16 SOUND WAVES

SOUND AND MUSICAL NOTES

Sound is a wave which moves through a medium which can produce sensation of hearing. It is produced by sources which vibrate. When a vibrating object disturbs a medium, waves are produced and they travel outward from the source. This wave motion through a medium is called sound. Sound is a product of vibration.

OBJECTIVES

At the end of the topic, students should be able to:

- identify the vibrating sources when sound is produced;
- use reflection of sound to explain echoes;
- state the application of echoes;
- distinguish between
    - â€¢ noise and music;
    - â€¢ intensity and loudness;
    - â€¢ pitch and frequency as applied to sound.

Sources of sound

Anytime an object vibrates, sound waves are produced. Vibrating objects producing sound include:

(a) the plucked strings of a musical instruments like piano, violin and guitar.

(b) vibration of solids when struck by a hammer. Examples are bells and talking drums.

(c) compression and expansion of air column in wind instruments such as in flute and trumpet.

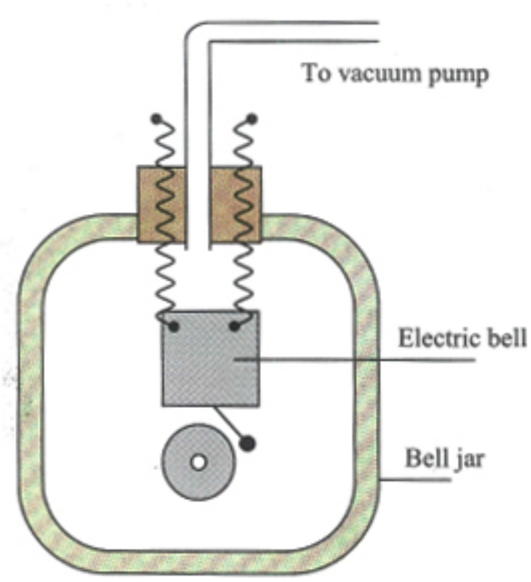


Figure 16.1 Sound requires a medium to travel from one place to another

Propagation of sound

Sound is a mechanical longitudinal wave. It requires a medium (a solid, liquid or gas) to transfer its energy from point to point. We can demonstrate that sound needs a medium to propagate its energy with the setup in Figure 15.1 An electric bell is placed inside a bell jar containing air. When the bell is switched on, sound produced by the bell is heard outside. As the air is pumped out slowly from the bell jar, the sound of the bell becomes fainter and fainter until no sound is heard when the air is completely pumped out, though the bell is still ringing. If the air is returned into the jar, the sound of the ringing bell is heard again outside the jar. This proves that sound cannot pass through a vacuum but requires a medium to transfer its energy from one place to another.

Velocity of sound

The velocity of sound in air depends on temperature. Velocity of sound in air is about 330 ms^{-1} at 0Â°C. Its value increases slightly with rise in temperature, velocity of sound increases in air by 0.6 ms^{-1} for each degree rise in temperature.

Velocity of sound in air – Velocity at 0Â°C + 0.6 Ã— Rise in temperature

At a temperature of 10Â°C, the speed of sound in air is about 336 ms^{-1}.

The velocity of sound is higher in liquids and solids. Speed of sound in water at 8Â°C is about 1435 ms^{-1} and about 5000 ms^{-1} in iron.

Factors affecting the velocity of sound in air

(a) Temperature: The velocity of sound in air increases slightly with rise in temperature.

(b) Wind: The direction of wind affects the speed of sound in air;

speed of sound in air is higher if it moves in the direction of wind.

(c) Density: The speed of sound in air increases if the density of air is lowered. Any factor that lowers the density of air, like temperature, will increase the speed of sound in air.

How sound travels through air

Sound waves are longitudinal (i.e. the vibration of the medium is in the same direction as the motion of the wave). Sound waves consist of series of **compressions** (region of squeezed air particles) and **rarefactions** (region of stretched out air particles).

As sound waves are passed through air, they push air molecules together at a slightly higher pressure. The region of squeezed air molecules is called **compression** (c). In some places, the air molecules are stretched slightly so that the pressure is low. These regions of low pressure are called **rarefactions**. The compressions and rarefactions of air molecules move out at the speed of sound towards the ear as illustrated in Figure 16.2.

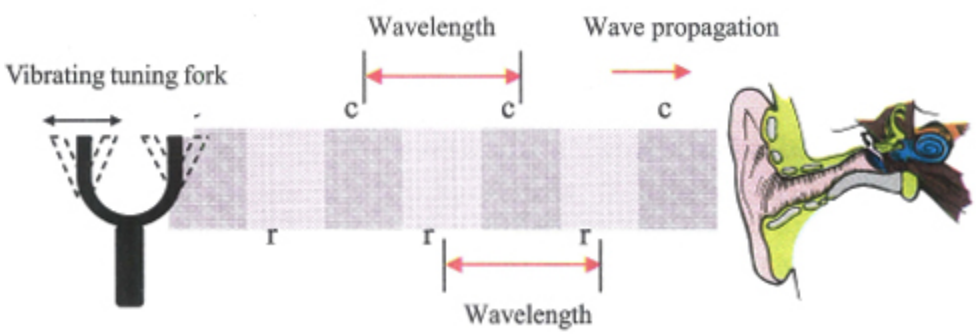


Figure 16.2: Sound waves produced by a vibrating tuning fork

Properties of sound waves

Sound waves are longitudinal mechanical waves and they behave exactly like other waves except that they cannot be polarized. The way a wave behaves is called its property. These properties are **reflection, refraction, diffraction** and **interference.**

Sound waves are refracted or bent when they travel from cold air to warm air. The velocity of sound in warm air is higher than its velocity in cold air; therefore, sound wave is refracted towards the normal as it enters the cold air from warm air.

Sound waves are also diffracted or spread out as they pass round an obstacle or openings like doorways and windows. Most openings are smaller than the wavelength of sound; therefore, it spreads out on passing through them. This is why we can hear sound even when the speaker is out of sight.

Reflection and echoes

Reflection of sound waves is the most common property of a sound wave. If sound waves hit a hard smooth solid surface like walls or cliff, it is reflected. A sound reflected from an obstacle is called an **echo**.

An echo is a sound reflected from a hard and smooth surface.

How an echo is heard

When we hear a sound, the sensation of sound lasts for 0.1 seconds before it fades out. If the sound reflected from an obstacle reaches the ear in a time less than 0.1 seconds, the ear cannot distinguish between the original sound and the reflected sound. When the reflected sound reaches the ear in a time longer than 0.1 seconds, the reflected sound is heard as a new sound. The reflected sound is called an **echo.**

Echo is heard if the cliff or the reflecting surface is at least 16.5 m away from the source of the sound, if the speed of sound in air is 330 ms^{-1}.

$$x = \frac{vt}{2} = \frac{330 \times 0.1}{2} = 16.5\ m.$$

Reverberation

In a large hall, the walls and ceilings produce multiple echoes of varying intensities by reflecting sound many times. This is known as **reverberation**. The time the sound lasts before the walls and ceiling of the building finally absorbs it is called **reverberation time**.

