Architectural Acoustics

❖ ***INTRODUCTION:***

- Acoustics is a science of Sound which deals with the properties of Sound waves, their origin, propagation and their action on obstacles.
- Acoustics finds wide application in many fields. Some of the important applications in the field of engineering are electro-acoustic, design of acoustical instruments and architectural acoustics.
- Architectural acoustic deals with the design and construction of music halls and sound recording rooms to provide best audible sound to the audience.

❖ ***CLASSIFICATION OF SOUND:***

Sound is a vibration in elastic medium with definite frequency and intensity which can be heard by the human ear.

On the basis of frequency(f) sound waves are classified into three types as follow;

1. Infrasound (f>20 Hz)
2. Audible sound (20 Hz< f <20 kHz)
3. Ultrasound (f>20kHz)

The sound waves having frequencies less than 20 Hz are called **infrasound.** This sound is not audible.

The sound waves having frequency between 20 Hz and 20 kHz are called **audible sound.**

The sound waves having frequency greater than 20 kHz are called **ultrasound** and are also not audible sound.

❖ ***CLASSIFICATION OF AUDIBLE SOUND:***

The audible sound is generally classified into two categories:

1. Musical Sound 2. Noise

I. Musical Sound: The sound which produces pleasing effect on ear is called Musical sound. Ex. Sound produced by Musical instruments like sitar, violin, flute, piano, etc.

Properties of Musical Sound: The Musical sound waveforms are regular in shape, have definite periodicity, and they do not undergo a sudden change in amplitude, as shown in figure below.

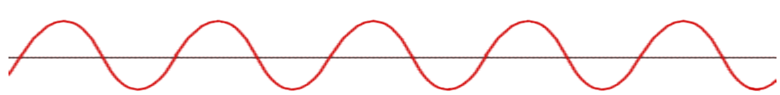


Fig. Music Waveform

II. <u>Noise:</u> A Sound that produces a jarring effect on the ear and is unpleasant to hear is called noise.

Ex. Sound produced by flying aero plane, road traffic, crackers, etc.

Properties of Noise: Noise waveforms are irregular in shape, they do not have definite periodicity and they undergo a sudden change in amplitudes, as shown in figure below.

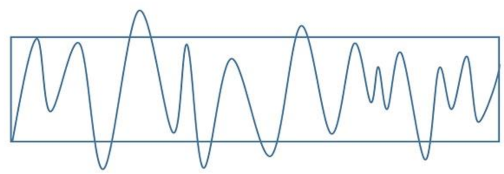


Fig. Noise waveform

❖ CHARACTERISTICS OF MUSICAL SOUND:

The characteristics of musical sound are:

1. **Pitch:** Related to frequency of sound.
2. **Loudness:** Related to intensity of sound.
3. **Timbre:** Related to quality of sound.

Pitch: It is a sensation that depends upon the frequency. Pitch helps in distinguishing between a note of high frequency and low frequency sound of the same intensity produce by the musical instrument. A shrill sound is produced by a sound of high frequency.

The sound produced by ladies and children is of high pitch type because the frequency is high. Similarly, the sound produced by a bee or a mosquito is of high pitch due to a high frequency.

Thus, greater the frequency of a sound the higher is the pitch and vice versa. The pitch of sound changes due to Doppler's principle when either the source or the observer or both are in motion.

Loudness: Loudness is a characteristic which is common to all sounds, whether classified as musical or noise.

Loudness is a degree of sensation produced on ear. Thus, loudness varies from one listener to another. Loudness depends upon intensity are related to each other by the relation.

Loudness and intensity are related to each other by relation

$$L \alpha \log_{10} I$$

or

$$L = K \log_{10} I$$

Where, K is constant.

From this relation it is seen that loudness is directly proportional to the logarithm of intensity, and is known as **Weber-Fechner law.**

From the above equation, $\frac{dL}{dI} = \frac{K}{I}$

Where $\frac{dL}{dI}$ is called ***sensitiveness*** of ear. Therefore, sensitiveness decreases with increase in intensity. Loudness is a physiological quality.

Timbre: It is a quality of sound which enables us to distinguish between two sounds having the same loudness and pitch. It depends on the presence of overtones.

It helps us to distinguish between musical notes emitted by different musical instruments and voices of different persons even though the sounds have the same pitch and loudness.

❖ ***INTENSITY:***

Intensity I of sound wave at a point is defined as the amount of sound energy Q flowing per unit area in unit time when the surface is held normal to the direction of the propagation of sound wave. i. e,

Therefore, if A = 1 m^2 and t= 1 sec, then I=Q, where Q is sound energy.

The intensity is a physical quantity which depends upon factors like amplitude a, frequency f and velocity V of sound together with the density of the medium ρ.

Therefore, the intensity I in a medium is given by

$$I = 2\pi^2 f^2 a^2 \rho v$$

The unit of intensity is Wm^{-2}.

The minimum sound intensity which a human ear can sense is called the **threshold intensity**. Its value is 10^{-12} watt/m^2. If the intensity is less than this value then our ear can't hear the sound.

This minimum intensity is also known as **zero or standard intensity**. The intensity of a sound is measured with reference to the standard intensity.

Intensity Level (Relative Intensity) I_L: The intensity level or relative intensity of a sound is defined as the logarithmic ratio of intensity I of a sound to the standard intensity I_0.

i.e., $I_L = K \log (I/I_0)$

let I and I_0 represent intensities of two sounds of a particular frequency; and L_1 and L_0 be their corresponding measures of loudness. Then, according to Weber Fechner-law,

$$L_1 = K \log_{10} I \qquad \text{...... (1)}$$

$$L_0 = K \log_{10} I_0 \qquad \text{...... (2)}$$

Therefore, the intensity level or relative intensity is

$$I_L = L_1 - L_0$$
$$= K \log_{10} I - K \log_{10} I_0$$
$$= K (\log_{10} I - \log_{10} I_0)$$
$$I_L = K \log_{10} (I/I_0) \qquad \text{....... (3)}$$

If K=1, then I_L is expressed in a unit called **bel.**

From the relation (1), it is seen that, 10 times increase in intensity, i.e., $I = 10I_0$ corresponds to 1 bel. Therefore, bel is the intensity level of a sound whose intensity is 10 times the standard intensity.

Similarly, 100 times increase in intensity, i.e., $I = 100I_0$ corresponds to 2 bel and 1,000 times increase in intensity, i.e., $I = 1000I_0$ corresponds to 3 bel and so on.

In practice, ***bel is a large unit***. Hence, another unit known as **decibel dB** is more often used.

$$1 \text{ dB} = \frac{1}{10} \text{ bel}$$

i.e., one decibel is $\frac{1}{10}$th of a bel.

Thus, $$I_L = 10 \log_{10} (I/I_0) \text{ dB} \qquad \text{........ (4)}$$

Physical significance of 1 dB

From equation (4), the intensity level in dB is

$$I_L = 10 \log_{10} (I/I_0) \text{ dB}$$

Using the above equation, let us determine the change in intensity that is produced when the intensity level is altered by 1 dB.

Case 1

If $I_L = 0$ dB,

Then, $0 = 10 \log_{10} (I/I_0)$.

Therefore, $10 \neq 0$, $10 \log_{10} (I/I_0) = 0$

Therefore $I/I_0 = 10^0 = 1$ .... (5)

Case 2

If IL = 1 dB,

Then 1 dB = $10 \log_{10} (I/I_0)$ dB

Therefore, $\frac{1}{10} = \log_{10}\left(\frac{I}{I_0}\right)$

$$0.1 = \log_{10}\left(\frac{I}{I_0}\right)$$

Or $\left(\frac{I}{I_0}\right)$ = $(10^{0.1})$

Therefore, $\left(\frac{I}{I_0}\right)$ = 1.26 ………. (6)

Thus the difference between equation (5) and (6) gives,

$$\left(\frac{I}{I_0}\right) = 0.26$$

Or $I = 0.26\ I_0$

Therefore, it is observed that a change in intensity level of 1 dB alters the intensity by 26%.

