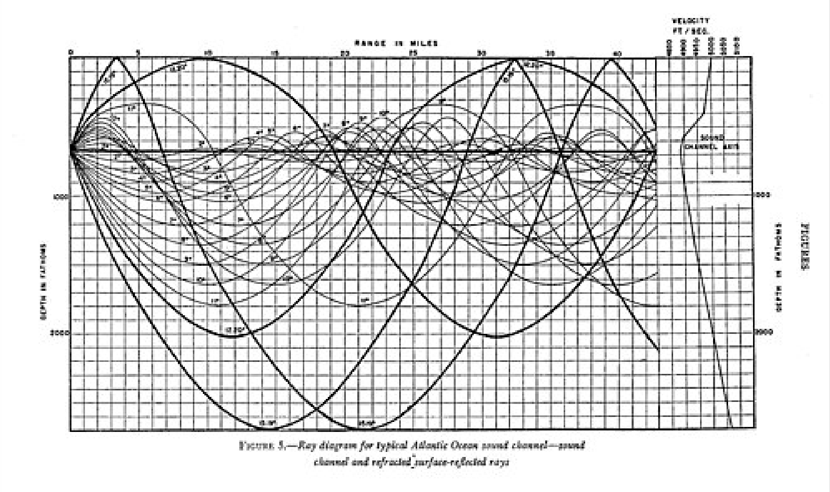
Marine mammal use

Many whales and dolphins use the SOFAR channel for long-distance communication:

- Blue whales and fin whales produce very low-frequency calls (15–40 Hz)
- These calls can be detected thousands of kilometres away
- Humpback whales may also exploit the channel for migration and mating calls[4]

Historical and modern applications

- WWII / Cold War: SOFAR bombs for locating downed pilots and submarines
- Ocean acoustic tomography: mapping ocean temperature and currents on a global scale
- Climate monitoring: tracking ocean warming through changes in sound speed
- Marine mammal tracking and conservation[4]



Sound ray paths trapped in the SOFAR channel. Sound waves are refracted back toward the axis of minimum sound speed.

