SOUND WAVES

Sound waves are produced when particles in a medium are set into vibration.
The medium can be any gas, liquid or solid.
The vibrating objects cause the surrounding air molecules to vibrate. When these air molecules reach our ear a sensation of sound is produced.

Properties of sound waves

(i) Sound waves require a material medium for propagation. They cannot travel through a vacuum.
(ii) sound waves can be reflected, refracted, diffracted and can undergo interference
(iii)Speed of sound waves depends on the medium

- Density and elasticity of the medium

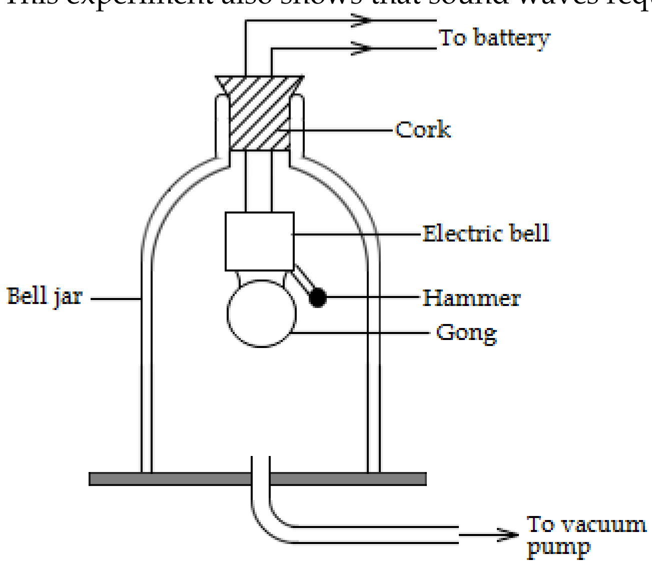
Sound travels faster in a less dense medium than in a dense medium

- The temperature and wind in case of air as the medium.

At constant pressure, an increase in temperatures increases the speed of sound waves.
Note: Sound waves travel fastest in solids faster in liquids and slowest in gases.

Experiment to demonstrate that sound waves cannot travel in a vacuum

This experiment also shows that sound waves require a material medium for their propagation.



Procedure

- A small electric bell is suspended inside the bell jar connected to a vacuum pump as shown in the diagram.
- The bell is switched on with the vacuum pump off and the sound of the bell is heard as the hammer hits the gong.
- The vacuum pump is started and air is gradually pumped out of the bell jar.

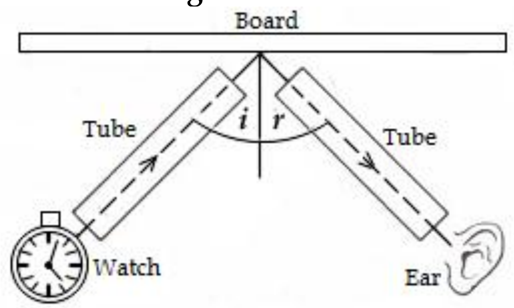
Observation

The sound of the bell gradually becomes faint until it is no longer heard though the hammer is seen hitting the gong.
At this point, the space inside the bell jar is a vacuum and since no sound is heard, it implies that sound waves do not travel through a vacuum.
When air is slowly pumped back into the bell jar sound is heard again.

Reflection sound waves

Sound energy, like light energy, obeys the laws of reflection:
1. The angle of incidence is equal to the angle of reflection.
2. The incident wave, reflected wave, and the normal at the point of incidence, all lie in the same plane.

