National Aeronautics and Space Administration

SPEED OF SOUND

Speed of Sound

Lesson Overview

As scientists and engineers work to reduce aircraft noise, a thorough understanding of the physics of sound is necessary. The speed of sound and how that speed depends on certain variables are important concepts. With aircraft design, every aspect of an airplane from the airframe through the engines matters, since noise affects each component of an aircraft. In this lesson, participants will learn about motions and forces and the interactions of energy and matter as they use the principle of resonance to set up an experiment in the classroom to measure the speed of sound in air. The speed of sound will be calculated using the standard relationship between velocity, frequency and wavelength.

Time: 60 minutes + set-up & explanation

Materials:

Per group:

- Plastic PVC pipe, 1” interior diameter (ID), 2 ft. in length
- Ruler
- Clear packing tape (preferably water-resistant)
- (optional) Thermometer
- Tall container to hold approximately 1 gallon of water
- Tuning forks set of 4 (one should be 256 Hz)
- Rubber tuning fork activator block (tuning forks can be shared between groups)

Safety

Groups should use care when using tuning forks and proper instruction should be conducted ahead of time to prevent damage to the tuning forks.

Groups will be working with tall cylinders of water. Guidance should be provided to help ensure water containers do not spill over the floor.

Objectives

Students will:

1. Calculate the speed of sound in a gas (air) using simple materials.
2. Utilize the basic wave equation: velocity = wavelength · frequency ($v = \lambda \cdot f$).
3. Compare lab calculations and results to theoretical speed of sound.
4. Transfer lab results to real-life work being done at NASA to reduce the amount and type of sound generated by aircraft.

Background

As scientists and engineers work to reduce or even alter the noise from aircraft, a thorough understanding of the physics of sound is necessary. The speed of sound and how it depends on certain variables are important concepts related to the physics of sound.

Sound is one of the most important ways we have of sensing our surroundings and communicating with others. Sound itself is a sensation created in the brain as a response to sensory inputs from the inner ear. However, not all sounds are desirable or beneficial. The following information is presented to help the reader develop a better understanding of sound, including how it is made and how it travels:

- Sound is produced by vibrations.
- Sound is transmitted through the air and can travel through solids, liquids, or gases.
- The speed of sound in air is slower than it is in solids and liquids. To some this may seem counter-intuitive.
- Sound cannot travel through a vacuum.
- The speed of sound is affected by temperature, the type of medium it travels through, and the density of that medium. If sound travels through a gas such as air, for example, its density changes as a result of altitude and temperature, which will change a sound's speed.

	Solid Steel	Sea Water	Air
Speed of sound in m/sec at 21°C (70°F)	5,180 m/s	1,524 m/s	331 m/s
Speed of sound in mph at 21°C (70°F)	11,600 mph	3,414 mph	740 mph

Fig. 1. *Speed of sound in different mediums*

Given normal atmospheric conditions, the temperature, and thus speed of sound, varies with altitude:

Altitude	Temperature	m/sec	Km/h	mph	knots
Sea Level	15°C (59°F)	340	1225	761	661
11,000m –20,000m (Cruising altitude of commercial jets)	-57°C (-70°F)	295	1062	660	573
29,000m (Flight of X-43A)	-48°C (-53°F)	301	1083	673	585

Fig. 2. *Speed of sound in air at different altitudes*

- The speed of sound is dependent on temperature. As the temperature of the air increases, the speed of sound in air increases.
- Sound waves are longitudinal. They move by alternately squeezing (compression) and stretching (rarefaction).
- Wave science: frequency = number of waves/sec.
- Hertz (Hz) is a unit of frequency where one Hertz equals one cycle, or wave, per second.
- Velocity = wavelength (meters) X frequency (Hz or cycles/sec).
- Frequency of sound and pitch are related. The higher the pitch, the greater the frequency.
- Frequency and pitch depend on the length of the object that is vibrating. For example, a short string vibrates faster than a long string resulting in a higher frequency and a higher pitch.
- Multiple sound waves can reinforce or interfere with each other.
- Sound insulation is designed to absorb sound energy. Many of the same materials used in temperature insulation can be used to reduce sound as well.
- The typical range of sound that a human can hear is between 40 – 18,000 Hertz (Hz).
- Many animals can detect a wider range of sound frequencies than humans can.
- Sound can be reflected (bounced off) or refracted (bent) or absorbed.
- Sound levels decrease rapidly as the distance from the point of origin to the receiver increases. If the distance from the source is doubled, then the intensity decreases about one-fourth.
- The decibel is a unit that expresses the relative intensity of sound.