The threshold of audibility is 0 dB and the maximum intensity level is 120 dB.

The sound of intensity level 120 db produces a feeling of pain in the ear and is therefore called the threshold of feeling.

The units used to measure loudness are **Phon** and **Sone**.

Define Phon and Sone?

Phon: The measure of Loudness in phons of any sound is equal to the loudness in decibel of an equally loud tone of frequency 1000Hz.

Sone:

Definition 1: Defined as loudness of a 1000 Hz tone of 40 dB intensity level.

Definition 2: It is equal to the loudness of that particular sound having loudness level of 40 phon.

❖ **<u>Differentiate between Loudness and Intensity</u>.**

Sr. No.	Loudness	Intensity
1	It is a degree of sensation produced on the ear.	It is the quantity of sound energy flowing across unit area in unit time.
2	It varies from listener to listener.	It is independent of listener.
3	It is physiological quantity.	It is physical quantity.
4	Its unit is sone.	Its unit is Wm^{-2}

❖ **<u>Define Absorption Coefficient ‘a’</u>.**

<u>Definition 1</u>: The sound absorption coefficient ‘a’ of a material is defined as the ratio of sound energy absorbed by it to the total sound energy incident on it.

Definition 2: It is defined as the reciprocal of the area of the sound-absorbing material which absorbs the same amount of sound energy as that of 1 m^2 of an open window.
The unit of absorption coefficient is **sabine** and also called **O.W.U.** (open window unit)

❖ ***Discuss briefly about sound absorbing materials:***

The special materials used to increase the absorption of sound waves or to reduce the reflection of sound waves in a room or a hall is known as sound absorbing materials.
All sound absorbing materials have absorption coefficients that are different at different frequencies. Depending upon the economy, interior design and required reverberation time, proper sound absorbing materials are chosen to get good acoustic condition in a room or a hall.

A good sound absorbing material should have following properties:

1. It should have high sound absorbing efficiency.
2. It should be easily available, cheap, easy to fix, durable, light weight, good looking etc.
3. It should be water proof and must have good resistance to fire.
4. It should be efficient over a wide range of frequencies.
5. It should have sufficient structural strength.

Different types of Sound absorbing materials:

Sound absorbing materials are broadly classified into following four categories.

a. Porous absorbents.
b. Cavity resonators.
c. Resonant absorbents or panel absorbers.
d. Composite absorbents.

(a) **Porous absorbents:** The common examples for porous absorbents are fiber boards, rock wood, wood wool, soft plasters, mineral wool, glass silk, asbestos fiber spray etc. Whenever sound waves strike the surface of porous material, part of waves get reflected while the other part enter the porous material. The part of reflected wave energy is reduced while the part of waves that entered into the porous material is converted into heat.

(b) **Cavity resonator:** A cavity resonator is a chamber or a container having a small opening for sound waves to enter.

When sound waves enter the resonator; due to multiple reflections inside, the sound waves are absorbed. The cavity resonator may be designed to absorb sound of any particular frequency generated by machines such as air conditioner plant, machine etc, for which it is designed.

(c) **Resonant absorbents or panel absorbers:** The common examples are; windows, doors, rigid plastic boards, wood and hard-board panels, suspended plaster ceilings, gypsum boards etc.

In this system, the absorbent material is fixed on a framing with an air space between the framing and the wall. When sound waves strike the panel, then due to flexural vibration of panel, certain amount of sound energy is absorbed by the panel which is converted into heat energy.

(d) **Composite absorber:** The common examples of this type of absorbers are, bottle or an empty jar, glass wood, quilt or slab, perforated hard-board backed by perforated fiber board etc.

A composite absorber is a single unit which does the function of the other three absorbers mentioned above. The composite absorber consists of a perforated panel fixed over an air space containing porous absorbent. The panel may be of metal, wood, plywood, hard-boards, plaster boards etc. When sound waves strike the panel, they pass through it and damped by resonance of the air in the cavity.

❖ ***<u>Define Reverberation and Reverberation time:</u>***

Reverberation: The persistence or prolongation of sound in a hall even though the source of a sound is cut off is called reverberation.

Reverberation time: The time taken by the sound to fall below the minimum audibility level after the source stopped sounding is called reverberation time.

❖ **Sabine's Formula:** Sabine defines the reverberation time as the time taken by sound intensity to fall to one millionth of its original intensity after the source stopped emitting sound.

i.e, $$E = \frac{E_m}{10^6} \text{ at } t=T$$

According the Sabine, the reverberation time is given by

$$T = \frac{0.167V}{\sum aS}$$

Where, V is the volume of the hall,

a is the absorption coefficient

S is the surface area.

Thus the reverberation time, T is directly proportional to the volume of the hall and inversely proportional to the total absorption made by the hall.

❖ **<u>Why Reverberation time is important</u>?**

The reverberation time always has to be maintained at an optimum value. This is because, if the reverberation time is too small the loudness will be inadequate and the sound will die away instantaneously. Such a hall is said to have a dead effect. On the other hand, if the reverberation time is too large, the greater will be the confusion due to mixing or overlapping of different syllables. Therefore, the reverberation time has to be maintained at an optimum value.

❖ **<u>Measurement of Absorption coefficient</u>:**

The absorption coefficient ‘a’ of a sound absorbing material can be determined by measuring the reverberation time describe as follows;

Step 1

The reverberation time T_1 in a hall is measured without placing the sound-absorbing material in the hall. Thus the reverberation time is

$$T_1 = \frac{0.167V}{\sum aS} \qquad \text{......... (1)}$$

Step 2

The sound absorbing material of absorption coefficient a_1 having surface area S_1 is placed in the hall and the reverberation time T_2 is measured. Thus,

$$T_1 = \frac{0.167V}{\sum aS + a_1 S_1} \qquad \text{......... (2)}$$

Therefore, from equation (1) and (2)

$$\frac{1}{T_2} - \frac{1}{T_1} = \frac{a_1 S_1}{0.167V}$$

Therefore, $$a_1 = \frac{0.167V}{S_1}\left[\frac{1}{T_2} - \frac{1}{T_2}\right]$$

Hence, knowing the values of T_1, T_2, S_1 and V, the absorption coefficient a_1 of the material can be determined.

❖ ***<u>Discuss the Factors affecting Acoustics of Building and their Remedies</u>:***

The various factors affecting the acoustics of building such as reverberation time, loudness, focusing, echo, echelon effect, resonance and noise with remedies are explained in brief in this section.

I. **Reverberation time:** Reverberation time is the persistence or prolongation of sound in a hall even after the source stopped sound.

The reverberation time is the time taken by the sound to fall below the minimum audibility level.

In order to have good acoustic effect, the reverberation time has to be maintained at optimum value. The reason is, if the reverberation time is too small, the loudness becomes inadequate. As a result the sound may not reach the listener. Thus, this gives a hall a dead effect. On the other hand, if the reverberation time is too long, it will lead to more confusion due to mixing of more syllables. This makes the sound unintelligible. Thus, reverberation time should neither be too large nor small. Hence to maintain a good acoustic effect the reverberation time should be maintained at optimum value.

Remedies: The reverberation time can be maintained at an optimum value by adopting following ways.

1. By providing windows and openings.
2. By having full capacity of audience in the hall or room.
3. By using heavy curtains with folds.
4. By covering the floor with carpets.
5. By decorating the walls with the beautiful pictures, maps, etc.
6. By covering the ceiling and walls with good sound absorbing materials like felt, fiber board, false roofing, etc.

