Lesson 3
Sound

Properties of Sound:

- Longitudinal wave produced by vibrations
- Sound energy must be transmitted through some medium – air is the most common.
- Sound cannot travel through a vacuum
- Sound energy is transferred by the collision of air molecules.
- Sound travels at different speeds in different media.
- The stiffer the material the faster the speed of sound. This means that sound travels fastest in solids and least in gases. Particles in solids are closer together making the sound transmission easier.

Example:
Your voice echoes off a wall and you hear the echo 5.0 s afterward. If the speed of sound was 340 m/s, how far away is the wall?

CORE LAB: SPEED OF SOUND

The speed of sound in air is dependent on the air temperature. As temperature increases, the speed increases because the air molecules are moving more rapidly.

$$v = 332\frac{m}{s} + \left(0.6\frac{m/s}{^{\circ}C}\right)T$$

where,
T = air temperature in degrees Celsius

Example:
Calculate the speed of sound in air at 16°C.

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Mach Number
The ratio of the speed of the sound source to the speed of sound of air in that location. Typically used for aircraft that near or exceed the speed of sound.

$$MN = \frac{v_{source}}{v_{sound}}$$

If the speed of the source equals the speed of sound then the Mach Number is 1.

If the Mach Number is greater than 1 then the aircraft is travelling at supersonic speeds.

If the Mach Number is less than 1 then the aircraft is travelling at subsonic speeds.

Speeds greater than or equal to Mach 5 are called hypersonic.

Example:
What is the speed of an airplane travelling at Mach 2.5 where the speed of sound is 320 m/s?

Example:
What is the Mach number for a plane flying at 751 m/s in air of temperature 11 °C?

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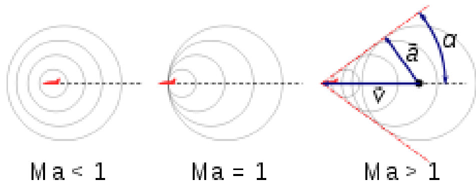
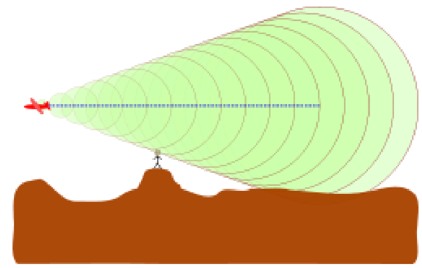
Sonic Boom
As an airplane approaches Mach 1, the air waves it produces pile up, creating a high pressure region called a sound barrier. To exceed the speed of sound, extra thrust is needed until the aircraft breaks through the sound barrier. Only certain aircraft can withstand the vibrations caused in breaking through the sound barrier to reach supersonic speeds.

An object travelling at supersonic speeds produces a shock wave. The source of sound (the plane) actually overtakes its own waves, causing the compressions to overlap one another (see p. 457).





As the plane breaks through the sound barrier the shock wave is left behind and travels down to the surface of Earth. It is heard as a loud boom or a thunder like noise. Sonic booms can do damage to buildings, livestock and our ears. To prevent sonic booms supersonic aircraft are required to travel at high altitudes.

Sound Intensity

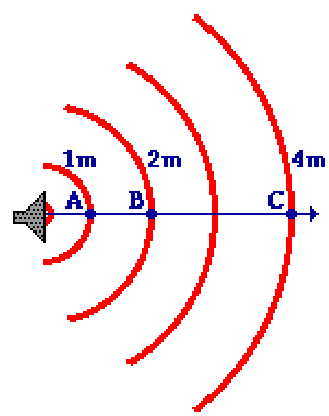
When a source emits a sound, the intensity of the sound decreases with distance. Sound intensity is the power, P, that passes through a surface with an area, A, perpendicular to the wave's direction.

$$I = \frac{P}{A} = \frac{P}{4\pi r^2}$$

$$units: \frac{W}{m^2}$$

As the distance from the source increases, the intensity decreases by a squared amount.

$$I \alpha \frac{1}{r^2}$$



Example:

The sound intensity at 1.0 m from a loudspeaker is 27 W/m^2. What is the sound intensity at 3.0 m from the loud speaker?

Example:
How far away would you have to move in order to decrease sound intensity from 16 W/m^2 to 4.0 W/m^2?