As an aircraft moves through the air, the air molecules near the aircraft are disturbed and begin to move around the aircraft. If the aircraft passes through the air at a low speed, typically less than 250 mph, the density of the air remains the same. But when aircraft travel at higher speeds, some of the energy from the aircraft goes into compressing the air and changes the density of the air around it. This compressibility effect alters the amount of resulting force on the aircraft. The effect becomes more important as speed increases. Near and beyond the speed of sound, about 330 m/s or 760 mph, small disturbances in the flow are transmitted to other locations on the aircraft.

Jet plane at takeoff	110-140dB
Loud rock music	110-130dB
Chain saw	110-120dB
Thunderstorm	40-110dB
Vacuum cleaner	60-80dB
Normal voices	50-70dB
Whisper	20-50dB
Purring cat	20-30dB
Falling leaves	10dB
Silence	0dB

Fig. 3 *Examples of sound intensity*

A sharp disturbance generates a shock wave that affects both the lift and drag of an aircraft. The ratio of the speed of the aircraft to the speed of sound in the gas determines the magnitude of the many compressibility effects. Because of the importance of this speed ratio, aerodynamicists have designated it with a special parameter called the Mach number in honor of Ernst Mach, the late 19th century physicist who studied gas dynamics. The Mach number (M) allows us to define flight conditions in which compressibility effects vary.

Subsonic conditions occur for Mach numbers less than one ($M < 1$). For the lowest subsonic conditions, compressibility can be ignored.

As the speed of the object approaches the speed of sound, the flight Mach number is nearly equal to one ($M \approx 1$), and the flow is said to be **transonic**. At some places on the object the local speed exceeds the speed of sound. Compressibility effects are most important in transonic flows and led to the early conclusion that a sound barrier existed. Historically, a flight faster than the speed of sound was thought to be impossible. Some engineers thought that the aircraft would self-destruct in this region of flight. We now know that there is no “sound barrier”. In fact, the sound barrier is only an increase in the drag near sonic conditions because of compressibility effects.

Because of the high drag associated with compressibility effects along with the variability of the aircraft’s performance due to fluctuations in airflow around different components on the aircraft (for example, some sections of the plane experiencing effects of air faster than the speed of sound while others are experiencing subsonic conditions), aircraft do not cruise near Mach 1.

Supersonic conditions occur for Mach numbers greater than one, (1 < M < 5). Compressibility effects are important for supersonic aircraft, and shock waves are generated by the surface of the object. For high supersonic speeds (3 < M < 5), aerodynamic heating also becomes very important in aircraft design. Even at (M=2) heating was an issue for the Concorde. During supersonic flight, the fuselage expanded by a foot due to heating. The nose of any supersonic aircraft is generally the hottest part of the aircraft other than the engines. During supersonic flight, the nose temperature of an aircraft can approach 260°F, almost 50° hotter than boiling water.

Fig. 4. *Mach number divisions*

For speeds greater than five times the speed of sound (M > 5), the flow is said to be **hypersonic**. At these speeds, some of the energy of the object goes into exciting the chemical bonds, which hold together the nitrogen and oxygen molecules of the air. At hypersonic speeds, the chemistry of the air must be considered when determining the forces on the object. The Space Shuttle re-enters the atmosphere at high hypersonic speeds, (M ~ 25). Under these conditions, the heated air becomes ionized gas, or plasma, and the spacecraft must be insulated from the high temperatures of the plasma.

