Ch. 4. Ultrasonics and Acoustics

<u>Section A Ultrasonics</u>

1. **Introduction to Ultrasonics:**

The word ***ultrasonic*** combines the Latin roots ultra, meaning ***'beyond'*** and sonic, or ***sound***.

The sound waves having frequencies above the audible range i.e., above 20 Hz to 20KHz are called ***ultrasonic waves***.

Generally, these waves are called as ***high frequency waves***.

The field of ultrasonic have applications for imaging, detection and navigation.

The broad sectors of society that regularly apply ultrasonic technology are the medical community, industry, the military and private citizens.

Properties of ultrasonic waves:

- They have a high energy content.
- Just like ordinary sound waves, ultrasonic waves get reflected, refracted and absorbed.
- They can be transmitted over large distances with no appreciable loss of energy.
- If an arrangement is made to form stationary waves of ultrasonics in a liquid, it serves as a diffraction grating. It is called an ***acoustic grating.***
- They produce intense heating effect when passed through a substance.

2. **Production of Ultrasonic Wave:**

Ultrasonic waves are produced by the following methods:

i. Piezo-electric generator or oscillator

ii. Magneto-striction generator or oscillator

i). Piezo-Electric Generator or Oscillator:

Piezo-electric effect: If mechanical pressure is applied to the opposite faces of certain crystal slices cut suitably, like quartz, then these faces will develop equal and opposite electrical charges with consequent difference of potential, their magnitudes being proportional to the pressure. But when crystal slices are under tension, the sign of charges is reversed. This phenomenon called as Piezo-electric effect.

The converse of piezo electric effect is also true.

If potential difference is applied to one pair of faces, the corresponding changes in the dimensions of the other pair of faces of the crystal are produced. This is known as ***inverse piezo electric*** effect or ***electrostriction***.

Piezoelectric effect exhibits in a large variety of crystals such as quartz, tourmaline and Rochelle salt.

Construction: The experimental arrangement of piezoelectric generator is as shown in Fig.