Demonstrating the laws of reflection for sound waves



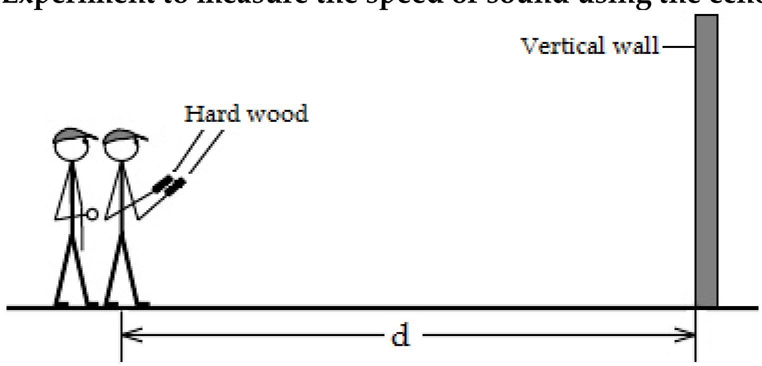
- A large wooden board is mounted vertically on a table at right angles to the wooden screen (Normal).
- Two tubes are placed at angle on each side of the screen.
- A ticking watch is placed at the end of one tube and the ear is placed at the end of the other tube.
- The tube and ear are moved slightly left or right, till a loud distinct tick of the watch is heard.
- The angles of incidence and reflection are measured and are found to be equal.
- The incident and reflected waves and the normal are in the same plane.
- This illustrates the laws of reflection.

Echoes

An echo is reflected sound.

An echo is produced by reflection of sound from a hard surface such as a wall or a cliff. The echo travels at the same speed as the incident sound. Strong echoes are produced when the reflecting surface is large, hard and is at a relatively long distance from the source of the sound.

Experiment to measure the speed of sound using the echo method



Two men stand at reasonable distance, d from a tall wall

One man claps using two wooden blocks and the other man does the timing using a stop clock for n claps.

The claps are made at regular intervals so as to coincide with the arrival of the echo from the previous clap.eg the second clap coincides with the echo from the wall from the first clap.

Total distance travelled is 2d

Time taken for to and fro movement of the sound waves is $\frac{t}{n}$

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

$$V = \frac{2d}{(^t/_n)}$$

$$V = \frac{2dn}{t}$$

Where V-Velocity of sound

d-Distance between the wall and source of sound

t-Time taken for n-claps

n- Number of claps made

Examples

1. A boy stands a distance of 495m from a tall cliff. He makes a loud sound and hears an echo after 3 seconds. Calculate the speed of sound in air.

$\text{Speed} = \frac{\text{Distance}}{\text{Time}}$

$\text{Speed} = \frac{2x}{t}$

$= \frac{2 \times 495}{3}$

Speed = 330ms^{-1}

2. A girl swimming at a point which is 99m away from a tall tree shouts and the echoreaches her 0.25 seconds later calculate the velocity of sound within water using these observations.

$\text{Velocity} = \frac{\text{Distance travelled}}{\text{Time}}$

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

$= \frac{2 \times 99}{0.25}$

Speed = 2400ms^{-1}

3. A student standing between two vertical walls and 480m from the nearest wall shouts. She hears the first echo after 3 seconds and the second 2 seconds later. Use this information to calculate the;

(i) Velocity of sound in air

$\text{Velocity} = \frac{\text{Distance travelled}}{\text{Time}}$

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

$= \frac{2 \times 480}{3}$

Speed = 320ms^{-1}

(ii) Distance between the walls

For second echo

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

$t = 3 + 2 = 5 \text{ seconds}$

$320 = \frac{2x}{5}$

$x = \frac{320 \times 5}{2}$

X = 800m

Distance between the two walls = 480 + 800 = 1280m

4. A woman standing between two vertical walls makes a loud sound. She hears the first echo after 1.5 seconds and the second echo after 2 seconds. Find the Distance between the two walls given that the speed of sound in air is 330ms^{-1}.

$\text{Velocity} = \frac{\text{Distance travelled}}{\text{Time}}$

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

$330 = \frac{2x}{1.5}$

$x = \frac{330 \times 1.5}{2}$

X = 247.5m

For second echo

$V = \frac{2y}{t}$

$330 = \frac{2y}{2}$

y= 330m

Why echoes are not heard in small rooms

For an echo to be heard separately from the original sound it must arrive 0.1seconds later.
Given the speed of sound is 330ms^{-1}, the distance covered in 0.1 seconds is 33m.
This implies that the minimum distance between the source of sound and the reflector must be 17m for the echo to be heard clearly.
When the echo cannot be differentiated from the original sound it appears to the receiver as if the original sound has been prolonged. This effect is called **reverberation**.

Definition

Reverberation is the persistence of sound in a particular space after the original sound is removed.
Reverberation is noticeable in cathedrals, theatres, auditoriums, discotheques where multiple sound connections can occur.

