SOUND WAVES

A sound wave is a wave motion that is conveyed through an elastic medium from a vibratory body to a listener. Sound wave is typical example of mechanical waves because material medium is required for its propagation. Sound wave is also an example of longitudinal wave because it travels in a direction parallel to its vibration (energy transport).
The speed of sound depends on the **density of the medium**(usually the linear density) and the **elasticity of a medium**. Sound travels fastest in solids, then in liquid and is least fastest in gases (or air)

SPEED OF SOUND

FACTORS AFFECTING SPEED OF SOUND IN AIR

1. **Temperature**: The speed of sound in air increases as the temperature increases. Mathematically, the speed of sound is directly proportional to the square root of the absolute temperature. (Absolute temperature is the temperature in kelvin.

$v \propto \sqrt{T}$

$v = k\sqrt{T}$

$k = \frac{v}{\sqrt{T}}$

For two cases,

$\frac{v_1}{\sqrt{T_1}} = \frac{v_2}{\sqrt{T_2}}$

Therefore, $\frac{v_1}{v_2} = \frac{\sqrt{T_1}}{\sqrt{T_2}}$

$\frac{v_1}{v_2} = \sqrt{\frac{T_1}{T_2}}$

Also, the speed of sound increases with temperature by about $0.61\,m s^{-1}$ for each degree rise in temperature.

2. **Wind**: Wind can be defined as the air in motion. The speed of sound of air increases when it travels in the direction of the wind but decreases when it travels opposite to the direction of the wind.
3. **Density**: The higher the density of air, the higher the speed of sound and likewise, the lower the density, the lower the speed of sound in air.
4. **Humidity**: Humidity has just a little effect on the speed of sound.

5. **Pressure**: Air pressure as a single factor has no effect on the speed of sound in air.

EQUATION FOR SOUND SPEED

Experiment has shown that sound waves require material media for their propagation. They cannot travel through vacuum.
In an ideal gas of molecular mass (M) and absolute temperature (T), the speed of sound is given as

$$v=\sqrt{\frac{\gamma RT}{M}}$$

R is the gas constant
γ Is the ratio of specific heat

$$\gamma=\frac{c_p}{c_v}$$

γ Is about 1.67 for monoatomic gases (or noble gases)
γ Is about 1.40 for diatomic gases (such as oxygen, nitrogen, hydrogen and so many more)
The speed of compressional waves in other materials (such as liquids and solids) is given by:

$$speed=\sqrt{\frac{modulus}{density}}$$

$$v=\sqrt{\frac{Y}{\rho}}$$

If the material is in the form of a bar (or solid), the young's modulus is used.
If the material is a liquid, the bulk's modulus is used.

FREUENCY OF SOUND

Sound waves are compressional waves in a material media such as air, water or steel. When the compressions and rarefactions of the waves strike the eardrum, they result in the sound we hear provided the frequencies of the sound waves are between 20Hz and 20,000Hz.
Not all sounds can be heard conveniently by the human ear. The frequency of sound that is audible to the ear is called the audible frequency. The audible frequency range is between 20Hz and 20,000Hz or 20kHz.
The frequency of sound that is too low is called Infrasonic Frequency and any frequency less than 20Hz is infrasonic
The waves with frequencies above 20kHz are called ultrasonic waves.

ULTRASOUNDS

Ultrasound tests also known as sonography can be used to create images of what's happening in the body. An instrument called a transducer emits a high frequency sound and the echoes the sound waves produce help to determine the size, shape and consistency of soft tissues and organs under the skin. This data is then transferred to images on a computer screen which is produced in real time. An ultrasound technician or a sonographer will perform the test and a radiologist or doctor will interpret the results

USES OF ULTRASONIC SOUNDS

1. In pregnancy:
a. They are used to analyze the development of an unborn baby
b. They can also be used to detect the gender of an unborn baby
c. It can also be used to predict the expected date of delivery (plus or minus two weeks)
d. It is used in fetal imaging (one of the most common use)
e. It can be used to detect the number of children in the womb

2. Diagnostics:
a. They can be used to detect and diagnose diseases including those in the heart, blood vessels, liver, spleen, kidney and almost all other internal organs
b. They can also be used to detect and treat soft tissue injuries