   The reverberation time depends on the size of the hall and the quality of sound. Thus, the reverberation time can be controlled either by inserting or removing sound-absorbing material in the hall or room.

II. **Loudness**: The uniform distribution of loudness in a hall or a room is an important factor for satisfactory hearing. Sometimes, the loudness may get reduced due to excess of sound-absorbing materials used inside hall or room.

Remedies: If the loudness is not adequate, the loudness can be increased by adopting the following methods.

1. By using suitable absorbents at places where noise is high. As a result, the distribution of loudness may become uniform.
2. By constructing low ceilings for the reflection of sound towards the listener.
3. By using large sounding boards behind the speaker and facing the audience.
4. By using the public address system like loudspeakers.

III. **Focusing and Interference effect:** The presence of any concave surface or any other curved surface in the hall or room may make the sound to be concentrated at this focus region. As a result, the sound may not be heard at all at other regions. The regions are referred as dead space. Hence, such surface must be avoided.

In addition to focusing there should not be interference of direct and reflected waves. This is because, a constructive interference may produce a sound of maximum intensity in some places and a destructive interference may produce a sound of minimum intensity in other places. Thus, there will be an uneven distribution of sound intensity.

Remedy: Curved surfaces can be avoided. If curved surfaces are present, they should be covered with suitable sound-absorbing materials.

IV. **Echo:** An echo is heard due to reflection of sound from a different sound-reflecting object.

If the time interval between the direct sound and reflected sound is less than $\frac{1}{15}th$ of a second, the reflected sound is helpful in increasing the loudness. But, those sounds arriving later than this cause confusion.

Remedy: An echo can be avoided by covering long-distance walls and ceiling with suitable sound-absorbing material. This prevents reflection of sound.

V. **Echelon Effect:** It refers to the generation of a new separate sound due to multiple echoes. A set of railings or any regular reflecting surface is said to produce the echelon effect. This echelon effect affects the quality of original sound.

Remedy: The remedy to avoid echelon effect is to cover such surfaces with sound-absorbing materials.

VI. **Resonance:** Resonance occurs due to matching of frequency. If the window panels and section of wooden portions have not been tightly fitted, they may start vibrating, thereby creating an extra sound in addition to the sound produced in the hall or room.

Remedy: The resonance may be avoided by fixing the window panels properly. Any other vibrating object which may produce resonance can be placed over a suitable sound-absorbing material.

VII. **Noise:** The unwanted sound is called noise. The hall or room should be properly insulated from external and internal noises. In general, there are three types of noises.

1. Air-borne noises.
2. Structure-borne noises.
3. Inside noises.

Airborne-noise: Extraneous noises which are coming from outside through open windows, doors and ventilators are known as air-borne noises. The air-borne noise can be avoided by following the remedies given below.

Remedies:

a) The hall or room can be made air conditioned.
b) By using the doors and windows with separate frames with proper sound insulating material between them.

Structure-borne noise: The noise which is conveyed through the structure of the building is called structure-borne noise. The structural vibration may occur due to street traffic, operation of heavy machines, etc.

Remedies:

a) The noise can be eliminated by using double wall with air space between them.
b) By using anti-vibration mount this type of noise can be reduced.
c) By covering the floors and walls with proper sound-absorbing material this noise can be eliminated.

Inside noise: The noise which is produced inside the hall or room is called inside noise. The inside noise may be produced due to machineries like air conditioner, refrigerators, generators, fans, type writers, etc.

Remedies:

a) The sound producing machineries can be placed over sound-absorbing materials like carpet, pads, wood, felt, etc.
b) By using the curtain of sound-absorbing materials.
c) By covering the wall, floor, and ceiling with sound absorbing materials.

❖ **Write the Conditions for Good Acoustics**

A hall or an auditorium is said to be acoustically good if they satisfy the following conditions.

1. The quality of sound should be uniform throughout the entire hall or auditorium.
2. There should not be any overlapping of sound.
3. The loudness of the sound should be uniform throughout the hall or auditorium. To achieve this, a public address system can be used in big halls.
4. The presence or absence should not affect the quality of sound.
5. Resonance effect should be avoided.
6. The hall should have proper reverberation time.
7. The external noises should not disturb the proceedings inside the hall or auditorium.
8. There should not be any echelon effect.

❖ ***Write a short note on Sound Insulation:***

The art of preventing the transmission of unwanted sound into any space inside a room or a hall or any auditorium is known as sound insulation. It is also called as sound proofing.

The purpose of sound insulation is to suppress the noise. The process of sound insulation can be achieved by anyone of the following methods, depending on the type of noise to be treated and the degree of sound insulation required.

1. The sound producing source can be isolated by fixing it inside a special mounting.
2. By using floating floors and suspended ceilings.
3. By placing the working machineries like air-cooler or air-conditioner machine on a sound absorbing pad.
4. By using double doors and windows with separate frames and having insulating materials between them.

5. By making the hall as an air conditioned one.

❖ ***Write a short note on Noise Pollution:***

The unwanted sound is called Noise. The noise may be due to high frequency of sound or intensity or both. The noise produces a jarring effect or displeasing effect. The pollution in air due to noise is called Noise pollution.

The principal source of noise may be classified as surface transport noise, aircraft noise, industrial noise, train noise, noise due to construction work etc.

Effects of Noise Pollution:

1. Noise pollution produces mental fatigue and irritation.
2. It affects the work efficiency.
3. Some strong noises may damage the ear drum and make the worker hearing impaired.
4. It produces a change in bodily activity. Like indigestion, sleeplessness, nausea, etc.
5. Noise may affect the pregnant women and the foetus.
6. It also has been studied that, blood gets thickened due to excessive noise.

❖ ***Discuss Noise Control In Machines:***

Machines which lack maintenance and which are not properly housed. Noise control may be affected by one or more of the following methods.

1. Sound absorbent materials may be installed near noise source.
2. The source of sound may be redesigned for quieter operation.
3. The source may be isolated with sound reducing housings.
4. Workers may use ear muffs and ear plugs.

Illustration of noise control in a machine:

Figure shows the proper design for noise reduction in a machine.

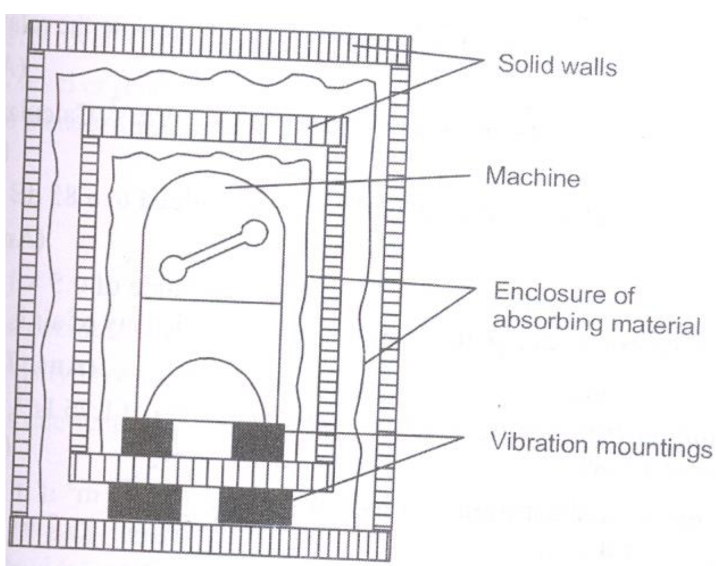


Fig. Schematic diagram of Noise Control in a Machine.

i. First, the machine is made to rest on soft vibration mounts kept beneath the machine.
ii. Next, it is enclosed by an absorbing material.
iii. Then it is enclosed by an air tight box resting on vibration mounts. Further, this box is enclosed by an absorbing material and finally once again enclosed by an air tight box.