Why are echoes desirable (Good)?

1. They prevent a hall from being acoustically dead.
2. To enhance hearing.

Why are echoes undesirable (Bad)?

1.They make sound appear indistinct (not distinguishable)
2.They make sound appear confused.

How echoes are minimised

Institutions where echoes are not required like cinemas halls, the following measures are taken
(i) Use of woolen carpets on the floor of theatres
(ii) Use of soft boards on the walls of cinema halls, theatre halls, disco halls e.t.c.
(iii)Use of large curtains

Echo sounder

An echo sounder is a device used for determining the depth of the seabed. It is also used to detect underwater objects like shoal of fish, sea rocks, ice bergs and submarines.
The echo sounder consists of a transmitter, a hydrophone and an electric timer circuit.

How an echo sounder works

The transmitter sends out ultra sound at regular intervals to the seabed as the ship is in motion.
The echo from the seabed is received by the hydrophone which is connected to an electric timer circuit.
The circuit calculates the depth and plots the graph from which the depth at a given point is read.

Range of Audible Frequencies

The human ear responds to sounds with frequencies in the range from 20 Hz to 20,000 Hz. This is called the audible human range.
Inaudible sound waves whose frequencies are less than 20 Hz are in the infrasonic range while those above 20,000 Hz are in the ultrasonic range.

Applications of ultrasonic sound (Ultra-sound)

(i) Measuring the depth of the sea or ocean
(ii) Testing the quality of linings and pads used in motor vehicle brakes.
(iii) In medicine ultra sound scanners are used to scan various body parts to diagnose various diseases.
(iv) cleaning of delicate machinery like surgical equipment
(v) Used in communication and navigation of bats, dolphins, cats etc.

Musical instruments

Musical note (tone)

This refers to the sound of regular frequency. A combination of different tones gives music

Characteristics of musical notes

Pitch

This is the highness or lowness of musical notes.

The pitch of a musical note depends on the frequency of sound waves. The higher the frequency, the higher the pitch.

Loudness

Loudness depends mainly on the amplitude of the sound wave.

The larger the amplitude, the louder the sound.

Quality (Timbre)

This is a characteristic of a note which allows the ear to distinguish between sounds which have the same pitch and loudness. It depends on the frequency and amplitude of sound waves.

Intensity of sound waves

This is the measure of the degree of loudness or softness of a musical note.

It is determined by the amplitude of the musical note.

ie $I \propto a^2$ where I – Intensity, a – Amplitude

Music and Noise

Music is a combination of sound of regular frequency

Noise is sound with irregular frequency of disorderly vibrations.

Progressive and stationery waves

A Progressive wave

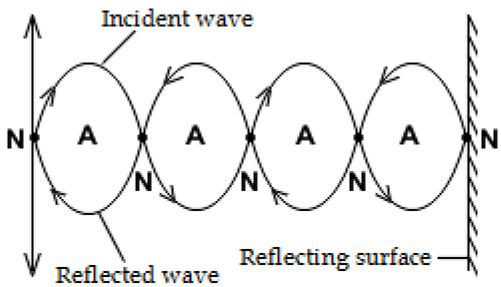
This is a wave that moves away from its source through a medium and spreads out continuously

A stationery wave

This is a wave pattern formed when two progressive waves of equal amplitude and frequency travelling with the same speed in opposite directions super impose on each other.

Stationary waves may be set up when a wave reflects back from a surface and the reflected wave interferes with the wave still travelling in the original direction.

A stationery wave pattern always consists of alternating nodes and antinodes as shown below.



N - Nodes **A** - Antinodes

Nodes (N)

These are points on a stationary wave which appear to be at rest

Antinodes (A)

These are points on a stationery wave which vibrate with maximum amplitude

Note: The distance between successive nodes or successive antinodes is equal to half the wave length.

Vibrations in strings

Vibrations from stringed instruments naturally vibrate at a series of distinct frequencies known as normal modes.

The fundamental frequency (f_o) is the lowest normal mode or frequency that can be obtained from musical instruments.