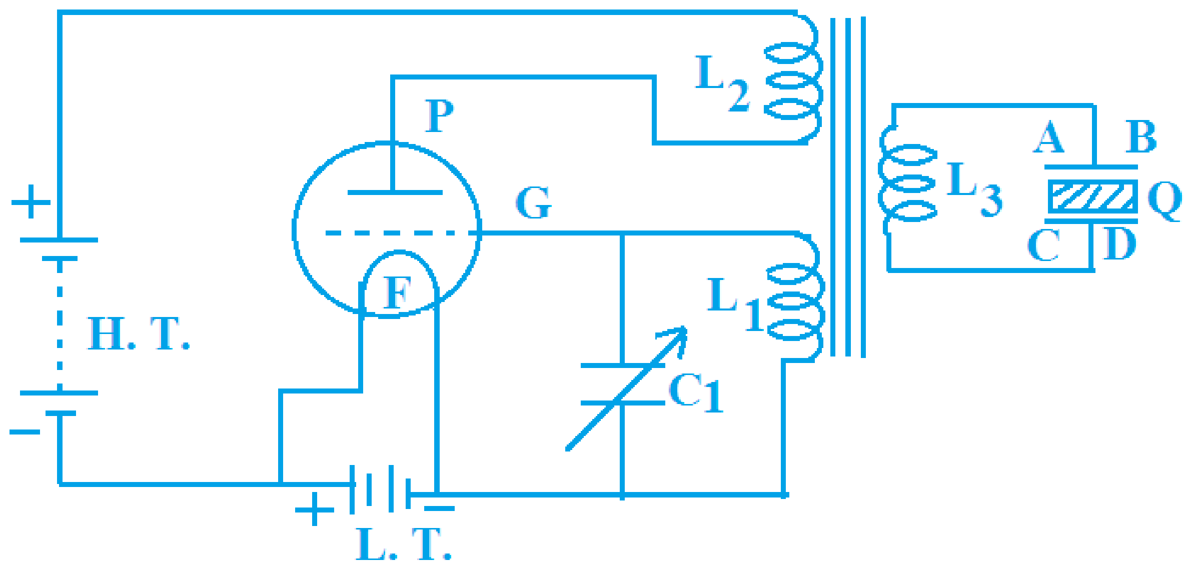


Figure 1 Piezoelectric generator

Langevin in 1917 developed a method of producing ultrasonic waves by using Piezo-electric effect. The quartz crystal is placed between two metal plates A and B. The plates are connected to the primary (L_3) of a transformer which is inductively coupled to the electronics oscillator. The electronic oscillator circuit is a base tuned oscillator circuit. The coils L_1 and L_2 of oscillator circuit are taken from the secondary of a transformer T. The plate coil L_2 is inductively coupled to grid coil L_1. The coil L_1 and variable capacitor C_1 form the *tank circuit* of the oscillator.

Working:

When H.T. battery is switched on, the oscillator produces high frequency alternating voltages with a frequency.

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

Due to the transformer action, an oscillatory e.m.f. is induced in the coil L_3. This high frequency alternating voltages are fed on the plates A and B.

Inverse piezo-electric effect takes place and the crystal contracts and expands alternatively. The crystal is set into mechanical vibrations.

The frequency of the vibration is given by,

$$n = \frac{p}{2l}\sqrt{\frac{Y}{\rho}}$$

where P = 1,2,3,4 … etc. for fundamental, first over tone, second over tone etc., Y = Young's modulus of the crystal and ρ = density of the crystal.

The variable condenser C_1 is adjusted such that the frequency of the applied AC voltage is equal to the natural frequency of the quartz crystal, and thus resonance takes place.

The vibrating crystal produces longitudinal ultrasonic waves of large amplitude.

Advantages

- Ultrasonic frequencies as high as 5 x 10^8Hz or 500 MHz can be obtained with this arrangement.
- The output of this oscillator is very high.
- It is not affected by temperature and humidity.

Disadvantages:

- The cost of piezo-electric quartz is very high
- The cutting and shaping of quartz crystal are very complex.

ii). Magnetostriction Generator:

Magnetostriction Effect:

If a bar of a ferromagnetic material like iron, nickel etc., is subjected to alternating magnetic field, the bar expands and contracts in length alternately. This effect is called as magnetostriction effect.

The frequency of expansion and contraction is twice the frequency of alternating magnetic field.

Construction

The experimental arrangement of magnetostriction oscillator is as shown in Figure.

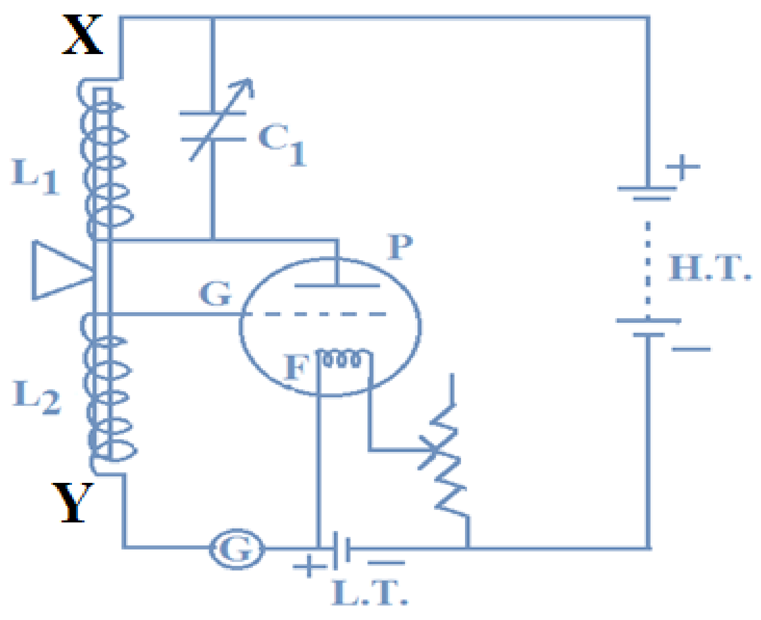


Figure 2 Magnetostriction generator

Let XY is a rod of ferromagnetic materials like iron or nickel. The bar is clamped in the middle and placed inside two coaxial coils L_1 and L_2. This bar is permanently magnetized in the beginning by passing direct current in the coil. The coil L_1 and C_1 are connected in parallel and combination is connected to plate of the electrode. An exciting coil L_1 forms the inductance in the tuned plate circuit of valve. The grid circuit contains a galvanometer and coil B is coupled to the plate coil.