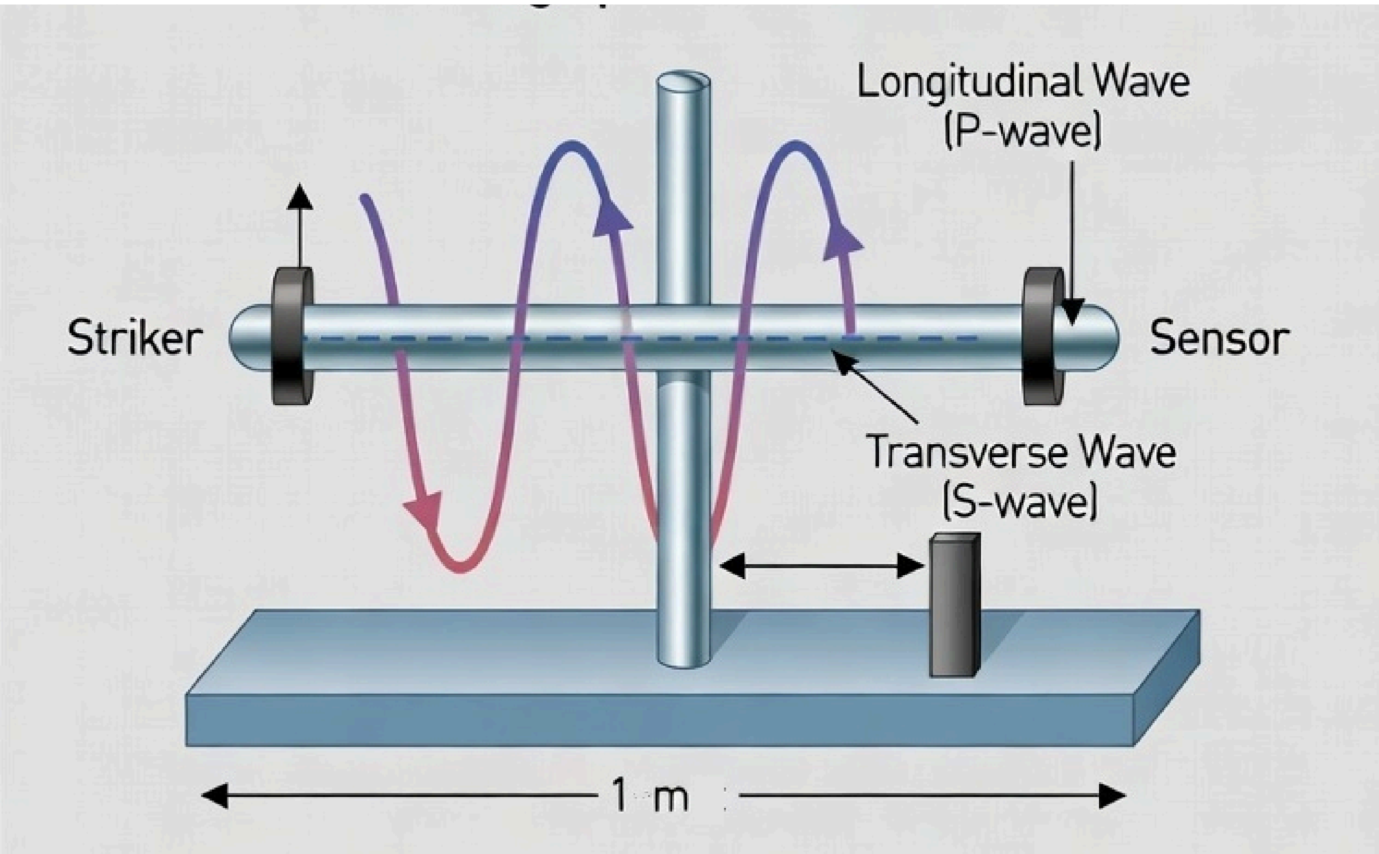
Safety notes

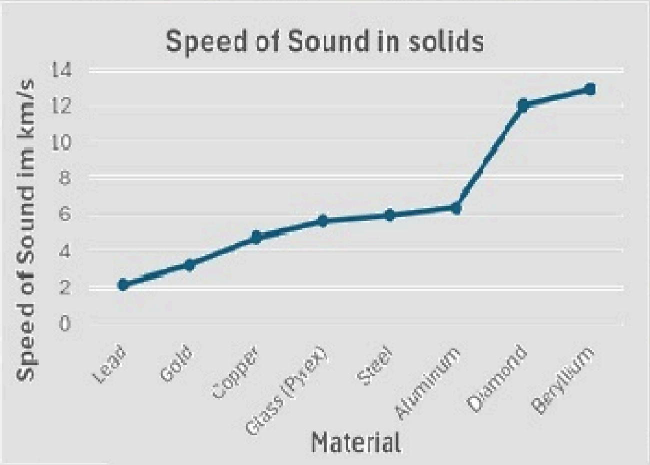
- Use only low-volume sound levels to protect hearing.
- Handle glass tubes carefully to avoid breakage.
- Use distilled water only.
- Ensure electrical equipment is properly grounded.