Overtone

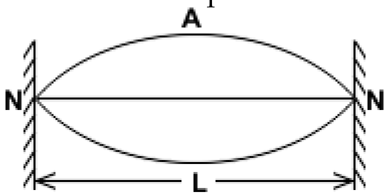
This is a higher frequency than the fundamental frequency

Harmonics

These are integral multiples of the fundamental frequency.

Vibration patterns

A stationery wave can be setup in a string by plucking it in the middle when both ends are fixed. The note produced is called the fundamental note (first harmonic)



To obtain the fundamental frequency f_o

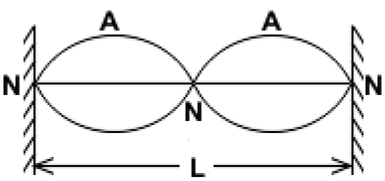
$v = f\lambda$

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

$L = \frac{1}{2}\lambda, \quad \lambda = 2L$

$\mathbf{f_o = \frac{v}{2L}}$

When the string is plucked quarter way from one the following pattern is obtained. The note produced is called the first overtone or second harmonic.



$f_1 = \frac{v}{\lambda}$ But $\lambda = L$

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

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

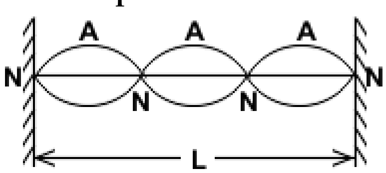
$f_1 = 2 \times \frac{v}{2L}$

$f_1 = 2 \times f_o$

$\mathbf{f_1 = 2f_o}$

When the string is plucked a sixth way from one end the following pattern is obtained. The note produced is called the second overtone or third harmonic.

The next pattern



$L = 1\frac{1}{2}\lambda$

$L = \frac{3}{2}\lambda$

$\lambda = \frac{2}{3}L$

$f_2 = \frac{v}{\lambda}$ But $\lambda = \frac{2}{3}L$

$f_2 = \frac{3v}{2L}$

$f_2 = 3 \times \frac{v}{2L}$

$f_2 = 3 \times f_o$

$\mathbf{f_2 = 3f_o}$

Note: The harmonics obtained in a string are $f_{o,} 2f_{o,} 3f_{o,} 4f_o \ldots \ldots \ldots \ldots$

Factors affecting the frequency of a note produced by a vibrating string

Length of the string, L

The shorter the length of the string used the higher the frequency of the note

$$\text{ie} f \propto \frac{1}{L} \ldots \ldots . . (i)$$

Tension in the string, T

The higher the tension in the string, the higher the frequency of the note produced

$$\text{ie } f \propto \sqrt{T} \ldots \ldots (ii)$$

Mass per unit length, μ (Thickness)

The higher the mass per unit length, the lower the frequency of the note produced

$$\text{ie } f \propto \sqrt{\frac{1}{\mu}} \ldots \ldots \ldots . (iii)$$

Combining (i), (ii) and (iii) gives

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

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

Note: Short, thin, tightly stretched wires produce high notes.

Examples

1. The frequency of sound produced by a vibrating string of length 0.8m is 540Hz. Calculate the
(i) Frequency of sound produced when the length is reduced to 0.6m
(ii)Length of the string that would give a frequency of 480Hz

(i) $f \propto \frac{1}{L}$

$f = \frac{k}{L}, \quad fL = k$

$f_1L_1 = f_2L_2$

$540 \times 0.8 = f_2 \times 0.6$

$f_2 = \frac{540 \times 0.8}{0.6}$

$f_2 = 720\text{Hz}$

(ii) $f_1 = 540\text{Hz}, f_2 = 480\text{Hz}, L_1 = 0.8\text{m}, L_2 = ?$

$f_1L_1 = f_2L_2$

$540 \times 0.8 = 480 \times L_2$

$L_2 = \frac{540 \times 0.8}{480}$

$L_2 = 0.9\text{m}$

2.A string produces a note of frequency 260Hz. Find the new frequency of the note if the tension on the string is increased 4 times with the other factors remaining the same.

3. The frequency of a note produced in a wire is 320Hz, when the tension is 200N. Find the new frequency produced if the tension is increased to 600N.

4. The frequency of a note produced by a vibrating string is 420Hz calculate the new frequency that can be produced if the length of the string is reduced by a half.