Sound Intensity Level
A more convenient scale for measuring sound intensity that uses a decibel scale. Observe that this scale is based on powers or multiples of 10. If one sound is 10^x times more intense than another sound, then it has a sound level which is 10*x more decibels than the less intense sound.

Source	Intensity	Intensity Level	# of Times Greater Than TOH
Threshold of Hearing (TOH)	$1*10^{-12}$ W/m^2	0 dB	10^0
Rustling Leaves	$1*10^{-11}$ W/m^2	10 dB	10^1
Whisper	$1*10^{-10}$ W/m^2	20 dB	10^2
Normal Conversation	$1*10^{-6}$ W/m^2	60 dB	10^6
Busy Street Traffic	$1*10^{-5}$ W/m^2	70 dB	10^7
Vacuum Cleaner	$1*10^{-4}$ W/m^2	80 dB	10^8
Large Orchestra	$6.3*10^{-3}$ W/m^2	98 dB	$10^{9.8}$
Walkman at Maximum Level	$1*10^{-2}$ W/m^2	100 dB	10^{10}
Front Rows of Rock Concert	$1*10^{-1}$ W/m^2	110 dB	10^{11}
Threshold of Pain	$1*10^{1}$ W/m^2	130 dB	10^{13}
Military Jet Takeoff	$1*10^{2}$ W/m^2	140 dB	10^{14}
Instant Perforation of Eardrum	$1*10^{4}$ W/m^2	160 dB	10^{16}

Note that the inverse square law only applies to W/m^2 and not to the decibel scale.

Example:
A mosquito's *buzz* is often rated with a decibel rating of 40 dB. Normal conversation is often rated at 60 dB. How many times more intense is normal conversation compared to a mosquito's *buzz*?

The intensity of sounds depends on their frequency. 1000-5000 Hz is the most sensitive range for human hearing. We can hear frequencies from about 25-19000 Hz. Higher frequencies have a higher pitch. Lower frequencies need a higher sound level (intensity) to be heard.

Listening to loud sounds for long periods of time can cause hearing loss. The aging process can also decrease the audible range in the higher frequencies. Use of an ipod is about 100 dB directly into the ear.

Quick loud sounds could cause the eardrum to burst. This can usually be repaired. Loud sounds over an extended period of time can cause permanent damage.

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Ultrasonic frequencies:

Frequencies beyond our hearing range (>19000 Hz). Dog's ears are sensitive to these ultrasonic frequencies.

Examples:

- Bats use ultrasonic frequencies for navigation in darkness.
- Ship's SONAR
- Used in TV remote controls
- Used in medicine (diagnostics and surgery)

Doppler Effect

The apparent changing frequency of sound due to an object's motion. The Doppler effect only occurs for Mach number less than 1.

As the police car moves to the right, the person behind the car hears a lower frequency than the person in front of the car. If the car were not moving both people would hear the same frequency.

Doppler Equation:

$$f_2 = \frac{f_1 v_s}{v_s \pm v_o}$$

where,

f_2 = frequency heard by the observer (Hz)
f_1 = actual frequency of the source (Hz)
v_s = speed of sound (m/s)
v_o = speed of object (m/s)

Use – if source is approaching observer
Use + if source is moving away from observer

Example:
The speed of sound in air is 341 m/s. If a car travelling at 25 m/s away from an observer is blowing its horn at a frequency of 200 Hz, what apparent frequency is heard by the observer?

Note: This formula changes if the object remains stationary and the observer moves towards or away.

$$f_2 = f_1\left(1 \pm \frac{v_o}{v_s}\right)$$

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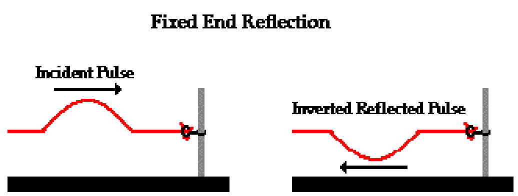
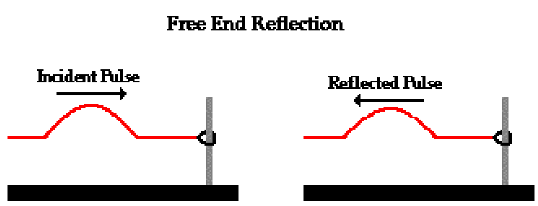
Wave Reflection

Fixed end reflection:



Pulse is reversed upon reflection.