Standing Waves and Resonance

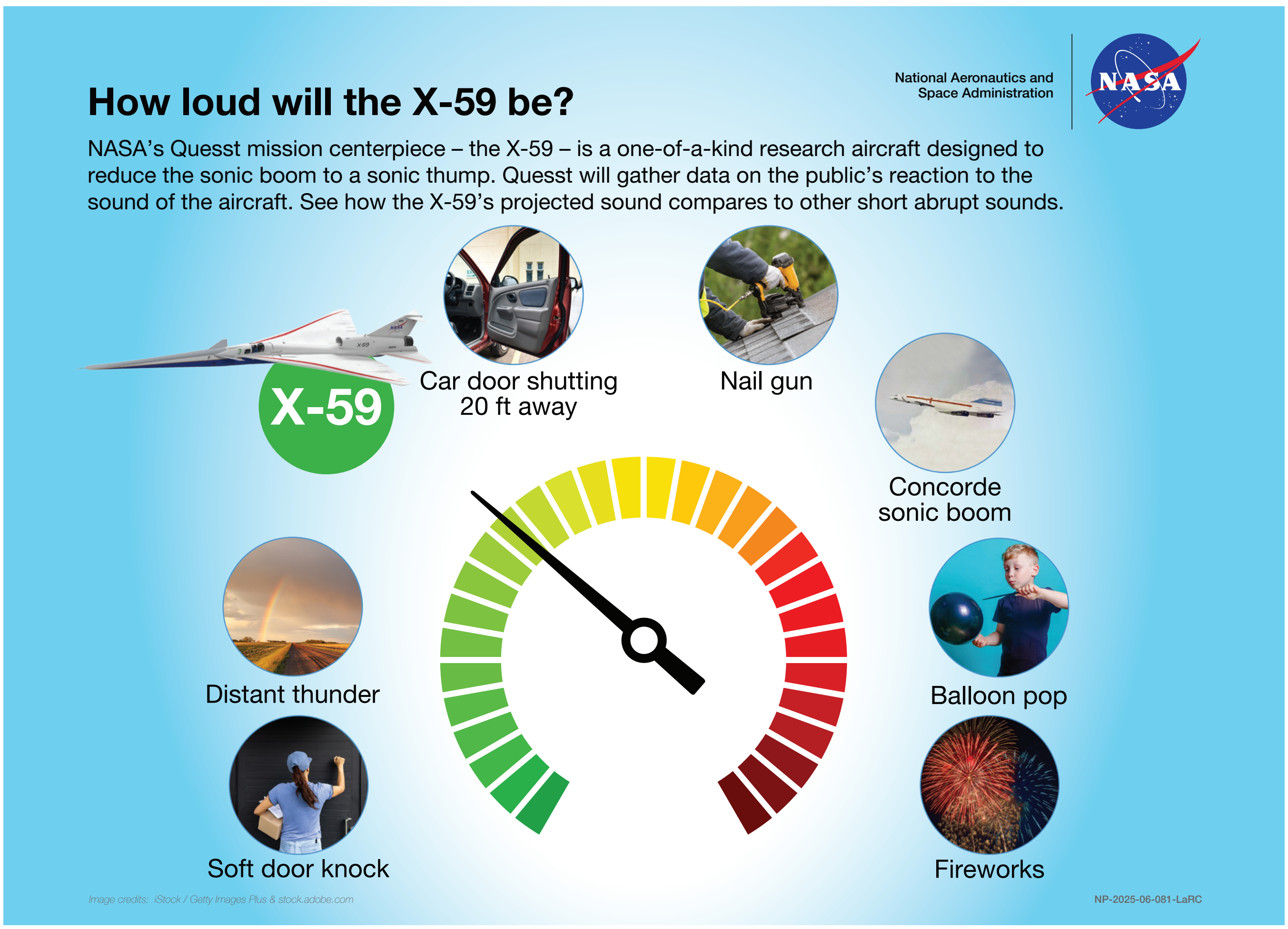
As scientists and engineers work to reduce aircraft noise, a thorough understanding of the physics of Imagine that you have a long rope attached to a wall. If you vibrate the end of the rope by shaking it, you can send a wave down the rope. The same type of wave occurs in columns of air as well. When the wave reaches the other end of the rope (or air column) it will be reflected back, but it will interfere with the oncoming wave. If you shake the rope at just the right frequency, a standing wave will be created as shown in Fig. 9. A standing wave is produced when two waves traveling in opposite directions, with the same amplitude and frequency, constructively interfere with each other and produce a larger amplitude. When a standing wave is created, resonance occurs. Another form of resonance occurs when one object is vibrating at the same natural frequency of a second object, which forces that second object into vibration. The frequency at which you are shaking the rope is called the resonant frequency.

In the activity within this guide, you will use this wave principle as it applies to sound in order to find the frequency of a sound wave using interference to help determine the frequency's length. Read on to find out about one of NASA's mission where the science of sound is used within our work.