Vibration in pipes

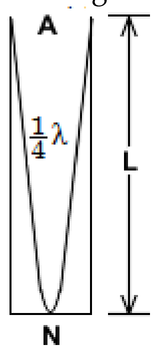
There are two types of vibrations in pipes closed pipes and open pipes

Vibration in closed pipes

When a tuning fork is held over the mouth of tube T, the air column inside it is set into vibration.

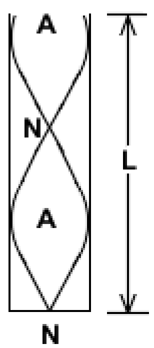
The wave sent downwards is reflected from the bottom surface and a stationary wave is set up. This is the fundamental note in a closed pipe.

Note: The distance between the node (N) and Antinode (A) is equal to a quarter of the wavelength.



$$L = \frac{1}{4}\lambda$$
$$\lambda = 4L$$
$$f_o = \frac{v}{\lambda}$$
$$\mathbf{f_o = \frac{v}{4L}}$$

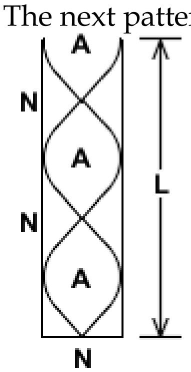
When air is blown further into the pipe the next pattern is as shown below.



From the diagram

$$L = \frac{3}{4}\lambda$$
$$\lambda = \frac{4}{3}L$$
$$f_1 = \frac{v}{\lambda}$$
$$f_1 = \frac{3v}{4L}$$
$$f_1 = 3 \times \frac{v}{4L}$$
$$\mathbf{f_1 = 3f_o}$$

The next pattern is as shown below

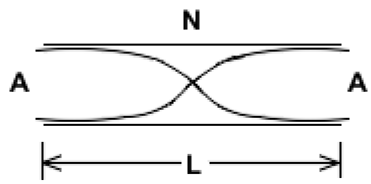


$$L = 1\frac{1}{4}\lambda$$
$$\lambda = \frac{4}{5}L$$
$$f_1 = \frac{v}{\lambda}$$
$$f_2 = \frac{5v}{4L}$$
$$f_2 = 5 \times \frac{v}{4L}$$
$$\mathbf{f_2 = 5f_o}$$

Note: For a closed pipe only odd harmonics are possible these are $f_o, 3f_o, 5f_o, 7f_o, 9f_o$ … … … ….

Vibration in open pipes

An open pipe is one that is open at both ends. For a fundamental note the length of the air column is equal to half the wave length.



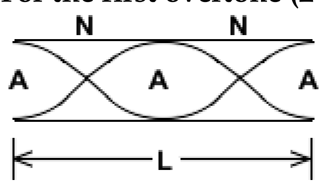
$v = f\lambda$

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

$L = \frac{1}{2}\lambda, \quad \lambda = 2L$

$\mathbf{f_o = \frac{v}{2L}}$

For the first overtone (2nd harmonic) f_1



$f_1 = \frac{v}{\lambda}$ But $\lambda = L$

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

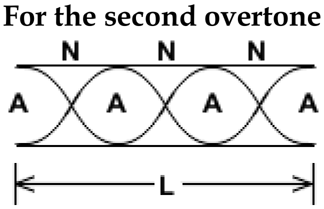
$f_1 = \frac{2v}{2\lambda}$

$f_1 = 2 \times \frac{v}{2L}$

$f_1 = 2 \times f_o$

$\mathbf{f_1 = 2f_o}$

For the second overtone (3rd harmonic) f_2



$L = 1\frac{1}{2}\lambda$

$L = \frac{3}{2}\lambda$

$\lambda = \frac{2}{3}L$

$v = f\lambda$

$f_2 = \frac{v}{\lambda}$

$f_2 = v \div \frac{2L}{3}$

$f_2 = v \times \frac{3}{2L}$

$f_2 = 3 \times \frac{v}{2L}$

$f_1 = 3 \times f_o$

$\mathbf{f_1 = 3f_o}$

The harmonics produced in an open pipe are $f_o, 2f_o, 3f_o, 4f_o$ … … … ….
Both odd and even multiples of the fundamental frequency are possible.