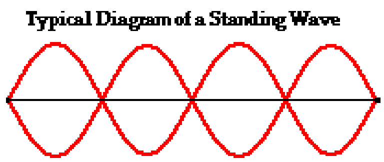
Free (open) end reflection:



Pulse is reflected on the same side as incident pulse.

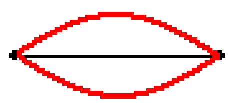
Standing Waves

Standing waves occur when periodic transverse waves of equal length and amplitude travel in opposite directions on a spring or rope. For a given length of rope, only certain wavelengths are capable of maintaining the standing wave interference pattern. (p. 492)

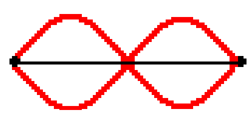


Node: position of zero amplitude that remains stationary.
Antinode: position of maximum amplitude.
Different standing wave patterns are produced in the same string, depending on the frequency of vibration. Standing waves can only be produced at whole number multiples of the fundamental frequency.

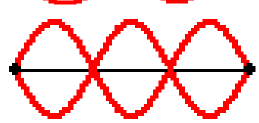
Fundamental
(1st harmonic)



2nd harmonic
(first overtone)



3rd harmonic
(2nd overtone)



Note that the distance between nodes is $\frac{1}{2}\lambda$.

For these patterns, $\lambda = \frac{2L}{n}$

where,

L = length of string (m)
n = harmonic number (number of antinodes)

Example:

A standing wave pattern is produced on a 6.0 m rope using a 5.0 Hz source. If there are 3 antinodes between the ends, what is the speed of the waves that produced the pattern?

Example:

A standing wave has a distance of 45 cm between 4 consecutive nodes. What is the wavelength of the wave? What is the speed of the wave in the medium if the frequency of the source is 30.0 Hz?
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Resonance
Every object has its own natural or resonant frequency at which a vibration occurs most easily. Small repeated forces can cause relatively large vibrations if they are at the resonant frequency (eg. Pushing a person on a swing, soldiers breaking step to cross bridges, windows rattling). When a resonant object receives transmitted energy, it responds by increasing its amplitude of vibration to the limits of its own system.

Mechanical resonance: the vibrating response of an object to a periodic force from a source that has the same frequency as the natural frequency of the object.

Even our bodies have resonant frequencies. When we tune radios we are adjusting the frequency of vibration of particles in the receiver so that they resonate with the frequency of a specific radio or TV signal.

Resonance is an important consideration for engineers. Whether a mechanical system fails or not is dependent on the amount of energy damping. Resonance can be decreased by changing the natural frequency through:

- Changing the mass of a part
- Changing the structural stiffness of a part
- Changing the geometry of the design

Resonance is also important in acoustics.

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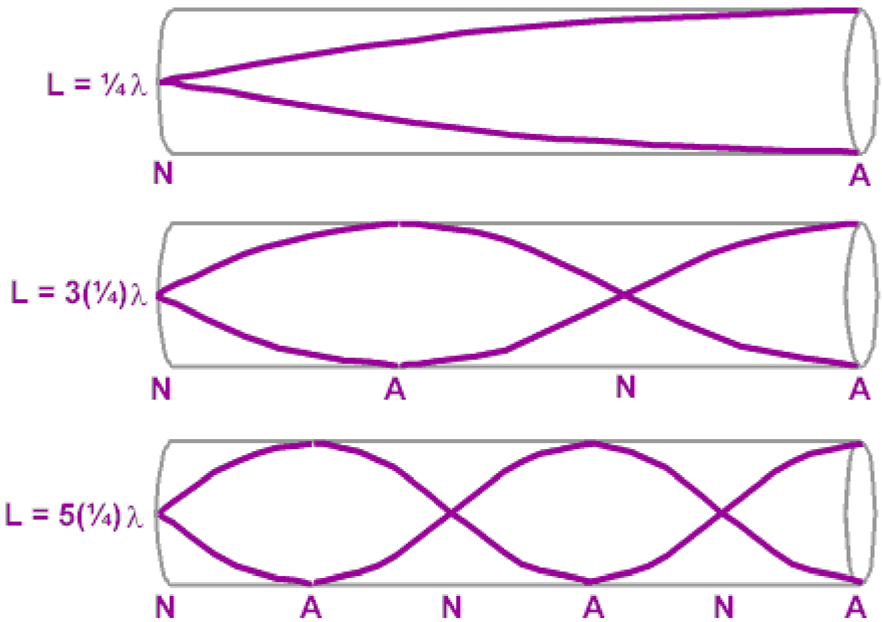
Standing Waves in Pipes
Standing waves can also be produced in open and closed pipes. Resonance occurs in an air column when a standing wave fits neatly into the column. This is important in musical instruments utilizing air columns. Resonance is achieved when a standing wave is formed inside the air column and the entire instrument begins to vibrate.