This type of noise reduction in a machine is called as double enclosure with double vibration mounts.

❖ ***EXAMPLES:***

1. What is the resultant sound level when a 70 dB is added to a 80 dB sound?

   Given, I_{L_1} = 70 dB; I_{L_2} = 80 dB; I_L = ?

$$\therefore \quad I_{L_1} = 10\log_{10}\left(\frac{I_1}{I_0}\right)$$

$$70 = 10\log_{10}\left(\frac{I_1}{I_0}\right)$$

$$7 = \log_{10}\left(\frac{I_1}{I_0}\right)$$

$$\frac{I_1}{I_0} = 10^7$$

   Or $$I_1 = 10^7\, I_0$$

   Similarly, $$80 = 10\log_{10}\left(\frac{I_2}{I_0}\right)$$

$$\therefore \quad \frac{I_2}{I_0} = 10^8$$

   Or $$I_2 = 10 \times 10^7\, I_0$$

$$\therefore \quad I = I_1 + I_2 = 10^7 I_0 + 10 \times 10^7\, I_0$$

$$I = 10\log_{10}\left(\frac{I}{I_0}\right) = 10\ \log_{10}(11 \times 10^7)$$

$$\therefore \quad I_L = 10 \times 8.0413$$

$$\therefore \quad I_L = 80.41\ dB$$

   Therefore, the resultant intensity is **80.41 dB**

2. The sound from a drill gives a noise level of 95 dB at a point a few meters away from it. What is the noise level at this point when four such drills are working at the same distance away?

   Given, $I_{L_1} = 95\ dB, I_{L_2} = ?, I = 4I_0; I_L = ?$

$$I_{L_2} = 10\log_{10}\left(\frac{4I_0}{I_0}\right)$$

$$\therefore \quad I_{L_2} = 10 \times 0.6020$$

$$I_{L_2} = 6.02\text{ dB}$$

Hence, $$I_L = I_{L_1} + I_{L_2}$$
$$= 95 + 6.02 \text{ dB}$$
$$\boldsymbol{I_L = 101.02\ dB}$$

3. A source of sound has a frequency of 426 Hz and amplitude of 0.65×10^{-2} m. calculate the flow of energy across 1 m^2 per second if the velocity of sound in air is 340 ms^{-1} and the density of air is 1.29 kg m^{-3}.

   Given, f= 426 Hz; a= 0.65×10^{-2} m; A=1 m^2; v= 340 ms^{-1}; ρ= 1.29 kg m^{-3}; I =?

   We know, $$I = 2\pi^2 f^2 a^2 \rho v$$
   $$= 2\times(3.14)^2\times (426)^2\times (0.65\times10^{-2})^2 \times1.29\times 340$$
   $$\mathbf{I = 6.631\times10^4\ Wm^{-2}.}$$

4. The volume of a room is 1,500 m^3. The wall area of the room is 260 m^2, the floor area is 140 m^2 and the ceiling area is 140 m^2. The average sound absorption coefficient for the wall is 0.03, for the ceiling it is 0.8 and for the floor it is 0.06. Calculate the average absorption coefficient and the reverberation time.

   Given, V= 1,500 m^3; a_1= 0.03 Sabine; a_2= 0.8 Sabine; a_3= 0.06 Sabine; S_1= 260 m^2; S_2= 140 m^2; S_3= 140 m^2; $\bar{a} = ?\ T = ?$

   Average absorption coefficient is
   $$\bar{a} = \frac{a_1S_1+a_2S_2+a_3S_3}{S_1+S_2+S_3}$$
   $$= \frac{0.03\times260+0.8\times140+0.06\times140}{260+140+140} = \frac{7.8+112+8.4}{540}$$
   $$\bar{a} = \mathbf{0.2374\ O.W.U}$$

   Therefore, the total sound absorption of the room is
   $$\bar{a}\sum S = 0.2374 \times 540 = 128.196\ O.W.U.m^2$$

   Therefore, the reverberation time is
   $$T = \frac{0.167V}{\bar{a}\sum S} = \frac{0.167\times1{,}500}{128.196} = \frac{250.5}{128.196}$$
   $$\boldsymbol{T = 1.9540\ sec}$$

5. A hall has a volume of 1, 20,000 m^3. It has a reverberation time of 1.55 sec. what is the average absorbing power of the surface if the total absorbing surface is 26,500 m^2.

   Given, V=1,20,000 m^3; T=1.55 sec; ΣS=26,500 m^2; ΣaS= ?, $\bar{a}$ = ?

We know $$T = \frac{0.167V}{\sum aS}$$

∴ $$\sum aS = \frac{0.167 \times 1{,}20{,}000}{1.55} = \frac{20{,}040}{1.55}$$

$$\sum aS = \mathbf{12929.0\ sabine - m^2.}$$

Therefore, the average absorbing power of the surface is

$$\bar{a} = \frac{\sum aS}{\sum S} = \frac{12{,}929}{26{,}500} = \mathbf{0.4878\ sabine.}$$

6. A hall has a volume of 12,500 m^3 and reverberation time of 1.5 sec. if 200 cushioned chairs are additionally placed I the hall, what will be the new reverberation time of the hall? The absorption of each chair is 1.0 O.W.U.

   Given, V= 12,500 m^3; T_1= 1.5 sec; a_2 S_2= 200 sabine-m^2; Σ a^1 S^1=?

   Let, $$T_1 = \frac{0.167V}{\sum a_1 S_1}$$

   Be the reverberation time before placing cushioned chairs.

   ∴ $$\sum a_1 S_1 = \frac{0.167 \times 12{,}500}{1.5} = \frac{2{,}087.5}{1.5}$$

   $$\sum a_1 S_1 = 1391.66\ sabine - m^2.$$

   Let, the reverberation time after placing the cushioned chairs be

   $$T_2 = \frac{0.167V}{\sum a_1 S_1 + a_2 S_2} = \frac{0.167 \times 12{,}500}{1{,}391.66 + 200} = \frac{2{,}087.5}{1{,}591.66}$$

   $$\mathbf{T_2 = 1.3115\ sec}$$

   Therefore, the new reverberation time after placing the cushioned chairs is 1.3115 sec.

***<u>Answer in short:</u>* ACOUSTICS**

1. Classify the Sound based on frequency.
   Based on frequency sound waves are classified as
   I. Infra sound (f < 20 Hz)
   II. Audible sound (20 Hz < f <20 KHz)
   III. Ultra sound (f > 20 KHz)
2. Define Music and Noise. Give example.
   Music: The sound which produces pleasing effect on ear is called Musical sound.
   Ex. Sound produced by musical instrument like Sitar, Violin, etc.
   Noise: The sound which produces a jarring effect on the ear and is unpleasant to hear is called noise. Ex. Crackers sound, road traffic, etc.