BENEFITS OF ULTRASOUNDS

1. They are painless
2. Individuals aren’t exposed to any form of radiation
3. They can capture some soft tissue images that don’t show well in x-rays

INTENSITY OF SOUND WAVES

The intensity of a sound wave is a power carried by the wave through a unit area in a direction (or perpendicular) to the direction of propagation of the wave

$$Intensity=\frac{Change \in energy}{Change \in Area \times Change \in time}$$

$$I=\frac{\Delta E}{\Delta A \Delta t}$$

But

$$Power=\frac{Energy}{Time}$$

$$I=\frac{\Delta E}{\Delta t}\times\frac{1}{\Delta A}$$

$$I=\Delta P\times\frac{1}{\Delta A}$$

$$I=\frac{\Delta P}{\Delta A}$$

The area (A) in the above formula is $4\pi r^2$ i.e. the area of a sphere

$$\Delta A=4\pi r^2$$

$$I = \frac{\Delta P}{\Delta A}$$
$$\Delta P = I \Delta A$$
$$\Delta P = I \times 4 \pi r^2$$
$$\Delta P = 4 \pi r^2 I$$
For two or more waves with the same power transfer,
$$4 \pi (r_1)^2 I_1 = 4 \pi (r_2)^2 I_2$$
$$(r_1)^2 I_1 = (r_2)^2 I_2$$
$$\frac{I_1}{I_2} = \frac{(r_2)^2}{(r_1)^2}$$
$$\frac{I_1}{I_2} = \left(\frac{r_2}{r_1}\right)^2$$
It can be seen that the intensity of a spherical wave is inversely proportional to the radius of the wave.
The intensity of a spherical wave decreases inversely with the square of its distance from the source.
The SI unit of intensity is Watts per square meters $W m^{-2}$
The table below gives the speed of sound in different materials.

Material	Speed
Air	340
Polythene	920
Helium	977
Water	1500
Marble	3810
Aluminum	5000
Iron	5120

Light travels faster in air than sound. That explains the reason lightning flashes are seen before the sound of thunder claps.
As humans age, the frequency of sounds become less audible to humans ear. This is called loss of hearing.

DIAGRAMMATIC REPRESENTATION OF SOUND WAVES
Regions in sound waves where the coils are tightly packed are called compressions and where they are loosely packed or further apart are called rarefactions.
The distance between two adjacent compressions is called the wavelength and the distance between two adjacent (or successive) rarefactions is also the wavelength. However, the distance between a compression and a rarefaction or a rarefaction and a compression is half the wavelength.
$$d_{r-r} = \lambda$$
$$d_{c-c} = \lambda$$

$$d_{c-r}=\frac{\lambda}{2}$$

$$d_{r-c}=\frac{\lambda}{2}$$

ECHO

This can be defined as the sound heard after the reflection of a sound wave from a (plane) surface. Multiple reflections of sound is called Reverberation.

Reverberation can also be defined as the persistence of a sound when the source of the sound has been removed.

Echo and reverberation are not desired in recording studios and cinemas because they mix noise and music (good sound) together. Echo and reverberation can be reduced by covering the walls with some form of perforated foam.

APPLICATIONS OF ECHO

It can be used to determine speed of sound in air using the formula.

$$v=\frac{2x}{t}$$

It can be used to determine the depth of the sea using a device called fathometer or sonar or echo sounder.

It can also be used in oil and gas exploitation to detect leakage.

CHARACTERISTICS OF SOUNDS

1. Pitch: The pitch of sound or a musical note is a subjective judgment of its highness or lowness. It is a characteristic of sound that helps to differentiate between a high note from a low one. The pitch is determined primarily by a frequency. The higher the frequency, the higher the pitch and vice versa
2. Quality: This is also known as Timbre or tone. It is the characteristic of a musical sound used to distinguish the sources of the note. It is also used to distinguish high notes from low ones of the same pitch. The quality is also called the timbre and it depends on overtones or harmonics. An untrained listener can identify a musical instrument that is generating a sound without seeing the instrument as a result of the quality
3. Loudness: This can be defined as a measure of the human perception of sound. The loudness of sound depends majorly on the amplitude. Mathematically