Working:

When High Tension (H.T) battery is switched on, the plate circuit oscillates with a frequency,

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

This alternating current flowing through the coil L_1 produces an alternating magnetic field along the length of the rod. By suitably adjusting the value of variable condenser C_1, the high frequency oscillating currents are set up in the plate circuit. This high frequency current flowing round the coil L_1 provides a periodically varying magnetic field, which produces changes in the length of bar causing it to compress and stretch alternately. The coil L2 serves to detect the variations of magnetization due to alternating stresses in the bar by having induced emf set up in it.

This induced emf is fed on the grid which reacting on plate circuit produces large variation in it. Thus, increasing the magnetostriction effect in the bar. By the adjustment of the variable condenser these alternations in the length of bar can be made to induce varying currents in the grid coil in unison with plate circuit. Evidently, the combined result of these actions and reactions is to maintain resonant longitudinal vibrations of bar, the variations in the deflection of grid galvanometer giving definite indications of this resonance.

The frequency of vibration of the rod is given by

$$n = \frac{p}{2l}\sqrt{\frac{Y}{\rho}}$$

where l = length of the rod, Y = Young’s modulus of the rod material and

ρ =density of rod material.

Thus, the capacitor C_1 is adjusted so that the frequency of the oscillatory circuit is equal to natural frequency of the rod and thus resonance takes plate. Now the rod vibrates longitudinally with maximum amplitude and generates ultrasonic waves of high frequency from its ends.

Advantages

- The design of this oscillator is very simple and its production cost is low
- At low ultrasonic frequencies, the large power output can be produced without the risk of damage of the oscillatory circuit.

Disadvantages

- It has low upper frequency limit and cannot generate ultrasonic frequency above 3000 kHz (ie. 3MHz).
- The frequency of oscillations depends on temperature.
- There will be losses of energy due to hysteresis and eddy current.

Applications of Ultrasonic: -

1) **Depth of Sea: -** Ultrasonic waves of high frequency are used to determine the depth of sea. A piezoelectric oscillator is used to measure depth of sea. In this a special type of quartz crystal transmitter with which he generated ultrasonics of 50,000 cycles per second. The arrangement consists of thin slices of quartz crystal with two steel plates attached to its faces. One side of this arrangement is in contact with the sea, the other being shielded by a water tight box. The alternating emf from a high-tension spark oscillatory circuit is applied to those discs and tuned to resonant frequency of quartz oscillator. The ultrasonic beam is sent from such a transmitter and the instant of its generation is indicated by slight deflection of spot of light on oscillograph. These waves go normally downwards and come back after reflection from the sea bed. During short interval in which this takes place, the oscillator is connected to the receiving circuit and acts as a detector. The reflected beam causes vibrations and spot of light undergoes another slight deflection at a point further on the scale. The time interval between the two kinks is accurately recorded. The velocity of the wave is known; hence the depth of the sea can be estimated.

2) **Medical effects of Ultrasonics: -** The vibration of ultrasonic waves have been found to produce a soothing massage action on affected joints and have been widely recognized as a useful tool in the treatment of muscular pain. It is used to cure neuralgic and rheumatic complaints. The most revolutionary use of this sound is in the treatment of mental patients. This is also used successfully on psychotic and neurotic patients. The newly developed technique of three-dimensional photographs with the help of ultrasonic has been used by the physicians to locate the exact position of eye tumor and its removal gave normal vision to the patient. Micro-organisms and small animals like frog, fish etc. are killed, red blood corpuscles are destroyed. Medical ultrasound (also known as diagnostic sonography or ultrasonography) is a diagnostic imaging technique based on the application of ultrasound. It is used to see internal body structures such as tendons, muscles, joints, blood vessels, and internal organs. Its aim is often to find a source of a disease or to exclude any pathology.