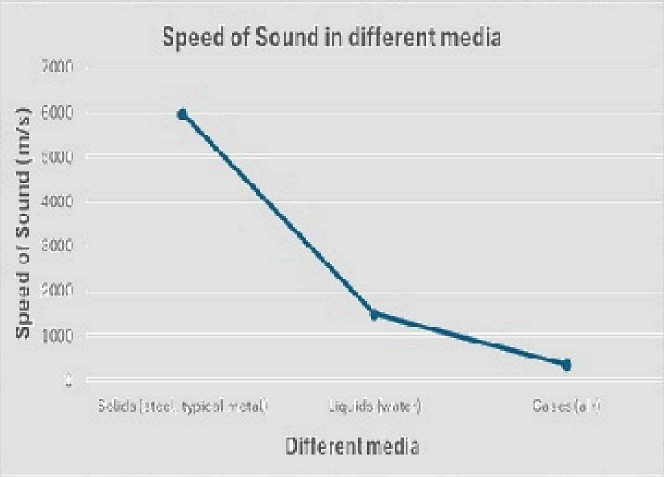
Speed of sound in solids

The speed of sound in solid matter is much higher than in gases (air ≈ 343 m/s) or liquids (water ≈ 1480–1500 m/s at room temperature). Typical values for longitudinal waves in common solids range from 4000–6000 m/s in metals, with some materials like diamond reaching ~12 000 m/s. This high speed arises from the strong interatomic bonds and high elastic moduli of solids compared to the weaker intermolecular forces in fluids.[2][6]

Unlike gases and liquids, which support only longitudinal (compressional) waves, solids can propagate both **longitudinal waves** and **transverse (shear) waves**. This is because solids resist shear deformation, while fluids do not.


Longitudinal Wave
(P-wave)
Striker
Sensor
Transverse Wave
(S-wave)
1 m


Speed of Sound in solids
Speed of Sound im km/s
14
12
10
8
6
4
2
0
Lead
Gold
Copper
Glass (Pyrex)
Steel
Aluminum
Diamond
Beryllium
Material


Speed of Sound in different media
Speed of Sound (m/s)
7000
6000
5000
4000
3000
2000
1000
0
Solids (steel, typical metal)
Liquids (water)
Gases (air)
Different media

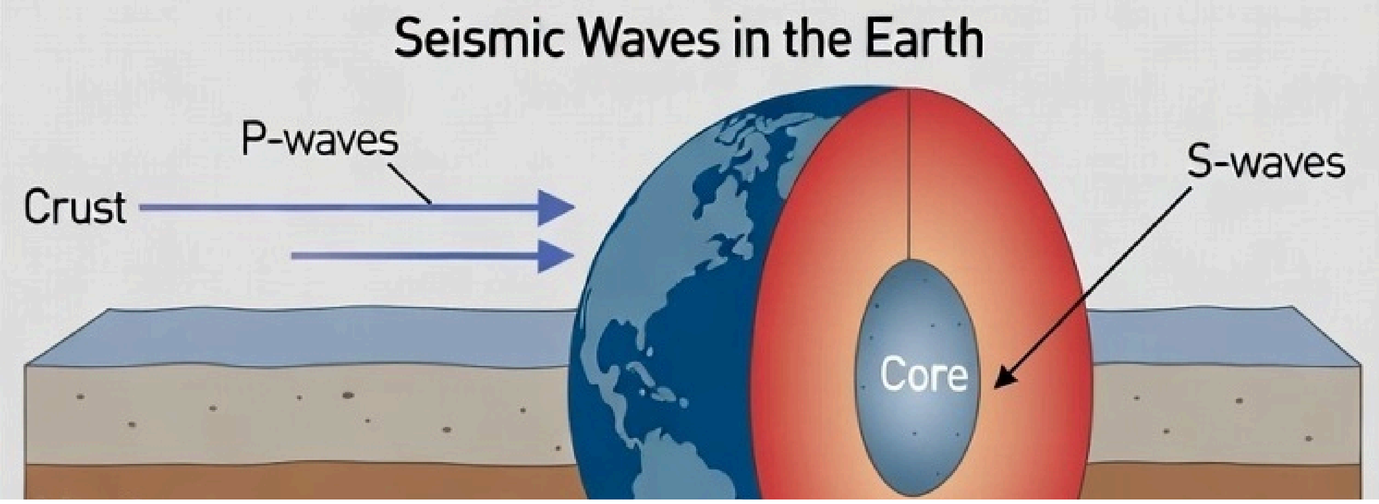

Seismic Waves in the Earth
P-waves
Crust
S-waves
Core

Illustration of longitudinal (top) and transverse (bottom) waves in a solid, showing particle motion relative to propagation direction.