Reverberation is a multiple reflection of sound from the walls, floor and ceiling of large buildings.

Disadvantages of echoes and reverberations

Echoes and reverberations can be a nuisance. The walls of large recording studios produce echoes from musical instruments; this reduces the quality of music recorded. Echoes and reverberations can be reduced by padding the walls and ceilings of recording studios and large halls with materials which reduces the reverberation time and thereby absorbing sound faster. Soft perforated materials absorb sound waves because they reduce reverberation time.

Uses of echoes

1. Measuring of speed of sound in air:

Echo is used to find the speed of sound in air. An observer stands in front of a hard smooth wall or cliff, which is at least 16.5 m away and produces sound. The echo or reflected sound is heard sometime later. This happens when the sound hits the cliff and travels back to the observer. The sound wave covers twice the distance between the observer and the cliff. If the distance between the observer and cliff is **x** metres, sound wave travels a total distance of **2x** to and from the cliff a time **t** seconds. The speed of sound is calculated using the formula:

$$\text{Speed of sound} = \frac{\text{Total distance covered}}{\text{Time taken}}$$

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

Worked example

1. A man stands 50 m in front of a cliff and claps his hand and the echo is heard 0.3 seconds later. Calculate the speed of sound in air.

Solution

$$v = \frac{2x}{t} = \frac{2 \times 50}{0.3} = 333\ m\,s^{-1}$$

2. Measuring the depth of the seabed:

Determining the depths of a sea by the use of echo sounding in water are the ship. Other important practical applications of echo. Locating shipwrecks, obstacles and submarines under water below. The ship sends an ultrasound from its transmitter into the water and is reflected by the seabed to the receiver attached to the ship. The time it takes the ultrasound to travel from the ship to the seabed and back is measured. The depth of seabed is calculated by the formula:

$$\text{Depth of seabed} = \frac{\text{Velocity} \times \text{time}}{2}$$

$$x = \frac{vt}{2}$$

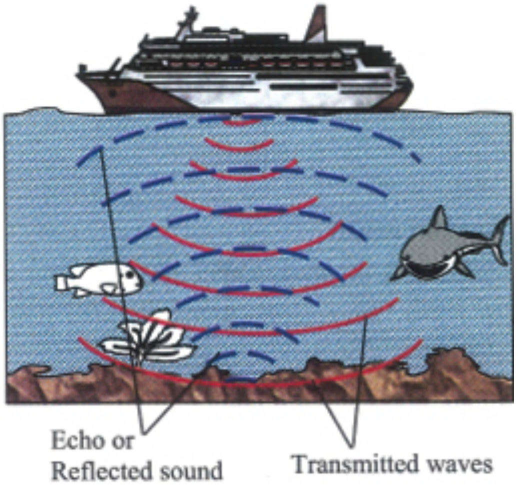


Figure 16.3: Measurement of sea depth

Worked example

A ship sailing on a sea sends a signal and receives the echo from a submarine sailing underwater 2.5 seconds later. Find the how far the submarine is from the ship if the speed of sound in seawater is 1450 ms^{-1}.

Solution

$$x = \frac{1450 \times 2.5}{2} = 1812.5m \text{ or } 1.8125km$$

3. Ultrasonic sounding

Geologists and geophysicists use ultrasound for oil and solid minerals exploration. Ultrasound is sent down into the earth and is reflected by different liquids and mineral solids. Geologists and geophysicists, on studying the echoes from different minerals, can predict the type of mineral reflecting the ultrasonic waves. The same principle is used in ultrasonic scanning to locate the position of a baby in the womb.

Noises and musical notes

Vibrating objects produce sound. The type of sound produced, depends on the mode of vibration of the source. We can distinguish between two types of sound: **noise** and **musical notes**. ***A noise is an unwanted sound because it is unpleasant to the ear. It is produced by sources vibrating at irregular frequency.***

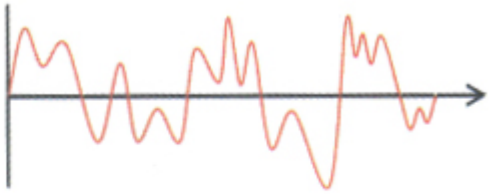


Figure16.4a: Wave pattern of noise

Musical notes are sound produced by sources vibrating at regular frequency; they are pleasant to the ear. The wave patterns of musical notes are repeated at regular intervals as shown in figure 15.4b. Music is a combination of musical notes at a regular pattern.

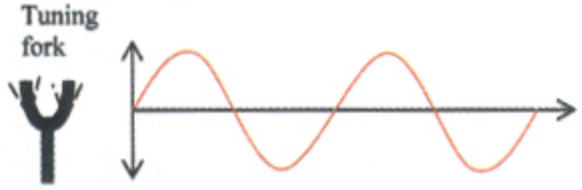


Figure 16.4b: Musical note from a tuning fork

Characteristics of musical notes

Every musical instrument produces a note. The notes from different musical instruments are distinguished from each other by their **pitch, loudness (intensity)** and **quality**. These are called properties or characteristics of musical notes.

1. Pitch and frequency

Pitch is the term used to describe how high or low a musical note is. A source, which vibrates at a high frequency, produces sounds of high pitch. A low-pitched note is produced by source of sound, which vibrates at a low frequency. The pitch of a note is therefore dependent on the frequency of the source.

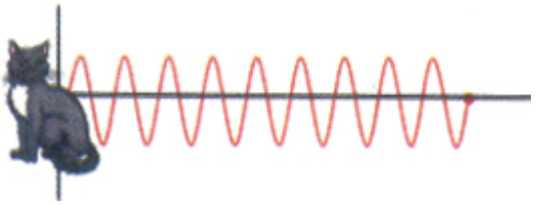


Figure 16.5a: Musical note of high pitch

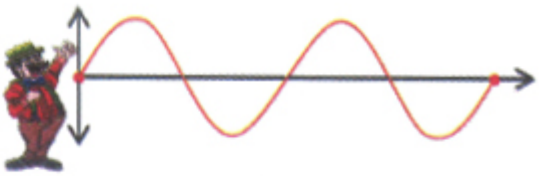


Figure 16.5b: Musical note of low pitch

2. Loudness and amplitude

Loudness is a term we use to describe the **intensity** or amount of energy transferred by a sound wave in a specific direction. *The loudness of a note depends on the **amplitude** of the sound wave*. A loud sound has a higher amplitude than a soft sound and therefore contains more energy.