3) **Chemical Effects: -**

Ultrasonic waves act like catalytic agents and accelerate chemical reactions. Some amorphous substances like paraffin may be transmitted into crystalline state. Ultrasonic waves have been employed in industry for washing clothes, specially silken fabrics, cleaning utensils, and for several other purposes such as for removing dust and soot from chimney gases, for dispersing fog at air ports and for removing water from paper during the manufacturing process. A glass rod oscillating with ultrasonic frequency can bore a hole in piece for steel or a glass plate.

When an intense beam of ultrasonics is passed through a liquid, it is heated to very high temperature. Iron and aluminium hydroxide are liquefied by them minute particles suspended in the liquid through which supersonic waves are passing tend to aggregate in lumps and settle down. They change colloidal solutions and immiscible liquids like water and oil into homogeneous stable emulsions. This property has found an application in manufacture of photographic films.

Section B Acoustics

The science of architectural acoustics deals with the planning of building or a hall so as to secure to most advantageous flow of properly diffused sound to the entire audience without affecting the speech intelligibility and tonal qualities of music.

1. **Reverberation:**

It is observed, for a listener in a room or Auditorium whenever sound is produced, he receives directly compressional sound waves from the source as well as waves from the walls, ceiling and other material from source. The waves received by the listener are i) direct waves and ii) reflected waves due to multiple reflection at various surfaces. Some of sound energy is reflected and some absorbed and thus the distribution of sound energy in the hall continuous to be affected. The reflected portions travel back into hall and reunite to form objectionable echoes and they produce indistinctness and interfere with good hearing. In other word, the sound from the source does not reach immediately after it is directly received but is lengthened out owing to the energy received by continuous reflections from surface portions of the walls etc. Thus the original on breaking up wanders about for some time in the air of the hall, and some of energy is still on its way from surface to walls and hence to ear and prolongation of sound .

This persistence of audible sound after the source has ceased to emit sound is called the **reverberation**.

Clearly if the reverberation of a syllable persists so long as to prolong the sound while several successive syllables are pronounced, intelligibility will suffer and acoustic condition will be bad.

The time during which sound persists in the hall is called the **reverberation time of sound**. It is measured from the time that the original sound is produced or in case of continuous note, from the time that the source stopped sounding to the time at which the sound becomes in audible. A certain amount of this reverberation is of course, desirable as it adds a pleasing characteristic to acoustical qualities of a room. Obtaining the right amount of reverberation is the secret of good acoustics.

If absorption is larger, the intensity falls off quickly and reverberation time will be small. On the other hand, if absorption is small, reflection will continue for a longer interval and reverberation time large. This effect is found to vary from room to room depending upon its dimensions as well as absorptive and reflective material used in its construction.

2. **Acoustical demands on an auditorium:** -

For obtaining good acoustical properties, the following conditions are necessary.

1. Each separate syllable should produce sufficient energy in every part of the hall i.e. sound should be sufficiently loud and intelligible at every point.
2. Sound of each syllable should soon decay so that succeeding syllable may be heard distinctly. This means that auditorium must be free from excessive reverberation.
3. There should not be present echoes more than necessary for maintaining continuity.
4. There should be no undesirable focusing of sound due to walls and ceiling nor there should be present zones of silence or regions of poor audibility anywhere in the hall.
5. There should not be any unpleasant reinforcement of any importance of complex sound, so that total quality may not be affected.
6. Extraneous noises and echelon effects including resonance within the building should be avoided.

3. **Sabine's Law:**

Period of reverberation i.e., time that the sound takes to fall in intensity by 60 decibels or to one millionth (10^{-6}) of its original intensity after source is stopped.

$$T = \frac{0.165V}{\sum as}$$

Where V is total volume of the hall and Σas is total absorbing power of the room.

This relation is known as Sabine's law.

Proof: Let a_1, a_2, a_3 ------- are absorption coefficient at each reflection of the surfaces s_1, s_2, s_3------ etc., in a room.

The average value of absorption coefficient is,

$$\bar{a} = \frac{a_1 s_1 + a_2 s_2 + a_3 s_3 + ---}{s_1 + s_2 + s_3 + ----}$$

$$= \frac{\sum as}{S}$$

$$\therefore \sum as = \bar{a}S \quad ----------(1)$$

Where S = $s_1+s_2+s_3+$------- total area of the surfaces.