Quesst X-59 Background & Resources

The Quesstion Mission and the X-59

The science of sound is a cornerstone of the experimental work NASA has designed and implemented with the Quesst mission. For years, since supersonic flight over land was banned in the 1970s due to the significant disruption of the sonic booms created by these aircraft, NASA and others have searched for ways to change the sound coming from aircraft flying faster than the speed of sound. The Quesst mission is the result of multiple research studies and testing conducted to get to this point. Quesst's aircraft, the X-59, has been designed to quiet the sonic boom and change how supersonic aircraft operate.



The X-59, a quiet supersonic research aircraft, is testing new technologies to quiet the typical sonic boom generated when an aircraft or any other object travels faster than the speed of sound. X-59 is a single engine aircraft that is 99.7 feet long with a wingspan of 29.7 feet, with nearly half of the length of the aircraft being its nose. This unique shape, along with other elements of its design, make the aircraft able to create a quieter sonic “thump” rather than a boom at supersonic speeds of Mach one and above. During testing, the X-59 flies at speeds up to 925 mph, or a Mach 1.4.

The Quesst mission has several goals. The first goal has been to build and successfully fly an experimental plane, or X-plane, that will make a quieter sound when breaking the sound barrier. The next goal is to test the aircraft to measure exactly how the sound changes. This is done in two ways—by measuring the sound created near the aircraft and to measure the sound on the ground. For some test flights, a “chase plane” follows the X-59. This chase plane carries specially designed shock-sensing probes to capture noise data in real time. For ground testing, engineers had to design special microphone stations to collect sound data on the ground. Since sonic booms, or thumps, do not just happen one time when the aircraft breaks the sound barrier, these microphone arrays have been designed to collect measurements along the entire “sonic corridor,” or the path of sound created along the entire distance the aircraft flies at supersonic speeds. A third goal will be to collect data on the public’s perception and tolerance of the noise created.

Learn More Resources

Learn more about Quesst the mission, the vehicle, the crew, and the science behind quieting the boom at https://www.nasa.gov/mission/quesst/.

Find more sound activities in the Quesst Supersonic STEM Toolkit at https://www.nasa.gov/directorates/armd/quesst-supersonic-stem-toolkit/.

Image Caption

NASA’s X-59 quiet supersonic research aircraft taxis across the runway during a low-speed taxi test at U.S. Air Force Plant 42 in Palmdale, California, on July 10, 2025. The test marks the start of taxi tests and the last series of ground tests before first flight.

Credit: NASA / Carla Thomas


X-59
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Speed of Sound Instructional Guide

Time: 60 minutes

Materials:

(Per lab station)

- Tall container of water
- Calculator
- Pencils
- PVC pipe, approximately 18”, with a 1” interior diameter (i.d.)
- Ruler
- Set of tuning forks and rubber fork activator
- Clear tape (preferably waterproof/resistant)

Speed of Sound Worksheet Reference Materials NASA Video:

The Physics of Waves: https://www3.nasa.gov/specials/Quesst/science-of-sound.html

Objectives

The purpose of this activity is for students to experience motion and forces, and the interactions of energy and matter as they measure length of a sound wave and calculate the speed of sound in air.

Students will become familiar with some of the variables that affect the speed of sound in air. The concepts of resonance and interference will also be introduced.

INSTRUCTIONAL GUIDE FOR FACILITATORS

Activity: Speed of Sound

Engage

Introduce NASA's Quesst mission and the work to quiet a sonic boom created by an aircraft when it travels faster than the speed of sound.

Explore

In this section, students will create sound waves, measure the sound's wavelength, and calculate the speed of sound.

Procedure

1. A minimum of two people per station are needed for this activity.
2. Fill the water container about ¾ full as shown in ***Fig. 1.***

Fig. 1. *Apparatus setup*

3. If not already prepared, tape a ruler to the PVC pipe with the "0" at the top of the PVC pipe. *Alternatively, the PVC pipe can be marked with a waterproof marker at in 1cm and/or 5cm increments.*
4. If not already prepared, tape a ruler to the PVC pipe with the "0" at the top of the PVC pipe. *Alternatively, the PVC pipe can be marked with a waterproof marker at in 1cm and/or 5cm increments.*
5. Place the PVC tube vertically in the water as shown in ***Fig. 1***. As the pipe is adjusted up or down, the water will act as a bottom for the pipe, allowing sound waves to travel through the pipe then back to the opening.