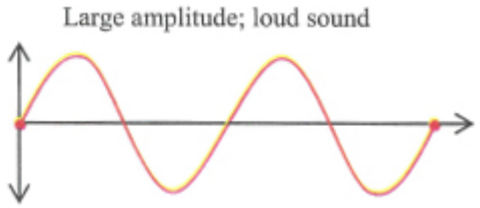


Figure 16.5c: Musical note of a loud sound

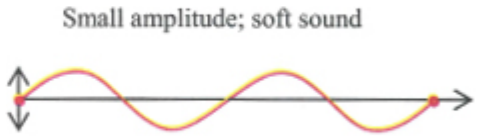


Figure 16.5d: Musical note of soft sound

Figure 15.5 represents two sound waves of the same frequency (pitch) but different amplitude.

The louder sound (with greater amplitude) transmits more energy per unit area in a given direction. Loudness of a sound depends on a number of factors:

(a) The total mass of air set into vibration:

When a tuning fork is set into vibration and held near the ear, a soft sound is heard. If the tuning fork is pressed on the surface of a table as shown in Figure 16.6, a loud sound is heard. The loud sound is produced because the tuning fork forced the tableâ€™s surface to vibrate, which in turn forces the air close to it to vibrate. The large mass of vibrating air produces the loud sound that is heard.

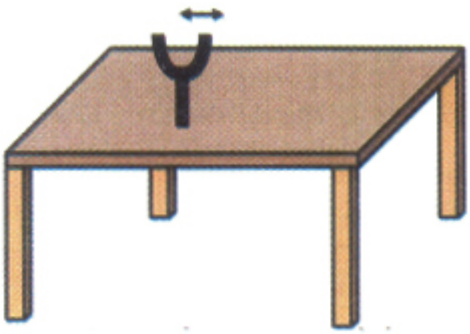


Figure 16.6: A vibrating tuning fork pressed on a table surface produces a loud sound

(b) The strength of the initial vibration of the source of sound.

(c) The distance of the source from the observer.

The amplitude (energy) of a sound wave decreases as the wave spreads out from source such that an inverse square law is obeyed. The intensity (energy transmitted per unit area in a given direction) of the sound decreases fast as the distance increases.

3. Qualify and overtones

Quality (timbre or **tone)** is the characteristic of a note, which helps us to identify sound from different musical instruments, which have the same pitch and loudness if played at the same time. **Quality** of a note depends on the **harmonics** or the **overtones**. The same note sounds differently if played on **piano, guitar** or **violin**. The difference in the notes produced by these musical instruments is due to the number and strength of the overtones combined or blended to form the note.

Overtone (harmonics) and waveform

A string of a fixed length can vibrate in many different ways. Figure 16.7 illustrates some ways a string fixed at both ends can be made to vibrate at different frequencies and wavelengths.

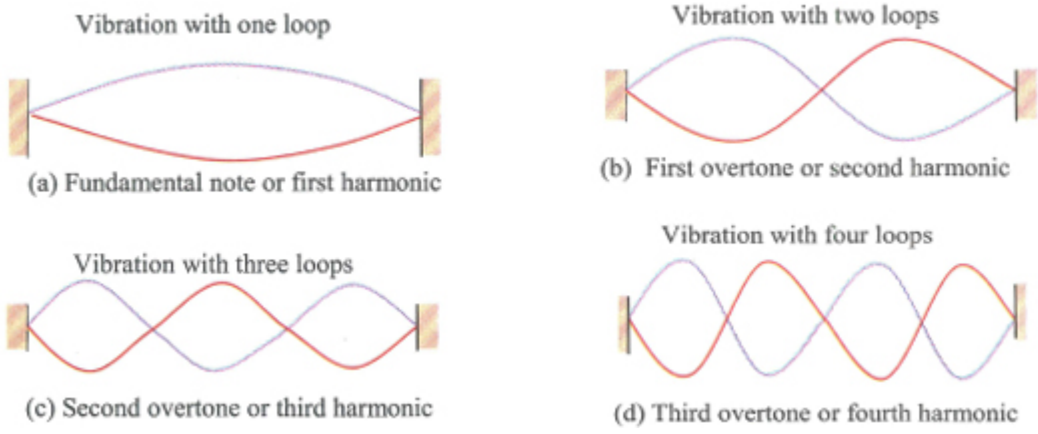


Figure 16.7: Some ways a fixed string can vibrate

The simplest mode of vibration is when the whole string vibrates with only one loop as shown in Figure 16.7a. *A sound of lowest pitch or tone produced is the* **fundamental note** or **first harmonic.**

Fundamental frequency is the frequency of a note with the lowest pitch or tone.

The string can vibrate with two or more loops. When it vibrates with two loops as shown in Figure 16.7b, the frequency of vibration is twice the frequency of the fundamental note. This mode of vibration of the string is known as **second harmonic** or **first overtone**. Vibrations with three loops produce frequency three times the fundamental frequency. This mode of vibration of the string is called **third harmonic** or **second overtone.**

Harmonics are frequencies produced by adding or multiplying the fundamental frequency by whole numbers.

Overtones are musical notes formed by blending or mixing the fundamental frequency with other higher frequencies.

Waveform: The blending of the fundamental frequency with the harmonics produces different waveforms. The pattern of waveform produced depends on the musical instrument played. When the sounds from these musical instruments are viewed on the cathode ray oscilloscope, the amplitude of the waveform produced varies. The wave pattern for tuning fork, piano and violin are shown in Figure 16.8.

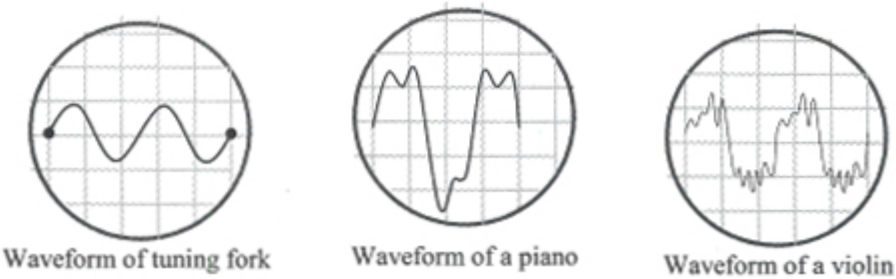
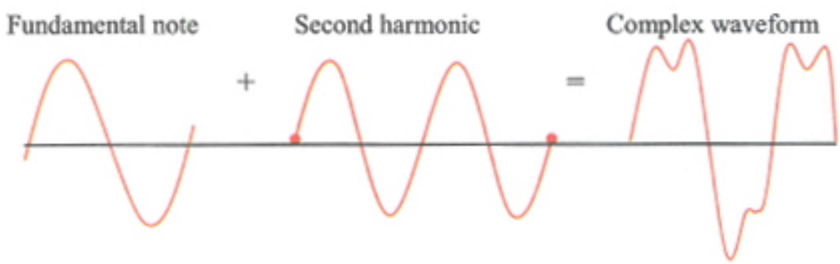


Figure 16.8: Wave patterns of tuning fork, piano and violin

Tuning fork produces a pure note, a waveform of constant frequency and amplitude.