3. What is Loudness? Give the relation between Loudness and Intensity of sound.
   Loudness of sound is degree of sensation produced on the ear.
   The relation between Loudness and Intensity is given by Weber-Fechner law.
   $$L= K\log_{10} I,$$
   That is, loudness is directly proportional to the logarithmic intensity of sound.
4. Define intensity level. Give its unit or define sound intensity level and write its unit.
   The intensity level or relative intensity of a sound is defined as logarithmic ratio of intensity of a sound to standard intensity I_0.
   i.e, $$I_L = K \log_{10} (I/I_0)$$
   Its unit is dB.
5. Define Bel and decibel.
   Bel is the intensity level of a sound whose intensity is 10 times the standard intensity.
   One Decibel is one – tenth of a bel,
   $$1 \text{ dB} = (1/10) \text{ bel}.$$
6. What is Threshold intensity?
   The minimum sound intensity which a human ear can sense is called the threshold intensity. Its value is $\mathbf{10^{-12}\ Wm^{-2}}$.
7. What is Threshold of feeling?
   The sound of intensity level 120 dB which produces a pain in the ear is called threshold of feeling.
8. Define Absorption coefficient. Give its value.
   It is defined as the ratio of sound energy absorbed by a sound-absorbing material to that absorbed by an equal area of an open window. Its unit is **Sabine** or **O.W.U**
9. Define Reverberation time.
   Def 1: It is defined as a time taken by s sound intensity to fall to one millionth of its initial intensity after the source stopped emitting sound.
   Def 2: It is defined as the time taken by sound to fall below minimum audibility level after the source stopped sounding.
10. Define Reverberation.
    It is the persistence or prolongation of sound in a hall even though the source of sound is cut off.
11. What are sound absorbing materials?
    The special materials used to increase the absorption of sound waves or to reduce the reflection of sound waves in a room or a hall is known as sound absorbing materials.
12. What are the types of sound absorbing materials?
    The sound absorbing materials are broadly classified into the following four categories.
    I. Porous absorbent
    II. Cavity resonator

III. Resonant absorbents or panel absorbers
IV. Composite absorbents.

13. Mention few important conditions to be satisfied for good acoustics.
    I. The loudness of the sound should be uniform through the hall or auditorium either by direct system or by using public address system.
    II. The hall should have proper reverberation time.
    III. The external noises should not enter the hall or auditorium.
    IV. There should not be any echelon effect.
14. What do you mean by Acoustic of building?
    It is the art of designing a building to provide uniform and good intensity of audible sound to everyone in the building.

.....Best of Luck.....

Ultrasonic Waves

INTRODUCTION: The sound waves of frequency greater than 20 KHz are called ultrasonic waves. These sound waves are inaudible to human ear. The ultrasonic waves due to their shorter wavelength have a greater penetrating power.

Ultrasonic waves are widely used in medical diagnostics, marine applications, NDT, etc.

In this chapter, two different methods of producing ultrasonic sound waves, their velocity determination and their application in SONAR are explained.

❖ ***Mention the Properties of Ultrasonic waves.***

i. The frequency of ultrasonic wave is greater than 20 KHz.
ii. Their wavelengths are small. As a result, their penetrating power is high.
iii. They can travel over a long distance as a highly directional beam.
iv. They have high energy content.
v. Their speed of propagation increases with increase in frequency.

❖ ***Name the methods of producing ultrasonic waves:*** Based on frequency range and power output, the ultrasonic waves generator are divided into two groups.

1. Mechanical generator
2. Electrical generator

In the following section, the electrical generator methods of producing ultrasonic waves are explained.

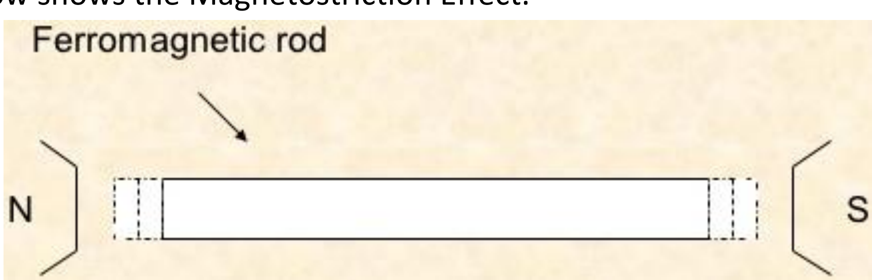
The electrical generators are subdivided into two categories.

i. Magnetostriction generator or Oscillator
ii. Piezoelectric generator or Oscillator.

The above two methods are widely used nowadays for producing ultrasonic waves.

❖ ***Describe the Method of Producing Ultrasonic waves by Magnetostriction Oscillator method.***

Principle: When a ferromagnetic material in the form of rod is subjected to an alternating magnetic field parallel to its length, the rod undergoes alternate contractions and expansions at a frequency equal to the frequency of applied magnetic field. This phenomenon is known as Magnetostriction effect. Figure below shows the Magnetostriction Effect.



Due to resonance, the rod is thrown into longitudinal vibrations, thereby producing ultrasonic waves in the surrounding medium. Such ferromagnetic materials which are used for the production of ultrasonic waves are called Magnetostriction materials.

Construction:

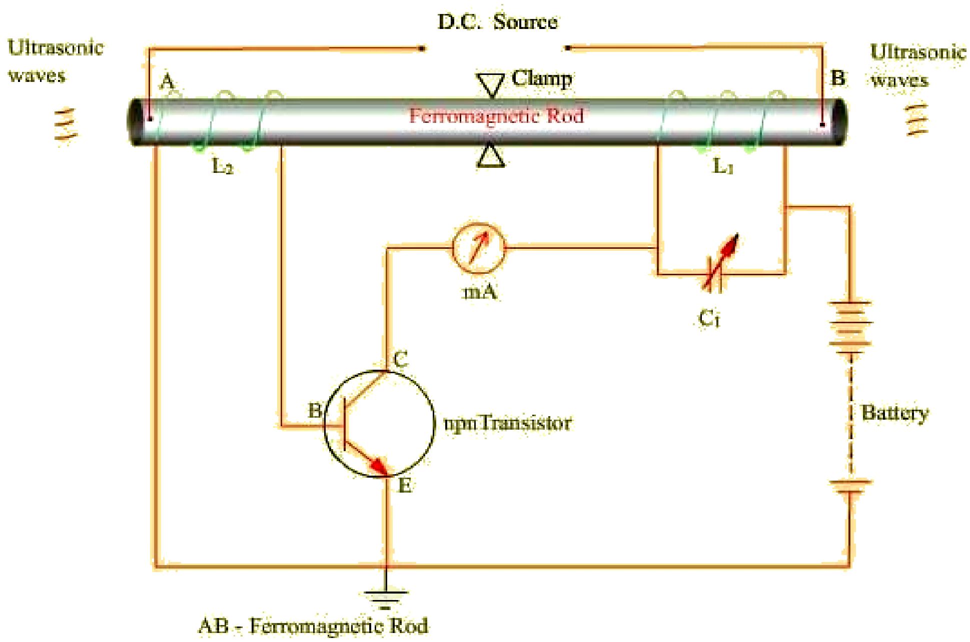


Fig. Circuit diagram for Magnetostriction oscillator method

The ferromagnetic rod AB is clamped at the middle X. The coils L_1 and L_2 are wound at the end of the rod. To the coil L_1 a variable capacitor C_1 is connected in the parallel and this combination forms the tank or resonant circuit. One side of the resonant circuit is connected to the connector of the transistor through the milliammeter. The other side of the resonant circuit is connected to the emitter through a battery. The coil L_2 is connected between the base and emitter and is used as a feedback loop.

Working: When the battery is switched on, the resonant circuit L_1C_1 in the collector circuit of the transistor sets up an alternating current of frequency,

$$f = \frac{1}{2\pi\sqrt{L_1C_1}}$$

As a result, the rod gets magnetized by the collector current. Any changes in the collector current bring about a change in the magnetization, and consequently a change in the length of the rod. This gives rise to a change in flux in coil L_2 in the base circuit, thereby inducing an emf in the coil L_2. This varying emf is applied to the base of the transistor and is fed back to the coil L_1, thereby maintaining the oscillations.