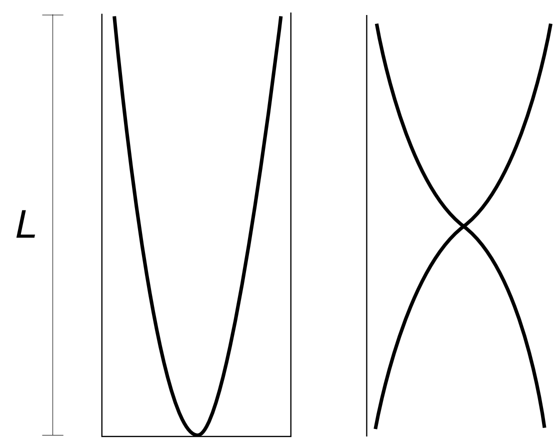

Fig. 2. *Resonance in closed and open pipes (λ = wavelength)*

6. Strike the tuning fork (256 Hz) on the rubber block activator, the bottom of your shoe, or other semi-solid surface **(Warning: DO NOT STRIKE THE TUNING FORK ON A TABLE OR OTHER HARD SURFACE. This can**

INSTRUCTIONAL GUIDE FOR FACILITATORS

damage the tuning fork!). When properly activated, you should have to bring the vibrating tuning fork within a few inches of your ear to hear it well.

7. Hold the vibrating tuning fork horizontal to the opening of the pipe, as shown in keep the vibrating tuning fork directly over the opening of the PVC tube.
8. Slowly move the white PVC tube AND the tuning fork up and down and listen for the volume of the sound to change. When you think you've found the length of the tube that produces the loudest sound (resonance), strike the tuning fork again and check your results. You may need to repeat this step several times.
9. Hold the white PVC tube in the position where resonance is heard.
10. Measure the length l (centimeters) and record on the worksheet. You will change your measurement to meters later. *Note: the length l is the distance from the top of the white PVC tube to the top of the water* ***(Fig. 1)****. For the 256 Hz tuning fork the volume should increase somewhere near l = .32 meters. This measurement is ¼ of the wavelength.*
11. Measure the air temperature inside the PVC tube. Record on the worksheet.
12. Use the formula given above to calculate the speed of sound in air.
13. If time permits, repeat the experiment using tuning forks with different frequencies (for example, 320- E, 385-G and 512-C). Predict how a higher frequency tuning fork will affect. (If the frequency increases, then l should decrease)

Explain

Share more information about types of waves, particularly sound waves, using information from the background section of this guide. Videos from Quesst's "The Physics of Waves" site can help with this: https://www3.nasa.gov/specials/Quesst/science-of-sound.html.

Elaborate

The Quesst Mission and the X-59

Supersonic commercial flight over land has been banned in the United States since the 1970's due to the loud noise produced by flying faster than the speed of sound, which is at Mach 1 or higher. NASA's Quesst Mission is researching the capabilities of an experimental aircraft built with a design and technology that will reduce the sound produced by supersonic flight. The two goals of the Quesst Mission are to design and build an experimental aircraft that will quiet the sonic boom to a thump and gather data from the public to pass on to national and international industry to help change the future of supersonic flight.

The X-59 is the quiet supersonic research aircraft that will be used to gather data that could change the future of supersonic flight over land. She is a single jet engine aircraft 99.7 feet long with a wingspan of 29.7 feet and a very unique nose along with technology that will help quiet the sound as she flies at supersonic speeds. The X-59 will fly at speeds up to 925 mph, or a Mach 1.4, at 55,000 feet followed by a "chase plane" that is equipped with technology to capture images and sound data in real time.

Understanding the physics of sound is a big part of the Quesst Mission to quiet the sounds made during flight especially at supersonic speeds. Before the X-59 was revealed, a subscale model of the quiet supersonic research aircraft was built to capture the measurements of the pressures that create sonic booms within NASA wind tunnels. Acoustic researchers built a simulated living room equipped with speaker and subwoofers to mimic the disturbances of sound produced by supersonic flight to gather data about the effect on homelife. This is just some of the early testing that helped to design the X-59 and the technologies it will use to quiet the boom.