Violin, piano and other musical instruments produce many frequencies or harmonics at the same time; these frequencies are blended together to form a complex waveform displayed by the oscilloscope. The way these waves are blended to form complex wave pattern is as shown below.



If more harmonics are blended, other complex waveforms are formed. The quality of a note produced by any musical instrument depends on the waveform, which also depends on the number of harmonics or overtones blended with the fundamental note. The closer a sound wave is to a waveform with constant frequency, the better the quality of the note.

Summary

â€¢ **A sound** is a mechanical longitudinal wave which moves through a medium and can produce sensation of hearing. It is produced by sources which vibrate. A sound cannot pass through a vacuum but requires a medium to transfer its energy from one place to another.

â€¢ **Velocity of sound** in air is about 330ms^{-1} at 0Â°C. Its value increases slightly with rise in temperature, in air, velocity of sound increases by 0.6ms^{-1} for every degree rise in temperature.

â€¢ The way a wave behaves is called its **property**. The properties of sound waves are **reflection, refraction, diffraction** and **interference**. A sound wave cannot be polarized.

â€¢ An **echo** is a sound reflected from a hard smooth surface. An echo is heard if the cliff or the reflecting surface is at least 16.5m away from the source of the sound if the speed of sound in air is 330 ms^{-1}.

â€¢ **Reverberation** is a multiple reflection of sound from the walls, floor and ceiling of large buildings.

â€¢ **Echoes and reverberations** can be reduced by padding the walls and ceilings of recording studios and large halls with materials which reduce the reverberation time and thereby absorbing sound faster.

â€¢ **Uses of echoes:**

  â€¢ Echo is used to find the speed of sound in air.

$$\text{Speed of sound} = \frac{\text{Total distance covered}}{\text{Time taken}}$$

  â€¢ Another important practical application of echo is echo sounding in water to determine how deep a sea is, to locate shipwrecks, obstacles and submarines under water.

  â€¢ Geologists and geophysicists use ultrasound to explore for oil and solid minerals beneath the earth.

â€¢ Two types of sound are **noise** and **musical notes**.

â€¢ **Noise** is an unwanted sound because it is unpleasant to hear. It is produced by sources vibrating at irregular frequency.

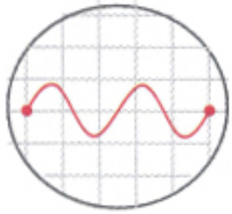
â€¢ **Musical notes** are sounds produced by sources vibrating at regular frequency; they are pleasant to hear.

â€¢ **Pitch** is the term used to describe the number of vibrations per second (frequency) produced by a source of sound.

- â€¢ **Loudness** is a term we use to describe the intensity amount of energy transferred by a **j** sound wave in a specific direction.
- â€¢ **Quality (timbre)** is the characteristic of a note which helps us to identify sound from different musical instruments which have the same pitch and loudness if played at the same time.
- â€¢ **Fundamental frequency** is frequency of a note with the lowest pitch or tone.
- â€¢ **Harmonics** are frequencies produced by adding or multiplying the fundamental frequency by whole numbers.
- â€¢ **Overtones** are musical notes formed by blending or mixing the fundamental frequency with other higher frequencies.

Practice questions 16a

1. (a) What is sound and how is it produced?
   (b) Describe an experiment to show that sound requires material medium to transmit its energy?
2. (a) State the factors that affect the velocity of sound in air.
   (b) A sound frequency 100Hz and wavelength 3.34m is travelling through air, calculate the velocity of sound in air.
3. (a) State the properties of sound waves.
   (b) Explain why sound cannot be polarized.
4. (a) Explain the following terms: reverberation and echo.
   (b) Explain how reverberation and echo affect the quality of sound recorded in a large studio.
   (c) How can echo and reverberation be reduced in the recording studio?
5. Explain how echoes may be employed:
   (a) to determine the speed of sound in air;
   (b) to locate a submerged ship;
   (c) to locate likely places to drill for oil.
6. (a) Why is echo considered a nuisance?
   (b) A boy standing 150 metres away from a large building produced a sound and received an echo after 0.88 seconds. What is the speed of sound in air?
7. (a) Distinguish between noise and musical notes.
   (b) State the characteristics of a musical note and **one** factor which affects each.
   (c) The diagram represents a pure note from a sounding tuning fork. Copy the diagram and draw close to it another graph for a note of;



(i) higher pitch but the same amplitude;
(ii) higher energy but the same pitch.

8. (a) Explain the terms; *fundamental note and overtones.*
   (b) Define *frequency* and explain the term *harmonics.*
   (c) How do harmonics determine the quality of a musical note?
9. Explain what is meant by; the pitch, quality and intensity of a musical note?

VIBRATION OF STRINGS AND AIR COLUMNS IN PIPES

Sound is produced by a vibrating source, the quality of sound produced depends on the mode of vibration of the medium and the geometry of the vibrating object.

OBJECTIVES

At the end of the topic, students should be able to:

- explain forced vibration and how it is used to amplify sound;
- explain the formation of standing waves and produce these waves in a stretched strings and pipes;
- state the factors on which the frequency of vibrating strings depends;
- use resonance tube to determine the velocity of sound in air;
- use the relationship $v = fl$ in solving numerical problems.

Forced vibration and resonance

Forced vibration and resonance were studied in detail in chapter 5. For the benefit of the student, we will summarize this topic here particularly as it relates to sound.

No vibrating object or system continues to vibrate forever because energy is lost continuously through friction and resisting forces. The amplitude of vibration steadily decreases until the oscillation stops completely due to loss of energy. To keep the system vibrating with constant amplitude, the lost energy is replaced constantly. This is achieved by applying an external periodic force to the vibrating system or object. The vibration of a system maintained by an external periodic force is said to be forced.

Forced vibration can increase the loudness of a sound. The vibrating tuning fork if pressed against a tabletop amplifies the sound because the tuning fork forces the tableâ€™s top and the air molecules close to it to vibrate.

Resonance occurs if an object or system is forced to vibrate at its natural frequency by another body oscillating at the same frequency.

A swimmer jumping on the diving board sets the diving board in resonance so as to gain enough upliftment during diving.