Advantage of open pipes over closed pipes in making musical instruments

Open pipes produce notes of various frequencies both odd and even multiples of the fundamental frequency hence producing sweeter music. Closed pipes produce notes of frequencies that are only odd multiples of the fundamental frequency.

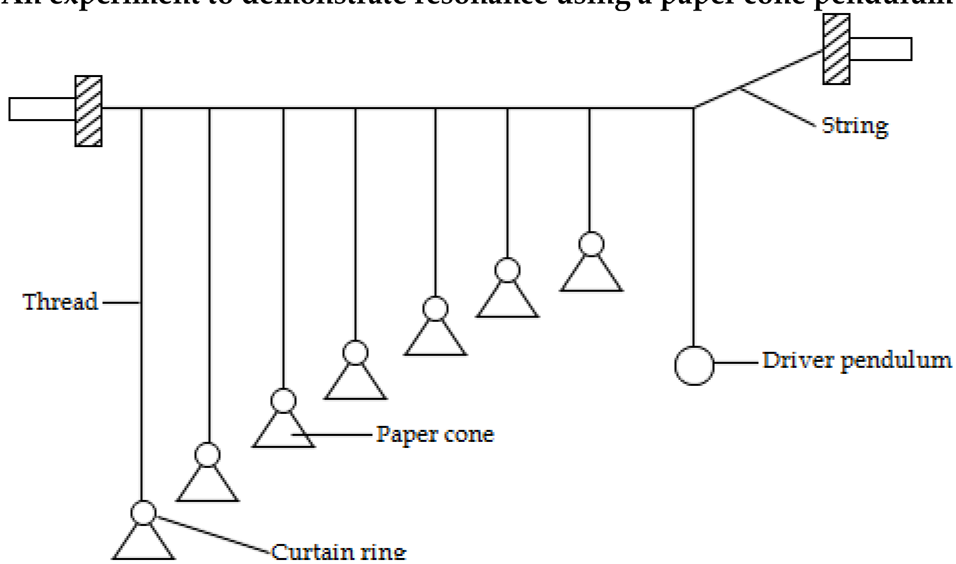
Examples

1. The frequency of the third harmonic in an open pipe is 590Hz. Find the length of the air column if the speed of sound in air is $330ms^{-1}$
2. A pipe closed at one end has a length of 10cm. If the velocity of sound in air of the pipe is $340ms^{-1}$ calculate the fundamental frequency and the frequency of the first overtone.
3. The length of an air column in an open pipe is 1.6m find the frequency of the third harmonic if the speed of sound in air is $320ms^{-1}$
4. The frequency of a vibrating wire is 280Hz when its length is 75cm find its frequency when the length is reduced to 50cm assume tension on the wire and its cross sectional area remain constant.

Resonance

Resonance occurs when a body or system is set into vibration of its own natural frequency by a nearby body vibrating at the same frequency.

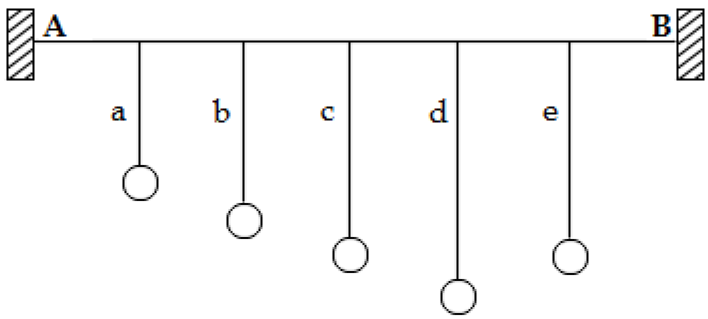
An experiment to demonstrate resonance using a paper cone pendulum



Procedure

- Paper cones tied on threads of different lengths are arranged on a string as shown in the diagram above
- When a heavy pendulum (driver pendulum X) is set swinging it forces all the light ones to swing at the same frequency but D which has the same length as X does so with a much larger amplitude.
- D is said to resonate X

Question



The diagram shows a stretched wire AB to which pendulums of lengths a, b, c, d, and e are attached

(i) Which pendulums will have different natural frequencies?