By varying a capacitor C_1, the frequency of oscillation of the tank circuit gets varied. If the frequency of the tank circuit matches with the natural frequency of the material, then due to resonance the rod vibrates vigorously producing ultrasonic waves at the end of the rod. The milliammeter reading gives maximum value at the resonance condition. The frequency of ultrasonic waves produced by this method depends upon the length *l*, density ρ and elastic constant E of the rod.

i.e. $$f = \frac{1}{2l}\sqrt{\frac{E}{\rho}}$$

Thus, by varying *l* and E of the rod, ultrasonic waves can be generated at any desired frequency. Hence, at resonance condition,

Frequency of the oscillatory circuit = frequency of the vibrating rod

i.e. $$\frac{1}{2\pi\sqrt{L_1C_1}} = \frac{1}{2l}\sqrt{\frac{E}{\rho}}$$

Merits:

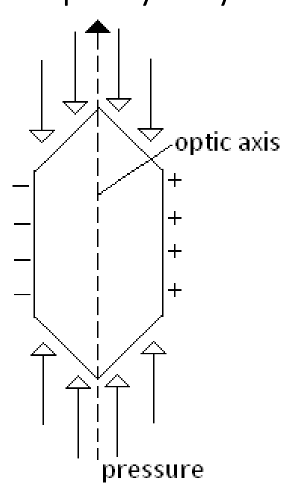
1. The design of this oscillator is very simple and production cost is low.
2. At low ultrasonic frequencies, large power output is possible without the risk of damage to the oscillatory circuit.
3. Frequency ranging from 100 Hz to 3,000 KHz can be produced.

Demerits:

1. It cannot generate ultrasonic of frequency above 3,000 kHz.
2. The frequency of oscillations depends greatly on temperature.
3. There will be losses of energy due to hysteresis and eddy current.

❖ ***Piezoelectric Method:***

Principle: : When pressure is applied to one pair of opposite faces of crystal like quartz, tourmaline, Rochelle salt, etc, cut with their faces perpendicular to its optic axis, equal and opposite charges appear across its other faces as shown in fig. This phenomenon is known as piezoelectric effect. The frequency of the developed emf is equal to the frequency of dynamical pressure.



The sign of the charges gets reversed if the crystal is subjected to tension instead of pressure. The electricity produced by means of piezoelectric effect is called piezoelectricity. The materials which can undergo piezoelectric effect are called piezoelectric materials or crystals.

The cross section of natural quartz crystal is hexagonal. The lines joining the opposite corners of the hexagon are called the mechanical axis or Y-axis.

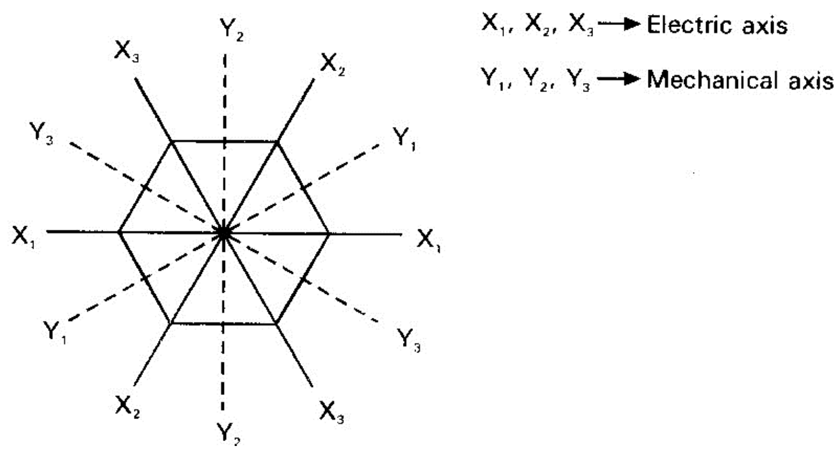


Fig. Piezoelectric crystal axis

The piezoelectric method of producing ultrasonic wave is based on the principle of inverse piezoelectric effect

❖ ***Inverse piezo-electric effect:***

Principle: If an alternating voltage is applied to one pair of opposite faces of the crystal, alternating mechanical contractions and expansion are produced in the crystal starts vibrating. This phenomenon is known as inverse piezo-electric effect or electrostriction effect.

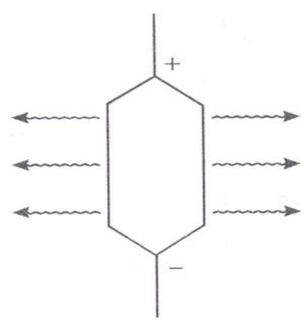


Fig. Inverse Piezoelectric effect

If the frequency of the applied alternating voltage is equal to the vibrating frequency of the crystal, then the crystal will be thrown into resonant vibration producing ultrasonic waves.

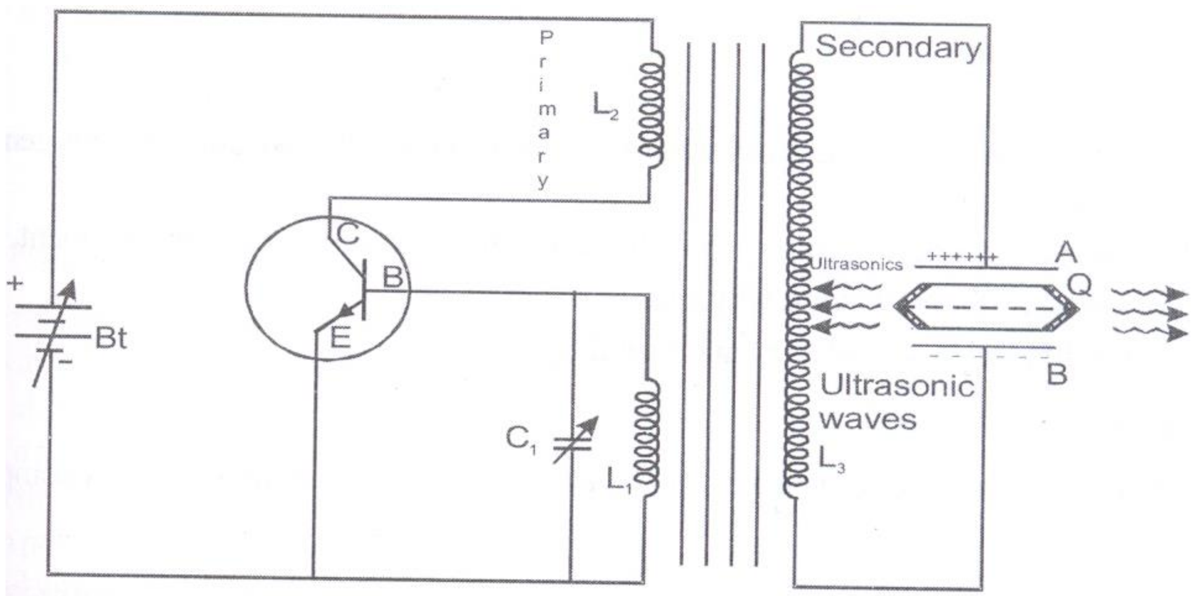


Fig. Piezoelectric oscillator method.

Construction: The quartz crystal Q is placed between two plates A and B are connected to the coils L_3. The coils L_1, L_2 and L_3 are inductively coupled to the oscillatory circuit of a transistor. The coil L_2 is connected to the collector circuit, while the coil L_1 with a variable capacitor C_1 forming the tank circuit is connected between the base and the emitter. The battery is connected between free end of L_2 and the emitter of transistor.

Working: When the battery is switched on, the oscillator produces high frequency alternating voltage given by

$$f = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

The frequency of oscillation can be controlled by the variable capacitor C_2. Due to transformer action an emf is induced in the secondary coil L_3.This emf is impressed on plates A and B and thus excites the quartz crystal into vibrations. By adjusting the variable capacitor C_1, the crystal is set into one of the modes of resonant conditions. Thus, the vibrating crystal produces longitudinal ultrasonic waves in the surrounding air. The frequency of vibration of the crystal is

$$f = \frac{1}{2l}\sqrt{\frac{E}{\rho}}$$

Where, E is Young's Modulus, ρ is density of the material and p = 1,2,3…for fundamental, first overtone, second overtone…..respectively.