Resonance in sound

An air column trapped in a pipe can be forced to vibrate inside the tube to produce loud sound. This happens if the air column vibrates with a natural frequency corresponding to the frequency of the vibrating tuning fork. A length of wire fixed at both ends can be forced to vibrate at its natural frequency by a sounding tuning fork.

Standing or stationary waves

Standing or stationary wave is formed when two progressive waves travelling in a medium in the opposite directions interfere. Standing wave set up in a string fixed at both ends is due to the interference of **incident** and **reflected** waves. Points of maximum vibration along the length of the wire are called the **antinodes** (A); the points of no vibration (where the wire is at rest) are called the **nodes** (N).

The distance between two adjacent **nodes** (N_1 N_2) or **antinodes** (A_1A_2) is $\frac{1}{2}$ Î». The distance between a node and the next antinode (N_1A_1) is $\frac{1}{4}\lambda$. The distance between N_1A_2 $\frac{3}{4}$ Î». The symbol Î» stands for wavelength.

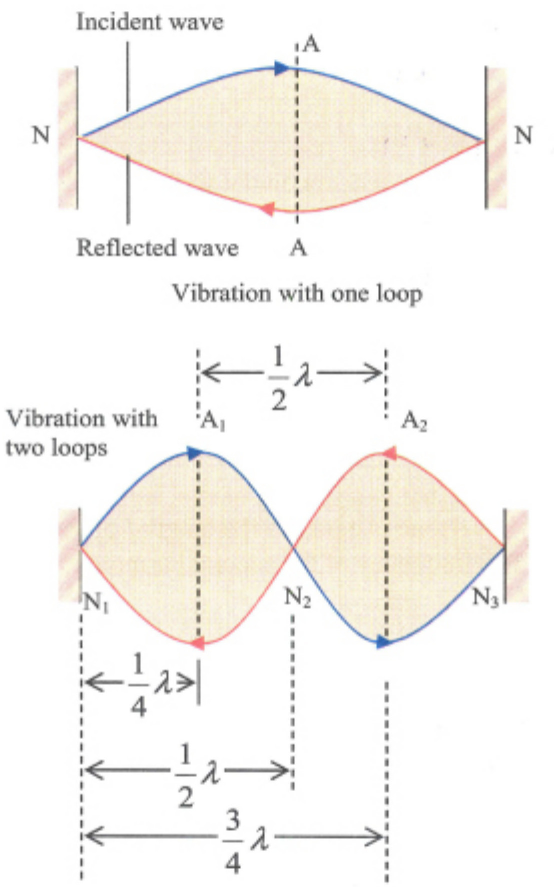


Figure 16.9: Standing or stationary waves

Vibration in strings

If a string of fixed length and tension is set into vibration, stationary waves are formed in the string. The simplest mode of vibration of the string is shown in Figure 15.10a; this is the fundamental note. The length of the string for a fundamental note is equal to half the wavelength of the wave travelling in the string.

The wavelength of the fundamental note is *Î» = 21*. The speed of a wave travelling through wire or string fixed at both ends is given by:

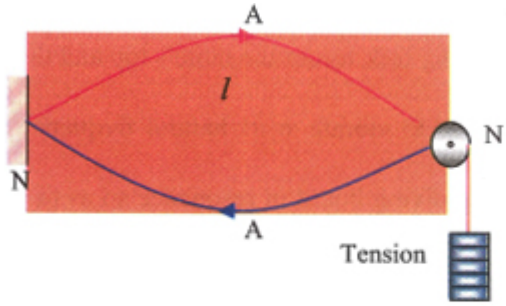


Figure 16.10a: Fundamental note

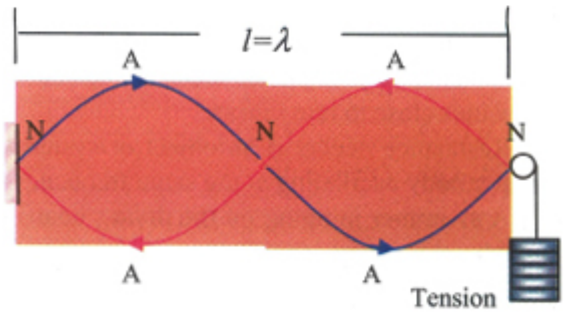


Figure 16.10b: 1st overtone or 2nd harmonics

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

Where T = tension on the wire and M is mass per unit length or thickness of the wire. The velocity of the wave through a wire is also given by *v = Î» f*.

Where $v = \sqrt{\frac{T}{M}}$ and *Î» = 21;* the fundamental frequency f_o *of* the note produced is given by:

$$f_o = \frac{v}{\lambda} = \frac{v}{2l} \qquad \text{Or} \qquad f_o = \frac{1}{2l}\sqrt{\frac{T}{M}}$$

The wire can be forced to vibrate to give more complex patterns called **overtones** or **harmonics**.

â€¢ The first overtone or second harmonic is shown in Figure 16.10b. The wavelength of the first overtone is equal to the length l of the wire or string (*l = Î» or 2l = 2Î»*)

The frequency of the second harmonic is given by:

$$f_1 = \frac{2}{2l}\sqrt{\frac{T}{M}}$$

â€¢ The second overtone or third harmonic has a wavelength equal to $\frac{2}{3}$ of the length of the wire or *2l = 3l* since $l = \frac{3\lambda}{2}$.

The frequency of the third harmonic is given by:

$$f_2 = \frac{3}{2l}\sqrt{\frac{T}{M}}$$

The equations above reveal that the frequency of a vibrating wire or string depends on:

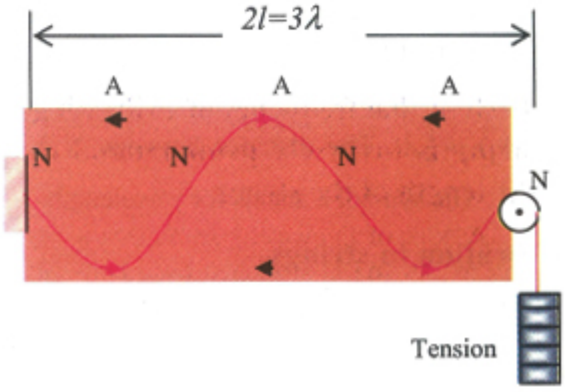


Figure 16.10c: 2nd overtone or 3rd harmonic

(i) The length (*l*) of the string: $\left(f \propto \frac{1}{l}\right)$

The frequency of vibrating string is higher for a short length of the string than for a longer length of the string.

(ii) The tension (T) on the string: $\left(f \propto \sqrt{T}\right)$

The frequency of a vibrating string is directly proportional to the square root of the tension applied to the string.

(iii) The mass per unit length (M) of the string: $\left(f \propto \frac{1}{\sqrt{M}}\right)$

The frequency of a vibrating wire is inversely proportional to the square root of its mass per unit length. A thicker wire vibrates with lower frequency.