Theory

In a bulk isotropic solid, the speed of **longitudinal waves** is $c_L = \sqrt{\frac{K + \frac{4}{3}G}{\rho}}$ and the speed of **transverse (shear) waves** is $c_T = \sqrt{\frac{G}{\rho}}$ where K is the bulk modulus, G is the shear modulus, and ρ is density. For thin rods or bars (common in student experiments), where lateral dimensions are small compared to wavelength, the longitudinal speed simplifies to $c = \sqrt{\frac{Y}{\rho}}$ where Y is Young's modulus.

Typical values

Typically, $c_L > c_T$ (often by a factor of ~1.7–2).

Approximate speeds of sound (longitudinal, room temperature):

The speed of sound in solids is significantly higher than in gases or liquids due to stronger interatomic bonds and higher elastic moduli relative to density. Values vary depending on whether the measurement is for bulk longitudinal waves or thin-rod approximations, as well as temperature and exact material composition.

The following table lists approximate **longitudinal speeds** of sound and densities for various materials (mostly at room temperature), **ordered from highest to lowest speed**. The values are compiled from standard engineering and NDT references.[2][6]

Approximate speed of sound and density in various materials

Material	Density (g/cm³)	Speed of sound (m/s)
Beryllium	1.85	12900
Aluminium (rolled)	2.70	6420
Steel (mild/carbon)	7.85	5940
Copper	8.96	4760
Skull bone	1.91	4080
Muscle	1.07	1580
Water	1.00	1483
Fat (soft tissue)	0.95	1450
Ethanol	0.79	1207
Helium	0.000178	965
Air (dry, 20 °C)	0.00120	343

Note: Values are approximate and represent bulk longitudinal wave speeds unless noted. Minor variations exist across sources due to alloys, temperature, or measurement method (e.g., rod vs. bulk).

Additional examples:

- Glass (crown/pyrex): ~4500–5900 m/s
- Wood (along grain): ~4000–5000 m/s
- Diamond: ~12000–18000 m/s (direction-dependent)[2]

Experimental measurement

A simple undergraduate experiment measures the speed of sound in a metal rod or bar:

- **Resonance method**: Suspend a long rod (1–3 m aluminium or steel) horizontally at its nodal points. Excite longitudinal vibrations (strike end or use driver). Measure fundamental or harmonic frequencies. For a free-free bar, fundamental wavelength ≈ $2L$, so $c = 2Lf$.
- **Pulse-echo method**: Use a transducer or hammer to send a pulse; measure round-trip time over known length (requires oscilloscope).
- **Basic timing**: Strike one end of a long rod and time the arrival of the sound at the other end (ear or microphone). Accuracy limited but demonstrates the high speed.

These experiments complement the resonance tube method used for air.

Applications: Seismic waves

In the Earth, sound waves manifest as **seismic waves** generated by earthquakes.

- **P-waves** (primary): compressional/longitudinal, faster (~5–8 km/s in crust).
- **S-waves** (secondary): shear/transverse, slower (~3–4.5 km/s in crust).

P-waves arrive first and can travel through liquids; S-waves cannot (helped prove Earth's outer core is liquid).