$$Loudness \propto (Amplitude)^2$$

$$L \propto A^2$$

$$L=kA^2$$

MEASURING SOUND LEVELS

A passing train generates sound intensities that may be about $10^4 10^6$times greater than the sound intensity of a buzzing mosquito yet we can hear both sounds clearly. Although our ears are sensitive to that enormous range of sound intensities, our subjective judgment of loudness does not directly correspond to them magnitude of the sound intensity.
Sound intensity level or loudness level can be measured in decibel (dB)
The intensity level (IL) is described mathematically as

$$IL = 10\log\left(\frac{I}{I_o}\right)$$

I_o Is known as the reference intensity
The standard reference intensity $\left(I_o\right)$ of sound waves is $10^{-12} W m^{-2}$
Bel in decibel is in honor of the inventor of the telephone Alexander Graham Bell.
The ear does not respond equally to well to all frequencies in the audio range. It is considerably macro sensitive to frequencies between 2000 and 5000Hz than either higher or lower frequencies.
The normal ear can distinguish between intensity levels that differ by about 1dB

STATIONARY WAVES IN SOUNDS

These are also called standing waves. They can be defined as waves obtained when two progressive waves of equal amplitude and frequencies travel in opposite directions and combine together. The instrument used to obtain a stationary wave is called a Stroboscope.
In a stationary wave, two points are known to be very important. They are the node and antinodes. Antinode is the total amplitude of the two waves. It is defined as the point of maximum displacement. Node is the point where the two waves intercept. It can also be defined as the point of no displacement or the point of no amplitude.
The distance between a node and the next node is half the wavelength. Also, the distance between two antinodes is half the wavelength. However, the distance between the node and an antinode is a quarter of the wavelength.

$$d_{n-n} = \frac{\lambda}{2}$$

$$d_{a-a} = \frac{\lambda}{2}$$

$$d_{n-a} = \frac{\lambda}{4}$$

$$d_{a-n} = \frac{\lambda}{4}$$

Common examples of stationary waves are waves produced in pipes and waves produced in strings

STATIONARY WAVES PRODUCED IN STRINGS

SONOMETER

A sonometer is an example of a stringed instrument used to obtain a stationary wave.

Stationary waves in a string are transverse

The string whose frequency is to be determined is be determined is attached to one end of the block. The string passes over a (frictionless) pulley via two pegs. The frequency obtained by the string depends on the following factors

1. Tension (T) of the string: The higher the tension (i.e. the string is more drawn and is tighter), the higher the frequency. Mathematically, the frequency is directly proportional to the square root of the tension of the strange.

$$f \propto \sqrt{T}$$

$$f = k\sqrt{T}$$

$$k = \frac{f}{\sqrt{T}}$$

$$\frac{f_1}{\sqrt{T_1}} = \frac{f_2}{\sqrt{T_2}}$$

$$\frac{f_1}{f_2} = \sqrt{\frac{T_1}{T_2}}$$

2. Length (l) of the string: The shorter the length, the higher the frequency produced in the string. Mathematically, the frequency is inversely proportional to the length of the string.

$$f \propto \frac{1}{l}$$

$$f = \frac{k}{l}$$

$$k = fl$$

$$f_1 l_1 = f_2 l_2$$

$$\frac{f_1}{f_2} = \frac{l_2}{l_1}$$

3. Linear density: This can be defined as the mass per unit length.

$$\mu = \frac{m}{l}$$

The frequency produced in a string is inversely proportional to the square root of the linear density.

$$f \propto \frac{1}{\sqrt{\mu}}$$

$$f = \frac{k}{\sqrt{\mu}}$$

$$k = f\sqrt{\mu}$$

$$\frac{f_1}{f_2}=\sqrt{\frac{\mu_2}{\mu_1}}$$

But if the length of the strings used are constant, then only the mass of the string will have an effect on the frequency of the string since

$$\mu=\frac{m}{l}$$

At constant length,

$$\frac{f_1}{f_2}=\sqrt{\frac{m_2}{m_1}}$$

Recall

$$f \propto \sqrt{T}$$

$$f \propto \frac{1}{l}$$

$$f \propto \frac{1}{\sqrt{\mu}}$$

On joining,

$$f \propto \frac{1}{l}\cdot\frac{1}{\sqrt{\mu}}\cdot\sqrt{T}$$

$$f \propto \frac{1}{l}\cdot\sqrt{\frac{T}{\mu}}$$

$$f=\frac{k}{l}\cdot\sqrt{\frac{T}{\mu}}$$

From mathematical investigation,

$$k=\frac{n}{2}$$

Therefore,

$$f=\frac{n}{2l}\cdot\sqrt{\frac{T}{\mu}}$$

Here, n is called the number of harmonics.