At resonance condition,

Frequency of the oscillatory circuit = Frequency of the vibrating crystal

i.e., $$\frac{1}{2\pi\sqrt{L_1 C_1}} = \frac{1}{2l}\sqrt{\frac{E}{\rho}}$$

Merits:

1. It is more efficient than Magnetostriction oscillator. Almost all the modern ultrasonic generators are of this type only.
2. Ultrasonic frequencies as high as 5*108 Hz can be obtained with this arrangement.
3. The output of this oscillator is very high.
4. It is not affected by temperature and humidity.

Demerits:

1. The cost of piezoelectric quartz is very high and its cutting and shaping are very complex.

❖ ***Determine the velocity of ultrasonic waves By Acoustic Grating Method:***

Principle:

When ultrasonic waves are passed through transparent liquid medium in a container, the waves get reflected. These reflected waves are called echoes.

The direct and reflected waves superimposed to form the stationary wave pattern.

These waves give rise to a periodic variation in the density of the liquid. The change in the density of the liquid in turn leads to a variation in the refractive index of the liquid. The density of the liquid would be maximum at nodal planes, while at the anti nodal planes it would be minimum. Such a liquid-column-subjected ultrasonic waves behaves like a grating. Under this condition, if a parallel beam of light is passed through the liquid at right angle of the wave, the liquid acts as a diffraction grating. Such a grating known as a acoustic grating.

Experiment:

The experimental arrangement is shown in figure below

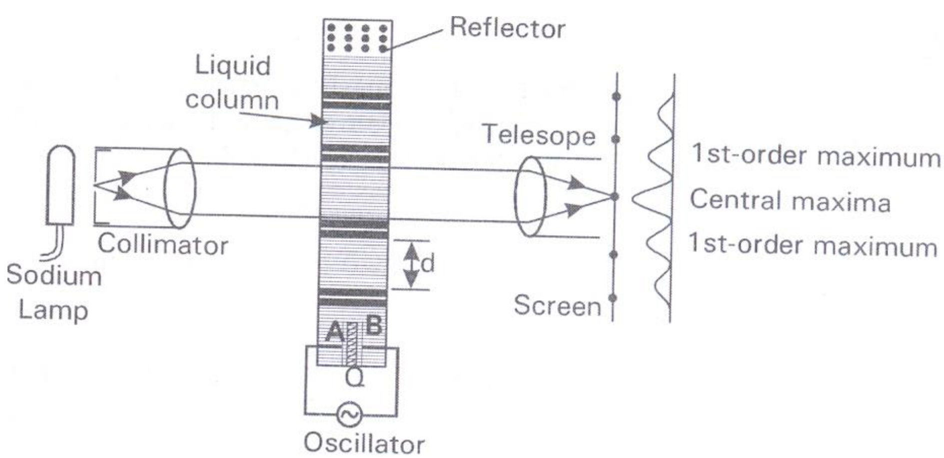


Fig. Experimental arrangement to determine the velocity of ultrasonic waves.

There is glass vessel containing the liquid with a reflector R fixed within the vessel at its top.

A quartz crystal Q placed between two metal plates A and B is mounted at the bottom of the vessel.

The metallic plates are connected to an oscillator whose frequency is so adjusted that the crystal vibrates in resonance with the frequency of the oscillator and thus produce ultrasonic waves within the liquid. Hence, the liquid behaves like a grating. This acoustic grating is mounted on the prism table of a spectrometer and a parallel beam of light from monochromatic source S is passed through the liquid at right angle to the wave. Since the liquid is behaving like a grating, the light beam on passing through it gets diffracted and produces a diffraction pattern. The diffraction pattern is viewed through the telescope.

The diffraction pattern is consists of a central maxima with principle maxima of different orders on either side. If Θ is angle of diffraction for the n^{th} order principle maxima then,

$$d \sin \theta = n\lambda \qquad \text{.......... (1)}$$

Where, λ is the wavelength of monochromatic light used and d is the grating element (the distance between adjacent nodal planes is defined as the grating element).

The grating element $d = \frac{\lambda_u}{2}$, where, λ_u is the wavelength of ultrasonic waves.

$$\therefore \ \frac{\lambda_u}{2} sin\theta = n\lambda$$

Or $$\lambda_u = 2\, n\lambda / \, sin\theta \qquad \text{............ (2)}$$

Thus, knowing λ and n and by measuring θ, the wavelength of ultrasonic waves can be determined. If the resonant frequency of the ultrasonic generator is f, then the velocity of the ultrasonic waves is given by

$$v = f\,\lambda_u \qquad \text{......... (3)}$$

Using this acoustic diffraction method, the wavelength and hence the velocity of ultrasonic waves through liquids and gases at various temperatures can be determined.

❖ ***Applications Of Ultrasonic Waves:***

(1) SONAR: SONAR stands for Sound Navigation and Ranging.

It is based on the principle of echo sounding. In this acoustical technique high-frequency ultrasonic waves are used. When ultrasonic waves are transmitted through water, they get reflected by the objects under water. The change in the frequency of the echo signals due to the Doppler effect helps us to determine the velocity, distance and the direction of objects.

In the absence of an obstacle the ultrasonic waves do not get reflected to the receiving transducer. But in the presence of an obstacle the ultrasonic waves get reflected and are picked up by the receiving transducer. Knowing the velocity of ultrasound and the elapsed time, the distance of the object can be determined.

Using SONAR, the distance and direction of submarines, depth of sea, and depth of rocks in the sea, the shoal of fish in the sea, etc., can be determined.

How can the Depth of the Sea be measured using Ultrasonic waves?

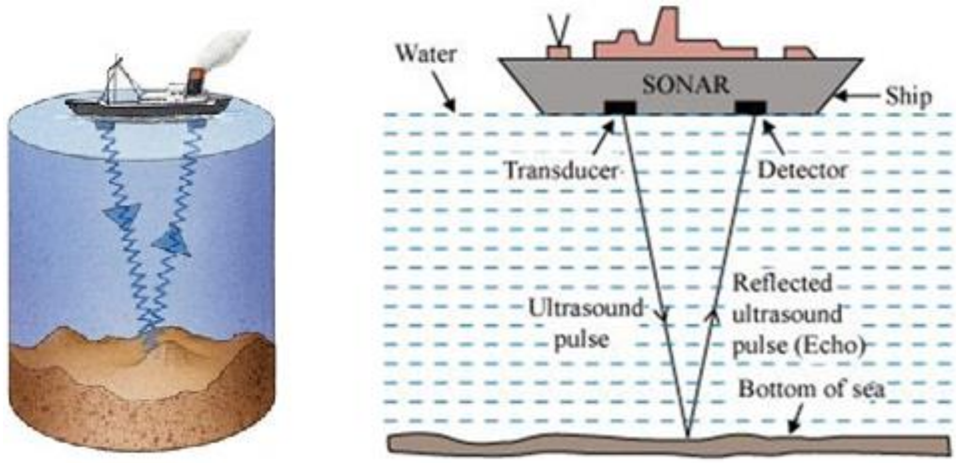


Fig. Determination of depth of sea.

The ultrasonic waves can be used to find the depth of the sea. It is based on the principle of echo sounding.

The ultrasonic waves sent from point A travel through sea water and get reflected from the bottom of the sea. The reflected waves are received at point B.