The sonometer

The sonometer is an instrument used to investigate the relationship between the frequency of a vibrating string and the length, the tension and the thickness or mass per unit length of the string. It consists of a hollow wooden box called the sounding box and a stretched string on two bridges or supports. The length of the string can be varied by adjusting the movable bridge while the tension on the string is increased by tightening the screw or by adding more weights on the string. The hollow box traps more air and sets them into vibration in order to amplify the sound produced by the vibrating string.

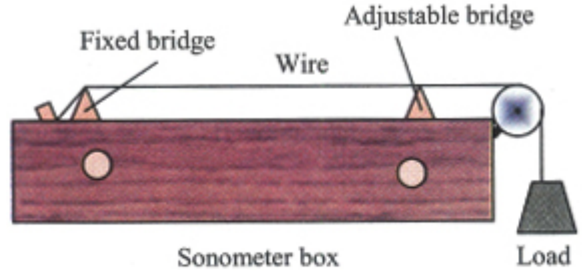
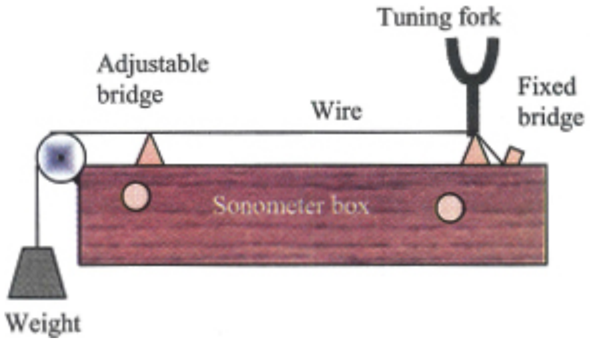


Figure 16.11: Sonometer



To show that frequency of a vibrating string is inversely proportional to the length of the string

A wire of known thickness (mass per unit length **M**) is stretched by a constant tension using the weights (W). The length of the wire is varied by adjusting the movable bridge until a specific length *l* of the wire is reached which will produce the same note as the tuning fork. The frequency of the vibrating wire is equal to the frequency of the tuning fork. The resonance frequency is obtained by placing a small piece of paper called paper rider at the centre of the wire. A tuning fork of known frequency is sounded and its stem pressed on the wire on the fixed bridge. The movable bridge is adjusted until the length *l* is reached, when the wire vibrates with maximum amplitude throwing the paper rider off the wire. The frequency of the wire when the paper rider is thrown off the wire is equal to the frequency of the tuning fork. The procedure is repeated using tuning forks of higher frequencies but keeping the tension and mass per unit length constant. The result of the experiment is tabulated as shown in the table below.

Frequency *f* (Hertz)	Length *l*(cm)	$\frac{1}{length}(cm^{-1})$

The graph frequency *f* plotted against the reciprocal of length $\frac{1}{l}$ is straight line passing through origin as shown in Figure 16.12a.

Conclusion: The shorter the length of the wire, the higher the frequency. Therefore, the length of the wire l is inversely proportional to its frequency.

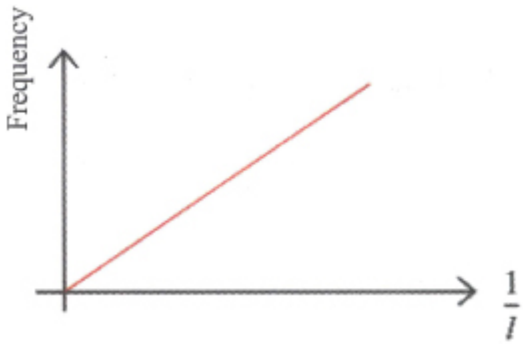


Figure 16.12a: Frequency versus $\frac{1}{l}$ graph

To show that frequency of a vibrating string is directly proportional to the square root of the tension on the string

The length l of the wire and its mass per unit length **M** are kept constant throughout the experiment while the tension **T** is varied. The tension when the paper rider is thrown off the wire is recorded. The experiment is repeated using tuning forks of higher frequencies. The frequencies and the tension at which the paper rider is thrown off the wire are recorded as shown in the table below.

Frequency f (Hertz)	Tension T (Newton)	$\sqrt{T}$ (Newton)

When the frequency f is plotted against the square root of tension $\sqrt{T}$, a straight line, which passes through the origin, is obtained as shown in Figure 16.12b.

Conclusion: The higher the tension on the wire, the higher the frequency therefore, frequency is directly proportional to the square root of the tension on the wire. $\sqrt{T}$

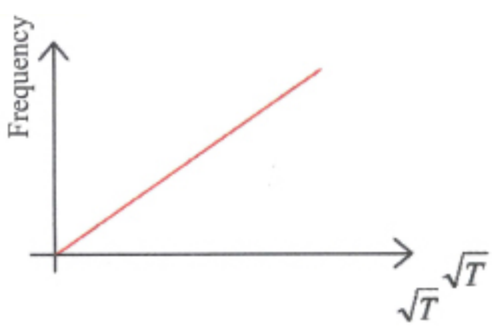


Figure 16.12b: Frequency vs

Worked example

A string of length 1.0 m is kept under tension by a constant force of 100 N. If the mass per unit length of the string is 2.5 Ã— 10^{-3} kg calculate:

(i) the fundamental frequency of the wire;

(ii) the velocity of wave as it travel through the wire;

(iii) wavelength of the wave.

Solution

(i) $$f_o = \frac{1}{2l}\sqrt{\frac{T}{M}} = \frac{1}{2\times1.0}\sqrt{\frac{100}{2.5\times10^{-3}}}$$

$$f_o = 100 \text{ Hz}$$

(ii) $$v = \sqrt{\frac{T}{M}} = \sqrt{\frac{100}{2.5\times10^{-3}}} = 200\ m\ s^{-1}$$

(iii) $\lambda = 2l = 2\times 1 = 2\ m.$

Vibrating air columns in pipes

Air column trapped inside a pipe can be forced to vibrate at its natural frequency, hence producing a loud sound. This occurs if a sounding tuning fork sends waves down the pipe, which is reflected at the closed end. A standing wave is set up in the pipe by the interference of incident and reflected waves.

The two types of pipes on which air column can vibrate to produce sound are:

â€¢ **The closed pipe:** A pipe which is open at one, end and closed at the other end.

â€¢ **The open pipe:** A pipe which is open at both ends.

Closed pipes

When a standing wave is set up in a closed pipe, a node (N) is formed at the closed end of the pipe and antinode (A) is formed at the open end. Nodes are always formed at the closed ends because air at the closed end of the pipe is not free to move. At the open ends where air is free to move, antinodes are formed. The position of the antinode at the open end is above the open end of the pipe by a small distance (c) called the **end correction**. The real length of the closed pipe is $l + c$, where l is the length of the pipe and c is the end correction. The end correction is related to the radius or the pipe by c = *0.6* r, where r is the radius of the pipe.