The lowest frequency of vibration of a string is called the **fundamental frequency**. The multiple values of this frequency are called the harmonics. The frequency that is double is called the second harmonic, triple times the frequency the frequency is called the third harmonic and so on.

All resonant frequencies which are higher than the fundamental frequency whether they are integer multiples or not are called overtones. Each resonance frequency corresponds to an oscillation of the entire string.

Fundamental frequency (1^{st} harmonic)

$$f_o=\frac{v}{2l}$$

Here, v is the velocity of the sound produced.

2^{nd} harmonic (1^{st} overtone)

$$f_1=\frac{v}{l}$$

$f_1=2\left(\frac{v}{2l}\right)$

$f_1=2f_o$

3rd harmonic (2nd overtone)

$f_2=3\left(\frac{v}{2l}\right)$

$f_2=3f_o$

The nth harmonic frequency can be written into

$f_{(n-1)}=n\left(\frac{v}{2l}\right)=nf_o$

The nth overtone frequency is expressed as

$f_n=(n+1)\left(\frac{v}{2l}\right)=(n+1)f_o$

The frequencies of overtones are the higher multiples of the fundamental frequencies. For example if the fundamental frequency

Two major factors that affect the velocity of sound in a string

Tension (T) in the string:

$v \propto \sqrt{T}$

The linear density:

$v \propto \frac{1}{\sqrt{\mu}}$

On combining,

$v \propto \sqrt{\frac{T}{\mu}}$

From

$f_n=n\left(\frac{v}{2l}\right)=nf_o$

$f_n=v\left(\frac{n}{2l}\right)$

$v=\sqrt{\frac{T}{\mu}}$

$f_n=\left(\frac{n}{2l}\right)\cdot\sqrt{\frac{T}{\mu}}$

Also,

$f=\frac{n}{2l}\cdot\sqrt{\frac{T}{\mu}}$

$v=\sqrt{\frac{T}{\mu}}$

Therefore,

$f=\frac{nv}{2l}$

$v=f\lambda$

$$\lambda = \frac{2l}{n}$$

Increasing the tension in the string raises the speed of waves along it and then raises the natural vibration frequency. Anytime we hear a string instrument being tuned, the musician is adjusting the tension in the string.

STATIONARY WAVES IN A PIPE/SOLID PIPE

Stationary waves can also be obtained in a pipe by blowing air through the pipe. There are two types of pipe. They are longitudinal waves

Open pipe: An open pipe is one that opened at both ends

Closed pipe: While a closed pipe is one that is closed at one end

In a pipe, the velocity (v) of the wave is given as

$$v = \sqrt{\frac{Y}{\rho}}$$

$$v = \sqrt{\frac{Modulus}{Density}}$$

The modulus could either be bulk's modulus or young's modulus. If the material used is a solid, then the young's modulus will be used

OPEN PIPE

$$f = \frac{nv}{2l}$$

$$n = 2\lambda$$

Nth harmonic is (n-1)th overtone.

For an open pipe,

$$\lambda = 2l$$

CLOSED PIPE

A closed pipe is also known as a resonant tube. When air is blown into a closed pipe, series of overtones can be obtained in the pipe.

In closed pipes, the number of harmonics is always an odd number in closed pipes

Here,

$$f = \frac{nv}{4l}$$

$$n = 2\lambda$$

For a closed pipe,

$$\lambda = 2l$$

1^{st} harmonic is the fundamental

3^{rd} harmonic is 1^{st} overtone

5^{th} harmonic is 2^{nd} overtone

7^{th} harmonic is 3^{rd} overtone

From the analyses above, it can be deduced that there are only odd numbers of harmonics in a closed pipe. Overtones can be converted into harmonics by the overtone by two and adding one.