The time t taken for ultrasonic wave to travel to the bottom of the sea and to get reflected back to the top of surface is noted using CRO. If the velocity V of the ultrasonic wave is already known, then

$$Velocity\ \mathrm{v} = \frac{Distance\ travelled}{Time\ taken}$$

$$\mathrm{v} = \frac{AC+CB}{t} \simeq \frac{2CO}{t}$$

Therefore, CO = Depth of sea = vt /2

Thus, the depth of the sea can be calculated using this formula.

Fathometer or Echometer is a device which is directly calibrated to determine the depth of the sea.

(2) <u>Applications in Science and Engineering:</u>

The ultrasonic waves find a wide application in many fields. Some of the important applications are listed below.

1. It is used to detect flaws or cracks in metals.
2. It is used to detect ships, submarines iceberg, etc. in the ocean.
3. It is used for soldering aluminum coil capacitors, aluminum wires, and plates without using any fluxes.
4. It is used to weld some metals which cannot be welded by electric or gas welding.
5. It is used for cutting and drilling holes in metals.

6. It is used to form stable emulsions of even immiscible liquid like water and oil or water and mercury which find application in the preparation of photographic films, face creams, etc.
7. It acts like a catalytic agent and accelerates chemical reactions.

(3) <u>Application in Medicine:</u>

1. it is used to remove kidney stones and brain tumors without shedding any blood.
2. It is used to remove broken teeth.
3. It is used for sterilizing milk and for killing bacteria.
4. It is used to study the blood flow velocities in blood vessels of our body.
5. It is used as a diagnostic tool to detect tumors, breast cancer and also the growth of foetus.

❖ ***<u>EXAMPLES</u>:***

1. Calculate the frequency to which piezoelectric oscillator circuit should be tuned so that a piezoelectric crystal of thickness 0.1 cm vibrates in its fundamental mode to generate ultrasonic waves. (Young's modulus and density of material of crystal are 80 GPa and 2654 kgm^{-3}).

   Given, E= 80 GPa = 80×10^9 Pa; ρ= 2654 kgm^{-3}; t= 0.1 cm = 0.1×10^{-2} m.
   The frequency of vibration is given by

$$f = \frac{P}{2t}\sqrt{\frac{E}{\rho}} = \frac{1}{2\times0.1\times10^{-2}}\sqrt{\frac{80\times10^9}{2654}} = \frac{5490.28}{2\times10^{-3}}$$

$$\boldsymbol{f = 2.7452 \times 10^6\ Hz}$$

2. Find the frequency of the first and second modes of vibration for a quartz crystal of piezoelectric oscillator. The velocity of longitudinal waves in quartz crystal is $5.5\times10^3\ ms^{-1}$. Thickness of quartz crystal is 0.05 m.

   Given, v=$5.5\times10^3\ ms^{-1}$; t= 0.05 m; v_1=?, v_2= ?
   In the lowest mode of vibration, the distance between the two faces of the crystal of thickness t will be λ/2.
   Therefore, $t = \frac{\lambda}{2}$ or λ = 2t = 2×0.05

$$\lambda = \mathbf{0.1\ m}$$

   Therefore, the frequency in the first mode of vibration

$$v_1 = \frac{v}{\lambda} = \frac{5.5\times10^3}{0.1}$$

$$\boldsymbol{v_1 = 5.5 \times 10^4\ Hz}$$

   The frequency in the second mode of vibration is

$$v_2 = 2v_1 = 2 \times 5.5 \times 10^4$$

∴ $$\boldsymbol{v_2 = 110 \times 10^3\ Hz}$$

3. An ultrasonic source of 0.09 MHz sends down a pulse towards the seabed which returns after 0.55 sec. The velocity of sound in water is 1800 m/s. Calculate the depth of sea and wavelength of pulse.

   Given, f= 0.09 MHz= 0.09×10^6 Hz; t= 0.55 sec; v= 1800 ms^{-1}; depth of sea= ?, λ_u = ?

   Depth of sea $d = \frac{vt}{2} = \frac{1800\times0.55}{2}$

   ∴ $d = 495\ m$

   The wavelength of ultrasonic pulse is $\lambda_u = \frac{v}{f} = \frac{1800}{0.09\times10^6}$

   ∴ $\lambda_u =$ **0.02 m.**

❖ ***Answer in short***:

1. **What are Ultrasonic waves?**
   Sound waves having frequency greater than 20 kHz are called ultrasonic waves.
2. **Why ultrasonic not produced by passing high frequency A.C current through a loud speaker?**
   At high frequencies, the inductive effect of a loud speaker coil is so huge that practically no current passes through it. Moreover, the diaphragm cannot vibrate at such high frequencies.
3. **Explain Magnetostriction effect.**
   When a rod of ferromagnetic material like iron, cobalt and nickel is magnetized longitudinally, the rod undergoes a small change in length. This is called Magnetostriction effect.
4. **What is Piezoelectric effect?**
   When a pressure is applied to one pair of opposite faces of crystal like quartz, tourmaline, Rochelle salt, etc., cut with their faces perpendicular to its optic axis, equal and opposite charges appear across its other faces. This is known as piezoelectric effect.
5. **What is inverse piezoelectric effect?**
   If an alternating voltage is applied to one pair of opposite faces of the crystal, mechanical contraction and expansion are produced across the other opposite faces. This phenomenon is known as inverse piezoelectric effect.
6. **Are the ultrasonic waves electromagnetic waves? Give proper reason to support your answer.**
   1. Ultrasonic waves are not electromagnetic waves because they are Sound waves.
   2. Electromagnetic waves travel with the velocity of light but ultrasonic waves travel with the velocity of Sound.
7. **Compare Magnetostriction oscillator and piezoelectric oscillator method of producing ultrasonic.**

Sr. No.	Piezoelectric generator	Magnetostriction generator
1	Produces ultrasonic waves of frequency as high as 500 MHz.	It produces waves of 100 kHz.
2	Used for low power application such as	Used for high power application such as

	flaw detector.	drilling, welding, etc.

8. What is Acoustic grating?

When ultrasonic waves propagate in liquid medium, the alternating compression and rarefactions change the density of the medium. This change in density results in variation of refractive index of the liquid.

Under this condition, if a parallel beam of monochromatic light is passed through them at right angle to the waves, the liquid causes the light to undergo diffraction. Such a liquid column behaving like a grating is called Acoustic grating.

9. What is a SONAR?

SONAR is device which stands for Sound Navigation and Ranging. It is based on the echo sounding technique of ultrasound.

It is the acoustical technique used for finding the distance and direction of submarines, depth of sea, depth of rocks in the sea, the shoal of fish in the sea, etc.

10. Expand SONAR and give its use.

SONAR stands for Sound Navigation and Ranging which uses highly directional ultrasonic waves for finding objects and determining their distance under the sea. It is based on the principle of echo-sounding technique of ultrasound.

11. What is the principle of SONAR?

When ultrasonic waves are transmitted through water, it gets reflected by the object in the water and produces an echo signal.

The distance of the object can be easily calculated by noting the time interval between the generation of ultrasonic pulse and the reception of the echo signal.

12. How can the depth of sea be measured using ultrasonic waves?

A pulse of ultrasonic waves is produced by the ultrasonic transducer and transmitted towards the bed of the sea. The waves reflected back from the sea bed is collected by the receiver.

The time interval 't' between the emitted signal and the received echo is measured by an oscillography.

Knowing the velocity of sound 'v' through sea water, the depth of the sea 'd' can be calculated using relation: $d = vt/2$

13. **What are the applications of ultrasonic in industry? Or write any two engineering applications of ultrasonic waves.**

1. Ultrasonic waves are used to detect flaws or defects in metal structure. This is known as non-destructive testing of materials.
2. Ultrasonic waves are used for material processing, that is, soldering, cutting, welding and drilling.