By statistical method Jager showed that the sound travels an average distance between two successive reflection is $\frac{4V}{S}$.

Where V is volume of room and S total area of the surfaces.

Let C is velocity of sound.

The time between two successive reflection is

$$= \frac{4V}{SC}$$

Therefore, Average number of reflections in time *t* is,

$$= \frac{SCt}{4V} ------(2)$$

Let I be average intensity in the room at any given instant.

The fall in intensity δI by absorption in a small interval of time δt is

$$\delta I = \bar{a}\, n\, I\, \delta t$$

Where $\bar{a}$ be mean absorption coefficient and n be total No. of reflections per second.

Let E is rate of emission of sound energy from the source per second.

The rate of growth of energy per second per unit volume of the room is,

$$\frac{dI}{dt} = \frac{E}{V} - \frac{\bar{a}\, S\, C\, I}{4V}$$

When source is stopped, the rate of emission E of sound energy from the source disappears, so that E = 0. Hence,

$$\frac{dI}{dt} = -\frac{\bar{a}\, S\, C\, I}{4V} ------(3)$$

$$\frac{dI}{I} = -\frac{\bar{a}\, S\, C}{4V}\, dt$$

Integrating both sides

$$\int_{I_0}^{I} \frac{dI}{I} = \int_0^t -\frac{\bar{a}\, S\, C}{4V}\, dt$$

Where I_0 be steady maximum value of intensity and I be its value at time t.

$$[log\ I]_{I_0}^{I} = -\frac{\bar{a}\, S\, C}{4V}\, t$$

$$log\ I - log\ I_0 = -\frac{\bar{a}\, S\, C}{4V}\, t$$

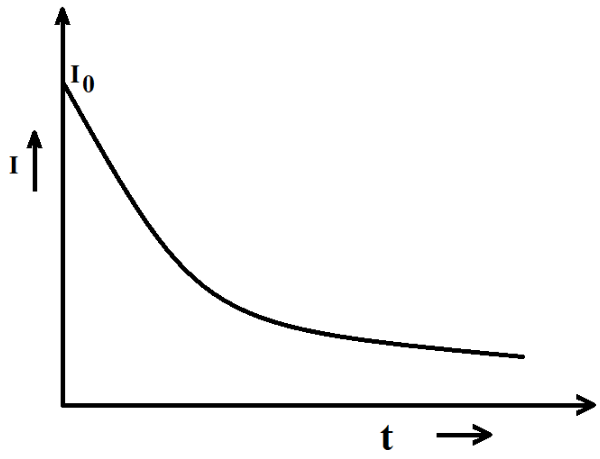
$$log\frac{I}{I_0} = -\frac{\bar{a}\, S\, C}{4V}\, t$$

$$\frac{I}{I_0} = \ e^{-\frac{\bar{a}\, S\, C}{4V} t}$$

$$\therefore I = I_0\, e^{-\frac{\bar{a}\, S\, C}{4V} t}$$

$$\therefore I = I_0\, e^{-\alpha t} - - - - (4)$$

Where $\alpha = \frac{\bar{a}\, S\, C}{4V}$



Eq[n](4) represents the decay of intensity with time after the source is cut off. The exponential curve as shown in Fig.

According to definition of reverberation period i.e. time for fall of intensity from initial value 10^6 times longer. i.e.

$$\frac{I}{I_0} = 10^{-6} = e^{-\alpha T}$$

$$\therefore e^{\alpha T} = 10^6$$

Taking logarithm on both sides

$$\log(e^{\alpha T}) = log_e{}^{10^6} = 6 log_e 10 = 6 \times 2.3026 = 13.8156$$

$$\alpha T = 13.8156$$

$$T = \frac{13.8156}{\alpha}$$

But $\alpha = \frac{\bar{a}\, S\, C}{4V}$

$$T = 13.8156 \times \frac{4V}{\bar{a}\, SC}$$

But C = 340 m/s velocity of sound.

$$T = 13.8156 \times \frac{4V}{\bar{a}\, S \times 340} = \frac{55.2624}{340} \times \frac{V}{\bar{a}S}$$

$$T = \frac{0.165V}{\bar{a}S} = \frac{0165V}{\sum aS} --------- (5)$$

Eq^n(5) is Sabine's reverberation formula. This shows that,

i) Rate of emission of energy by source is constant and is independent of intensity level in room.

ii) Directly proportional to volume of auditorium.

iii) Inversely proportional to surface area.