Figure 16.13 shows two simple modes of vibration for a closed pipe. The first audible sound heard when the tuning fork is placed above the pipe is the fundamental note. The length of air column for a fundamental note is equal to the one-quarter of wavelength ($\frac{1}{4}\lambda$) of the sound wave.

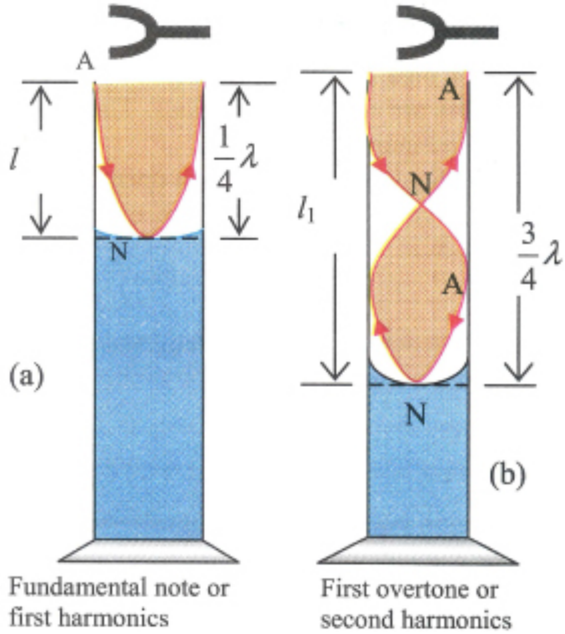


Figure 16.13: Vibrating air columns in closed pipes

$$l_o = \tfrac{1}{4}\lambda \quad or \quad \lambda = 4l_o$$

The frequency (f_o) of the fundamental note is given by:

$$f_o = \frac{v}{\lambda} = \frac{v}{4l_o}$$

Increasing the length of the air column produces a second audible sound when the length of air column is three-quarter wavelength ($\frac{3}{4}\lambda$) of the sound wave.

$$l_1 = \tfrac{3}{4}\lambda_1 \quad or \quad \lambda_1 = 4l_1$$

The second audible sound is called first overtone or second harmonic. The frequency (f_1) of the first overtone for a closed pipe is given by:
The second overtone is produced when the length of the air column $l_2 = \frac{5}{4}\lambda_2$. The frequency of the vibrating air column is given by:

$$f_2 = \frac{v}{\lambda} = \frac{5v}{4l_2} = 5f_o$$

Conclusion: Closed pipes produce only **odd integral harmonics** (multiples of fundamental frequencies): f_o, $3f_o$, $5f_o$, $7f_o$, $9f_o$, â€¦

Open pipes

An open pipe is open at both ends. The air is free to move at each end of the pipe, therefore antinodes are formed at the ends. The two simplest modes of vibration for an open pipe are shown in Figure 16.14.

The fundamental note of an open pipe has two antinodes, one at each end of the pipe and a node at the middle. The length of the air column is equal to half the wavelength of the sound wave.

$$l_o = \frac{1}{2}\lambda \quad or \quad \lambda = 2l_o$$

The frequency (f_o) of the fundamental note for an open pipe is given by:

$$f_o = \frac{v}{\lambda} = \frac{v}{2l_o}$$

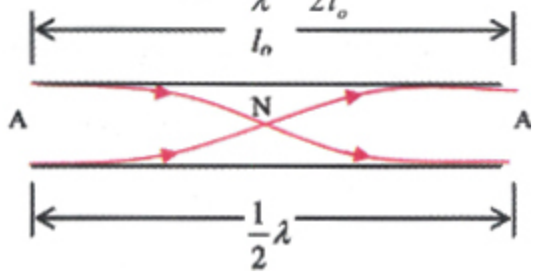


Figure 16.14: Fundamental or first harmonic for an open pipe

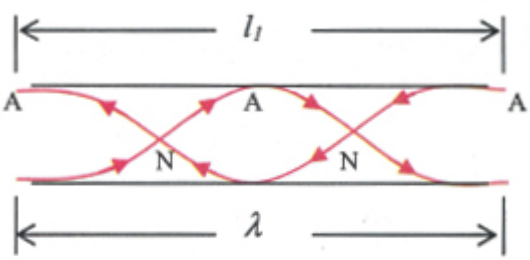


Figure 16.14: First overtone or second harmonic for an open pipe

The next audible sound is heard when the length of the air column in the pipe is equal to the wavelength of the sound wave. This is the first overtone or second harmonic of the open pipe. The frequency of the first overtone is given by:

$$f_1 = \frac{v}{\lambda} = \frac{2v}{2l_1} = 2f_o$$

The frequency *(f_2)* of the second overtone or third harmonic is equal to *$3f_o$*. It follows that **all harmonics are allowed in an open pipe**. That is, *f_o, $2f_o$, $3f_o$, $4f_o$, $5f_o$,* â€¦ are possible.

Resonance tube experiment to determine the speed of sound in air

Figure 16.15 is the resonance tube apparatus used to measure the speed of sound in air. A tuning fork of known frequency is sounded and placed above the open-end of the pipe. The length of air column in the pipe is increased slightly by allowing water to run off the tap until the first audible sound is heard. The length of air column producing the first audible sound is measured and recorded. ,

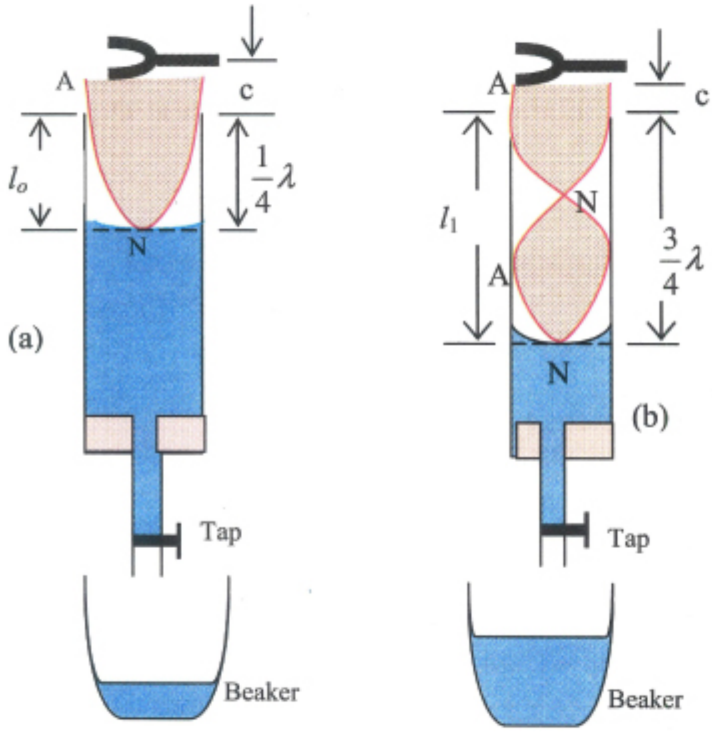


Figure 16.15: Determining the speed of sound in air

More water is allowed to run out from the pipe until a second audible sound is heard. The length of air column l_1 is measured and recorded.