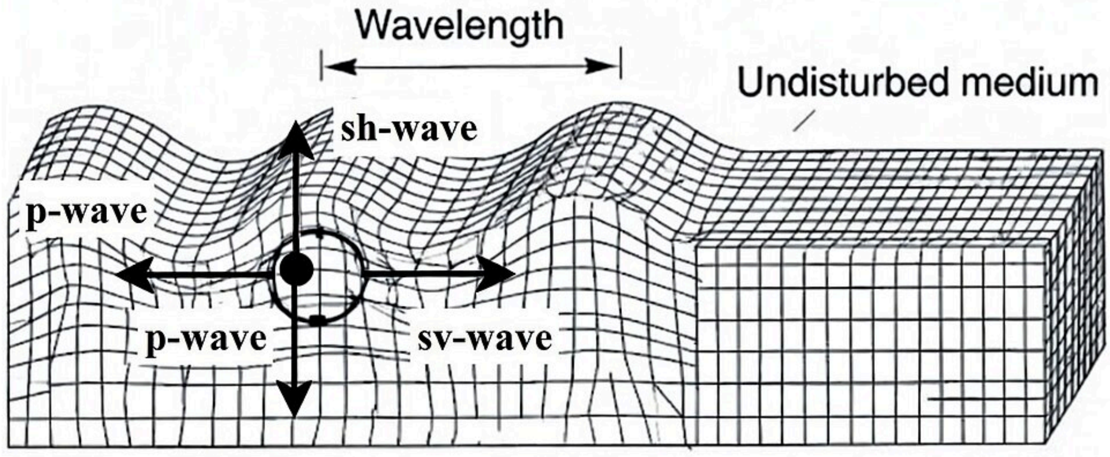


Diagram comparing P-waves (compressional) and S-waves (shear) propagation.

Other applications include:

- Design of musical instruments (wave speed in wood, strings)

Safety notes

- Wear eye protection when striking rods.
- Use moderate force to avoid damage.

Quiz

Test your understanding:

1. Why does the speed of sound increase in humid air?

Answer: Water vapour is lighter → reduces the average molar mass M

2. What is the main systematic error in resonance tube experiments?

Answer: End correction

3. What is plotted to obtain a straight line for dry air?

Answer: c^2 vs T

4. The mole fraction x equals?

Answer: $p_v(T)/P$

5. Name one limitation of the experiment.

Answer: Temperature gradients along the tube / incomplete saturation / ideal gas assumption

6. What is the formula for the speed of sound in an ideal gas?

Answer: $c = \sqrt{\frac{\gamma RT}{M}}$

7. What does the end correction e represent?

Answer: An additive length correction due to the open end of the tube (typically 0.3–0.6 × radius)

Answer: From the increase Δc → solve for mole fraction x → $p_v(T) = x \cdot P$

9. Why is c^2 plotted against T instead of c vs T?

Answer: Because $c^2 \propto T$, so the plot is a straight line through the origin

10. Approximately how much higher is the speed of sound in water compared to air at room temperature?

Answer: About 4–5 times higher (~1480–1500 m/s in water vs ~340 m/s in air)

11. What is the approximate speed of sound in water at 20 °C?

Answer: ~1480–1500 m/s

12. What is the general formula for sound speed in a liquid?

Answer: $c = \sqrt{\frac{K}{\rho}}$ (K = bulk modulus, ρ = density)

13. What is the SOFAR channel?

Answer: A natural acoustic waveguide in the ocean formed by a minimum in sound speed at ~800–1200 m depth

14. Why do sound rays bend in the ocean?

Answer: Due to vertical gradients in sound speed (Snell's law)

15. Which marine mammals use the SOFAR channel for long-distance communication?

Answer: Blue whales, fin whales, humpback whales

16. What is the typical travel distance for low-frequency sounds in the SOFAR channel?

Answer: 1000–5000 km

17. How does pressure affect sound speed in water at great depths?

18. What is the best frequency range for long-distance propagation in the SOFAR channel?

Answer: 10–100 Hz (low frequencies)

19. What was the SOFAR system historically used for?

Answer: Locating downed pilots and submarines using explosive charges (SOFAR bombs)

20. Name one modern scientific use of the SOFAR channel.

Answer: Ocean acoustic tomography / climate monitoring / marine mammal tracking

Quiz (additional questions on solids)

21. Why is the speed of sound much higher in solids than in air or water?

Answer: Solids have much higher elastic moduli (stiffness) relative to their density.

22. What type of wave can propagate in solids but not in fluids?

Answer: Transverse/shear waves

23. What is the approximate formula for longitudinal sound speed in a thin rod?

Answer: $c = \sqrt{\frac{Y}{\rho}}$ (Y = Young's modulus, ρ = density)

24. Which seismic wave is faster: P-wave or S-wave?

Answer: P-wave (primary/compressional)

25. Approximately how fast is sound in steel compared to air at room temperature?

Answer: ~17 times faster (~5900 m/s vs ~340 m/s)

26. Why can't S-waves travel through Earth's outer core?