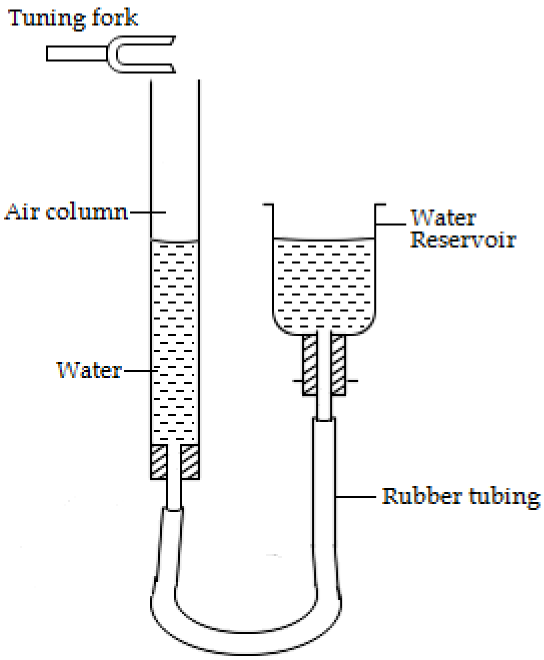
(ii) Which pendulums will have same natural frequencies?

(ii) If pendulum e is pulled to one side and released to oscillate freely, explain what happens to both c and e after some time.

Demonstrating resonance using a resonance tube

A resonance tube is a tube that is partially filled with water.

The air column above water is forced into vibration by placing a tuning fork near the open end of the tube.



The length of the air column in the tube is altered by raising or lowering the reservoir. When the tuning fork vibrates it forces the air in the tube to vibrate at its own natural frequency forming resonance. The effect of resonance is a loud sharp sound.

Uses of resonance

1. Production of sound in pipe instruments
2. Child swing
3. Swinging pendulum in the museum
4. Cooking food using a microwave oven

An experiment to measure the speed of sound in air using a resonance tube

A vibrating tuning fork of known frequency (f) is held directly above a tube full of water.

Water is slowly released from the tube increasing the length of the air column until the first sharp sound is heard, the tap is closed

The length of the air column is measured as L_1.

$$L_1 + e = \frac{1}{4}\lambda \ldots\ldots\ldots\ldots\ldots (i)$$

Where **e** is the end correction

The length of the air column is increased again by opening the tap until the second sharp sound is heard.

The length of the air column is measured as L_2.

$$L_2 + e = \frac{3}{4}\lambda \ldots\ldots\ldots\ldots\ldots (ii)$$

Where **e** is the end correction

Subtracting equation (i) from (ii)

$$L_2 - L_1 = \frac{3}{4}\lambda - \frac{1}{4}\lambda$$

$$L_2 - L_1 = \frac{1}{2}\lambda$$

$\lambda = 2(L_2 - L_1)$
$v = f\lambda$
$v = f \times 2(L_2 - L_1)$
The velocity of sound in air is calculated from the expression
$\mathbf{v = 2f(L_2 - L_1)}$

Examples

1. A tube closed at one end resonates first at a length of 28.5cm and again at 88.5cm when a tuning fork of frequency 275Hz is held near the open end. Find the velocity of sound
2. A tube is partially immersed in water and a tuning fork of frequency 425Hz is sounded and held above it. If the tube is gradually raised find the length of the tube when resonance first occurs if the speed of sound is $340ms^{-1}$
3. A sounding tuning fork held above the tube as shown in the diagram below produces the first loud sound when the air column is 31cm above the water surface. (Velocity of sound in air is $320ms^{-1}$)
(i) Find the frequency of the tuning fork
(ii) Explain why nothing is heard when the length of the air column is less than 31cm.
4. A long capillary tube is immersed in a beaker containing water. A tuning fork of frequency 512Hz is sounded and held above the tube and the tube is gradually raised. Find the length of the air column at second resonance position. (Speed of sound in air is $330ms^{-1}$)
5. A long open tube is partially immersed in water and a tuning fork of frequency 425Hz is sounded and held above it. The tube is gradually raised. Find the length of the air column when resonance first occurs. The Speed of sound in air is $340ms^{-1}$ (Neglect the end correction)