4. **conditions for good acoustical design of room**:

1). control of reverberation:

As reverberation is due to repeated reflections, the remedy lies in in increase absorption which may be brought about by having

a) a few open Windows, which by letting the entire sound energy out serve as perfect absorbers.

b) walls covered with absorbent materials such as Celotex, perforated cardboards, felt, absorbs, coarse cloth, maps and pictures, heavy curtains etc, or walls engraved and roughened with decorative materials so as to defuse the sound. Porous bodies by providing small capillaries absorb a good deal of sound energy incident on them and serve very well as sound suppressors.

c) Upholstered state which will be responsible for absorption and avoid approximately the presence and absence of the audience.

d) a good audience (one listener is equivalent to 4.7 sq. ft of an open window, women being rather better absorbers than men owing to the nature of their clothing).

2). Shape of the walls and ceilings: There should be no curved walls or corners bounded by two walls, firstly to avoid focusing and concentration of sound at one place and secondly to avoid dead spaces. Concave rear walls are responsible for troublesome echoes and delayed reflection in many cinema halls and auditoria. These unfavourable reflections can be converted into useful ones by introducing a ceiling spread between the ceiling and the rear wall.

3). Concave surfaces and balconies: Concave surfaces such as domes, curved arches and barrelled ceiling should be avoided unless given careful acoustical design in order to eliminate focusing effects, non-distribution of sound echoes. Balconies as a rule should have a Shallow depth and high opening, the depth should not exceed twice the height of the opening. Under these conditions sound flows readily into the space under the balcony.

4) Floor plan with diverging side walls: In this case reflections from the ceiling and these walls can be utilised for the establishment of a higher sound level at the rear of the hall. The geometrical law of reflection can be used to determine the proper angle for the ceiling and the side wall reflecting surfaces so that they will guide sound to those seats where the sound level is not adequate.

5) Seats: General plan of the hall with seats should be somewhat like that shown in figure,

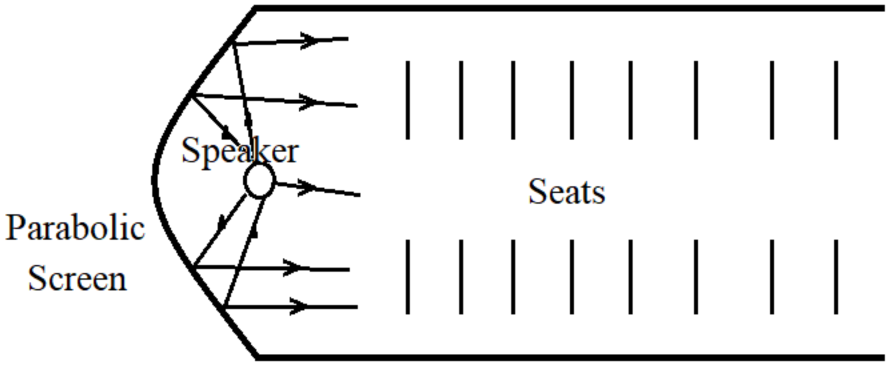


Fig. Seating plan in a hall

in order to secure good distribution of sound. Here the speaker is at the focus of the paraboloid reflecting surface and a plane beam of sound is sent down the hall. Moreover, from the standing point of hearing as well as seeing the seats are gradually elevated in order to promote a free flow of a direct sound from the source to the listeners. The desirable period of reverberation in seconds for halls with full audience is given by empirical formula t 0.75+0.0175$0.75 + 0.0175\sqrt[3]{V}$ where V is the volume of the hall in cubic ft.

It has been estimated that T for halls of about 10,000 cubic feet capacity is 1.03 seconds for speech so that each syllable is heard as distinctly possible. For purposes of music, this optimum reverberation period may be slightly increased