The first audible sound is the fundamental note and the length of resonating air column is one-quarter of the wavelength.

$$l_o + c = \frac{1}{4}\lambda \text{.......i}$$

The second audible sound is the first overtone or second harmonic. The length of resonating air column is three-quarter of wavelength.

$$l_1 + c = \frac{3}{4}\lambda \text{.......ii}$$

The end correction (c) is eliminated by subtracting equation (i) from equation (ii)

$$\therefore \quad l_1 - l_o = \frac{1}{2}\lambda$$

$$\lambda = 2(l_1 - l_o)$$

The velocity of sound in air is given by the wave equation *v = fÃ—Î»:*

$$\therefore \quad v = 2f(l_1 - l_o)$$

f is the frequency of the sounding tuning fork and *v* the speed of sound in air.

Worked examples

1. In a resonant tube experiment to determine the speed of sound in

air, a student measured the first two resonant positions as 16.6 cm and 49.8 cm respectively. If the frequency of the tuning fork used by the student is 512 Hz, calculate the velocity sound in air.

Solution

v = 2f(l_1 – l_0) = 2 Ã— 512(0.498 – 0.166) = *340 m.*

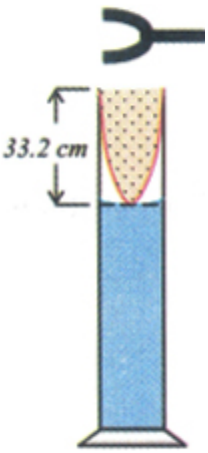
2. In the resonance tube experiment below, the frequency of the tuning fork is 256 Hz and the length of resonating air column is 33.2 cm. Calculate the velocity of the sound wave.

Solution

Wavelength of sound (*Î»*) = 4*l* = 4 Ã— 33.2

= 132.8 cm

v = 4*l* Ã— = 1.328 Ã— 256 *340 ms*$^{-1}$.



Summary

â€¢ **Standing wave** set up in a string fixed at both ends, is due to the interference of incident and reflected waves.

â€¢ **Antinodes** (A) are points of maximum vibration on a standing wave.

â€¢ **Nodes** (N) are points on a standing waves where the particles are at rest (no vibration).

â€¢ The **speed of a wave** travelling through wire or string fixed at both ends is given by:

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

Where T = tension on the wire and M is mass per unit length or thickness of the wire.

â€¢ The **frequency of vibrating wire** depends on the following factors:

(iv) The **length** (l) of the string: The **tension** (T) on the string: $\left(f \propto \frac{1}{l}\right)$

The **tension** (T) on the string: $\left(f \propto \sqrt{T}\right)$

(v) The **tension** (T) on the string: $\left(f \propto \sqrt{T}\right)$

(vi) The **mass per unit length** (M) of the string: $\left(f \propto \frac{1}{\sqrt{M}}\right)$

â€¢ The **fundamental frequency f_0** of the note is given by: $f_o = \frac{1}{2l}\sqrt{\frac{T}{M}}$

â€¢ Air vibrating in a pipe produces sound. The frequency of sound produced depends on the length of air column vibrating in the pipe. Vibration of air takes place in a closed or open pipe.

â€¢ **A closed pipe** is one which is open at one end and closed at the other end.

â€¢ **An open pipe** is one which is open at both ends.

â€¢ Closed pipes produce only **odd integral harmonics** (multiples of fundamental frequencies): f_o, $3f_o$, $5f_o$, $7f_o$, $9f_o$, *â€¦*

â€¢ An open pipe produces both **even and odd harmonics. All harmonics**, f_o, $2f_o$, $3f_o$, $4f_o$, $5f_o$ *â€¦* ***are allowed in an open pipe***.

â€¢ The **velocity of sound in air** using resonant tube is given by:

$\therefore v = 2f(l_1 - I_o)$

f is the frequency of the sounding tuning fork and *v* the speed of sound in air.

Practice questions 16b

1. Explain what is meant by *resonance* and state **two** examples of resonance in sound.
2. What *is forced vibration?* Explain how sound can be amplified through forced vibration. **I**
3. (a) What is a **standing wave?** Explain the terms **nodes** and **antinodes** as applied to standing waves.

   (b) Draw a wave pattern of a standing wave produced by a vibrating string with:

   (i) two loops

   (ii) three loops;

   Indicate the positions of nodes and antinodes.
4. (a) What *is frequency?* How does the *frequency* of a vibrating string depend on:

   (i) its length

   (ii) the tension on it?

   (b) Describe an experiment to show how the frequency of a vibrating string depends on its length.

(c) A string of constant thickness and length *l cm* is stretched by a force of T Newton. A tuning fork stamped 256 Hz sets the string vibrating at its fundamental frequency. Find the frequency of the string when:

(i) its length is doubled and the tension constant;

(ii) the tension is doubled and the length constant.

5. (a) State the effect of increase in the tension on a wire on its frequency.

(b) Describe an experiment to show that the tension on a fixed length of a wire at constant frequency depends on its tension.

(c) A wire under a constant tension of 10 N vibrates with a frequency of 256 Hz when the length is 50 cm. Calculate the mass per unit length of the wire.

6. (a) Explain the meaning of the term *resonance* giving **two** examples from any two branches of Physics.

(b) Describe an experiment to measure the velocity of sound in air using resonance tube.

(c) A tuning fork has its frequency covered. When it is sounded and held over a long tube open at one end, a loud sound is heard when the length of vibrating air column is 29.0 cm. When water is run out from the tube, another loud sound is heard when the length of vibrating air column is 93.5 cm. Calculate the frequency of the tuning fork.

{Velocity of sound in air is 330 ms^{-1}.}

7. (a) Explain the terms *fundamental frequency* and *overtone.*

(b) Sketch the mode of vibration in air trapped in a pipe closed at one end when the:

(i) fundamental note is produced;

(ii) first overtone is produced.

Indicate the positions of nodes and antinodes.

(c) If the length of the vibrating air column when a fundamental note is produced is 33.2 cm calculate:

(i) the frequency of the fundamental note;

(ii) the length of the air column producing the first overtone if the frequency is constant.

{Velocity of sound in air is 340 ms^{-1}}


Is this sound music or noise?