Engineers had to design special microphone stations to collect sound data from the ground as the X-59 flies over. These stations measure sound produced by the X-59 to assess the quiet sonic thumps. To gather sound data from the sky, NASA engineers also developed technology unique to withstanding the pressures of supersonic speeds. Shock-sensing probes that have been attached to chase planes that will follow the X-59 were adapted with specific features to capture pressure changes in the shockwaves produced by the X-59 when flying near and below the research aircraft.

The data collected from these technologies is vital to understanding the science of sound produced by supersonic speeds and how we can quiet them to be less disturbing to life on earth. Learn more about Quesst the mission, the vehicle, the crew, and the science behind quieting the boom at https://www.nasa.gov/mission/quesst/. Find more sound activities in the Quesst Supersonic STEM Toolkit at https://www.nasa.gov/directorates/armd/quesst-supersonic-stem-toolkit/.

Evaluate

(calculate speed of sound, percent error, account for and discuss differences between lab measurements and theoretical measurements)

v = wavelength · frequency = 4 (l + .3d) · frequency

l = length (meters) of the closed tube (Fig. 5) when resonance occurs

d = inside diameter (meters) of the clear plastic tube

frequency = 256 Hz, or the number inscribed on the tuning fork

Speed of Sound Student Worksheet

Materials:

(Per group or activity station)

- Tall container of water
- PVC pipe, 1” interior diameter (i.d.) with ruler attached
- Set of tuning forks (different stations may be sharing tuning forks)
- Worksheet
- Calculator
- (optional) Thermometer

Instructions

For this activity you will be creating sound waves that will travel through a PVC pipe then measure the wavelength of those waves, along with the speed of the sound you will hear during the activity. Following your instructor’s directions, you will set up your team’s station if it hasn’t been done for you, the carefully conduct the activity, making note of measurements along the way that will help you calculate wavelength and the speed of sound.

You will be comparing your results with theoretical results that have been gathered in carefully controlled settings; your results will most likely vary from theoretical results. There is also an option to calculate percentage error of your findings vs. theoretical findings, as well as increasing the accuracy of your results by taking into account additional variables such as the distance between the tuning fork and your PVC pipe. Your instructor will tell you which parts of the worksheet you will need to complete.

STUDENT WORKSHEET

Activity: Speed of Sound

1. A minimum of two people are needed per station.
2. Fill the water container about ¾ full as shown in **Figure 1**.

Fig. 1. *Apparatus setup*

3. If not already prepared, tape a ruler to the PVC pipe with the “0” at the top of the PVC pipe (*alternatively, the PVC pipe can be marked with a waterproof marker at 1cm and/or 5cm increments per instructions*).
4. Place the PVC tube vertically in the water as shown in **Figure 1**. As the pipe is adjusted up or down, the water will act as a bottom for the pipe, allowing sound waves to travel through the pipe then back to the opening.

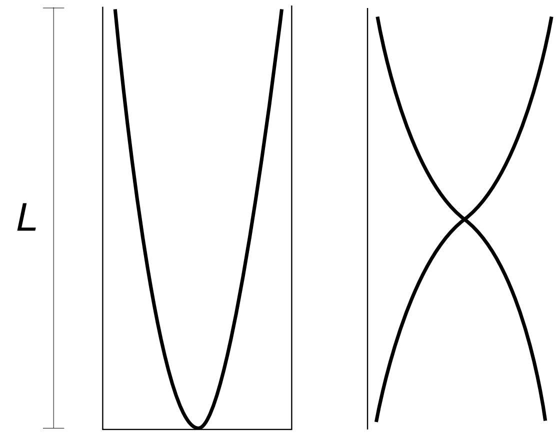

Fig. 2. *Resonance in closed and open pipes (λ = wavelength)*

5. Strike the tuning fork on the rubber block activator. You should not be able to hear a loud sound yet—you will be listening for the amplification of the sound wave later. **DO NOT strike the tuning fork on a solid surface such as the table or desktop since it can damage the tuning fork!**
6. Hold the vibrating tuning fork horizontally over the opening of the PVC pipe. Move the pipe up and down in the container of water, changing the length of the PVC pipe until you hear a distinct amplification of the sound coming from the tuning fork (you may have to lean in somewhat close to the tuning fork). Strike the tuning fork on the activator block again if you need to if it is not vibrating any longer.
7. When you hear the louder vibration, stop moving the PVC pipe. Record the distance

from the top of the PVC pipe to the surface of the water in cm. This is the anti-node of the soundwave, or ¼ the length of the actual sound wave (you will calculate all of this later, converting your measurement to meters).