Pipe closed at one end:



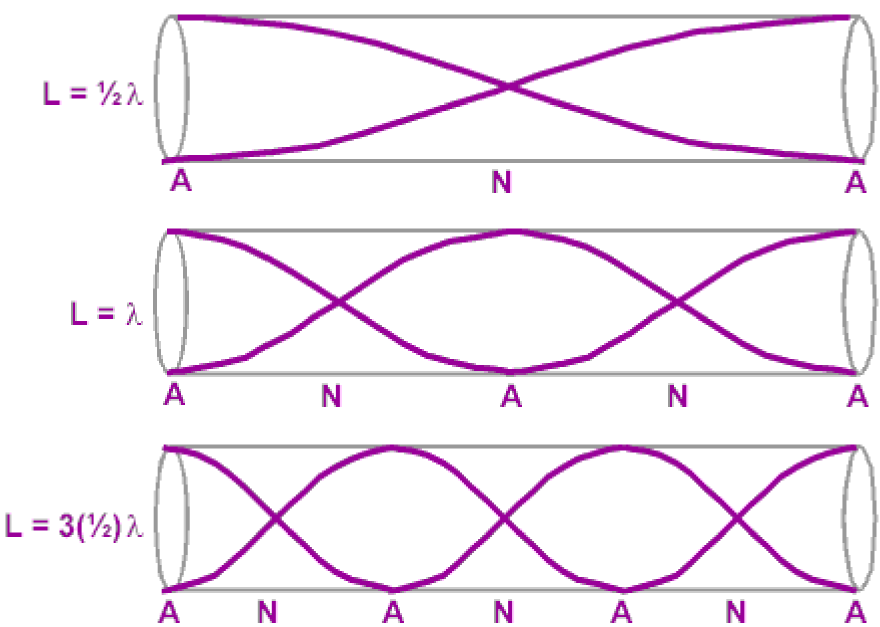
fundamental frequency
1st harmonic
f_o

1st overtone
3rd harmonic
$f_1 = 3f_o$

2nd overtone
5th harmonic
$f_2 = 5f_o$

Note that the frequency subscript matches the order of the overtone, NOT the order of the harmonic.

Pipe open at both ends:



fundamental frequency
1st harmonic
f_o

1st overtone
2nd harmonic
$f_1 = 2f_o$

2nd overtone
3rd harmonic
$f_2 = 3f_o$

Note that the frequency subscript matches the order of the overtone, NOT the order of the harmonic.

Example:
A 500 Hz tuning fork is sounded and held near the mouth of an adjustable column of air open at both ends. If the air temperature is 20.0 °C, calculate:
a) the speed of sound in air.
b) the wavelength of the sound.
c) the minimum length of the air column that produces resonance.

Example:
A closed air column resonates at two consecutive lengths of 94.0 cm and 156 cm. If the speed of sound is 351 m/s, what is the resonant frequency of the air column?

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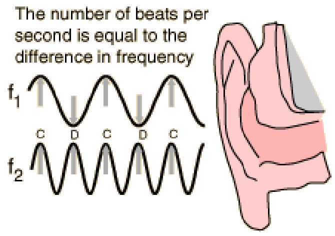
Beats
The loud and soft sequence of sounds produced when the frequencies of two sources producing the sounds are almost equal (see p. 509).

Beat frequency: the number of beats heard per second.

$$\text{Beat frequency} = \left|\text{higher frequency} - \text{lower frequency}\right|$$



When tuning pianos, strings are adjusted until no beat frequency is heard.

Example:

Two 384 Hz tuning forks are sounded together and no beats are heard. Then a metal clip is attached to a prong of one fork and again the forks are sounded together. This time a beat frequency of 4 Hz is heard. What is the new frequency of the fork with the clip?

Example:

Two vibrating tuning forks make 12 beats in 4.0 s. If one tuning fork is 1000 Hz, what are the possible frequencies of the other tuning fork?

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