For example, for the 3rd overtone we have

$(3\times 2)+1=7$

Therefore, 3rd overtone is the 7th harmonic.

The frequencies of overtones are the higher multiples of the fundamental frequencies. For example if the fundamental frequency of a wave is 320Hz

Overtones are

640 (2 times)

960 (3 times)

1280 (4 times)

And so on.

Although in a closed pipe (or resonant tube), it is quite different.

<u>OCTAVES</u>

A note is the octave of another if the frequency is twice the other. For example:

If A is the octave of B then:

$f_A=2f_B$

The formula used to calculate the speed of sound in air using resonance positions is given as

$v=2f(l_2-l_1)$

<u>BEATS</u>

This can be defined as the periodic rise and fall in the intensity of sound. The alternations of maximum and minimum sound intensity produced by the superposition of two waves of slightly different frequencies are called beat.

If two tuning forks of the nearly the same frequency are compressed together, a sound known as beat will be produced.

The number of beats per second (i.e. the frequency of the beat) is the difference between the frequencies of the two waves that combine

$f_b=f_2-f_1$

It can also be said to be the difference between the higher frequency and the lower frequency

$f_b=f_h-f_l$

Also,

$f_b=f_h-f_{loaded\ tuning\ fork}$

Tuning forks have pure tones i.e. they exhibit free vibration but a loaded tuning fork is of a lower frequency.

<u>DOPPLER EFFECT</u>

Doppler Effect can be defined as the (apparent) change in the frequency of sound due to a relative motion between a sound source and a listener (or an observer).

This concept was named after an Austrian physicist Christian Doppler.

An observer will experience different frequencies of sound when a sound source is moved to and from its original position. Similarly, different frequencies of sound will also be heard when an observer moves to and from a stationary sound source.
Suppose that a moving sound source emits a sound of frequency (f_o) and (v) is the speed of sound. If the source approaches the listener at a speed (v_s) measured relative to the medium conducting the sound. Suppose further that the observer is moving towards the source at a speed (v_o) measured relative to the medium, then the observer will hear a sound of frequency (f) given by

$$f = f_o \left(\frac{v + v_o}{v - v_s} \right)$$

Beat and Doppler Effect are also based on the principle of superposition of waves
Stationary waves in a string are transverse while sound waves in pipes are longitudinal waves

SIREN
This is a source used to produce sounds of high frequencies. The frequency depends on the number of holes (n) present in the siren and the speed (s) of revolutions per second

$$frequency\ of\ siren = number\ of\ holes \times speed$$

$$f_s = ns$$

But

$$speed = \frac{number\ of\ revolutions}{time}$$

$$s = \frac{r}{t}$$

Therefore,

$$f_s = \frac{nr}{t}$$

MUSICAL SOUND AND NOISE
Music is the sound that is originated from a particular source and vibrates at a regular frequency. Noise is an unpleasant sound originated from different sources and vibrates at a regular frequency.
So far in this topic, we’ve talked about musical sounds
MUSICAL INSTRUMENTS
Musical instruments can be divided into three based on the way sound is produced from them.
Stringed Instruments: Sound is produced from these instruments by plucking or striking the sting.
Wind Instruments: In these instruments, sounds are produced by blowing air through them.
Percussion instruments: These instruments produce sound by hitting them. A major example is the drum set

RESONANCE IN SOUND WAVES

This is an effect caused when a vibrating body sets another body into vibration until both sides have the same frequency. Resonance is an important phenomenon in physics and it occurs in all branches of physics. In sound waves, resonance occurs when the frequency of a tuning fork is equal to the natural frequency of air column.

Acoustic resonance is a phenomenon in which an acoustic system amplifies waves whose frequency matches one of its own natural frequencies of vibration (its resonance frequencies).

Experiment using two tuning forks oscillating at the same frequency. One of the forks is being hit with a rubberized mallet. Although the first tuning fork has been hit, the other fork is visibly excited due to the oscillation caused by the periodic change in the pressure and density of air by hitting the first fork creating an acoustic resonance between the forks