8. If instructed to do so, repeat this test with a different tuning fork that has a different wavelength and frequency.
9. Complete the worksheet to determine
   1. the length of each wave, and
   2. the speed of sound coming from that sound wave.

Calculations

Basic equation: velocity (v) = wavelength (λ) x frequency (f)

v = velocity

l = length of PVC pipe (in meters) when resonance occurs

f = frequency measured in Hz (listed on tuning fork)

d = inside diameter of PVC pipe (measured in cm, changed to meters)

Simple Equation

v= 4(l) x frequency

Equation option #2, for more accuracy (accounting for distance between tuning fork and PVC pipe):

V = 4(l + 0.4d) x frequency

Tuning Fork #1

Inside measurement of PVC diameter __________ (in cm)

Converted to meters. _____ (cm) / 100 = ____ m

Tuning fork frequency (found on the side of the tuning fork, in Hz) = _______ Hz

Measured length of PVC pipe when resonance is heard (measure from top of PVC pipe to water surface = ________ cm

PVC length (in cm), converted to meters. ________cm / 100 = _______ m

Use either the simple equation or the 2nd equation to calculate the velocity of the wavelength. Show work:

Tuning Fork #2 (if applicable)

Inside measurement of PVC diameter
__________ (in cm)

Converted to meters. ____ (cm) / 100 = _____ m

Tuning fork frequency (found on the side of the tuning fork, in Hz) = _______ Hz

Measured length of PVC pipe when resonance is heard (measure from top of PVC pipe to water surface = ________ cm

PVC length (in cm), converted to meters.
________cm / 100 = _______ m

Use either the simple equation or the 2nd equation to calculate the velocity of the wavelength. Show work:

Extension

Results can then be compared to the theoretical speed of sound and any percentage of error can be calculated.

The theoretical speed of sound in air at sea level and at 0C (dry air) is 331m/s.

Percentage error: Compare your results with the theoretical speed of sound and calculate your percentage error (show your work). Why do you think your results might be different?

theoretical result – actual result/actual result x 100 = %error

Possible reason for differences:

GLOSSARY

Acoustics:
The study of sound

Amplitude:
The height of a wave; the amplitude determines the amount of energy a wave carries; high volume sounds have large amplitudes

Antinode:
A point of destructive interference in a standing wave

Decibel:
A unit that expresses the relative intensity of sound

Frequency:
The periodic change in sound pressure; frequency is measured in cycles per second or in Hertz (Hz); in music it is called pitch; in music pitch can be high (soprano) or low (bass) or somewhere in between

Hertz:
Hertz (Hz) is a unit of frequency where one Hertz equals one cycle, or wave, per second second

Intensity:
The average rate at which sound energy is transmitted through an area between a source and a receiver. Sound energy is measured in watts/cm2 or in decibels (dB)

Interference:
Occurs when two waves interact with each other; in some cases the waves will reinforce one another and the volume or intensity will increase (constructive interference); at other times the waves will cancel each other out and little or no sound will be heard (destructive interference)

Longitudinal wave:
The oscillations are in the same direction as the line of travel; a sound wave is an example

Node:
A point of constructive interference in a standing wave

Noise:
Sound with no set patterns in rhythm or frequency

Period:
The time it takes for two successive wave crests to pass a given point; also given as the reciprocal of the frequency

Pitch:
The highness or lowness of a sound

Resonance:
The vibration of an object when exposed to sound at its own natural frequency, as in a window pane vibrating when a helicopter flies overhead; also occurs when two sound waves reinforce one another

Sound wave:
Produced whenever a vibrating object creates changes in the pressure of a medium, such as air

Speed:
How fast an object is moving with respect to another object; for example, how fast an airplane moves with respect to the ground

Standing wave:
Produced when two waves traveling in opposite directions interfere with each other and produce a large amplitude wave

Transverse wave:
The oscillations are perpendicular to the direction of travel

Ultrasound:
Sound that is too high in frequency to be heard by the human ear

Wavelength:
The distance between two successive crests in a wave

Velocity
Speed and direction; for example, an airplane moving at 350 kilometers per hour going East

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