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.

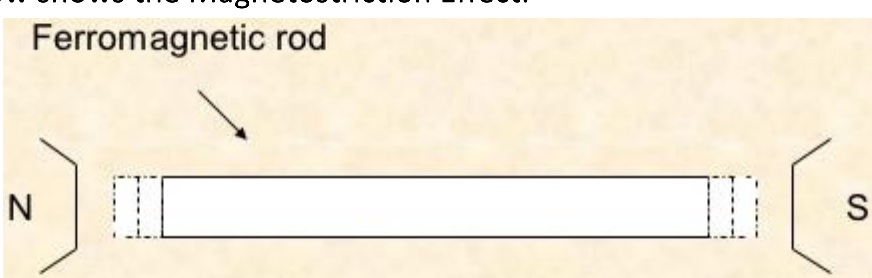
  The electrical generators are subdivided into two categories.

  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 ct. 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:

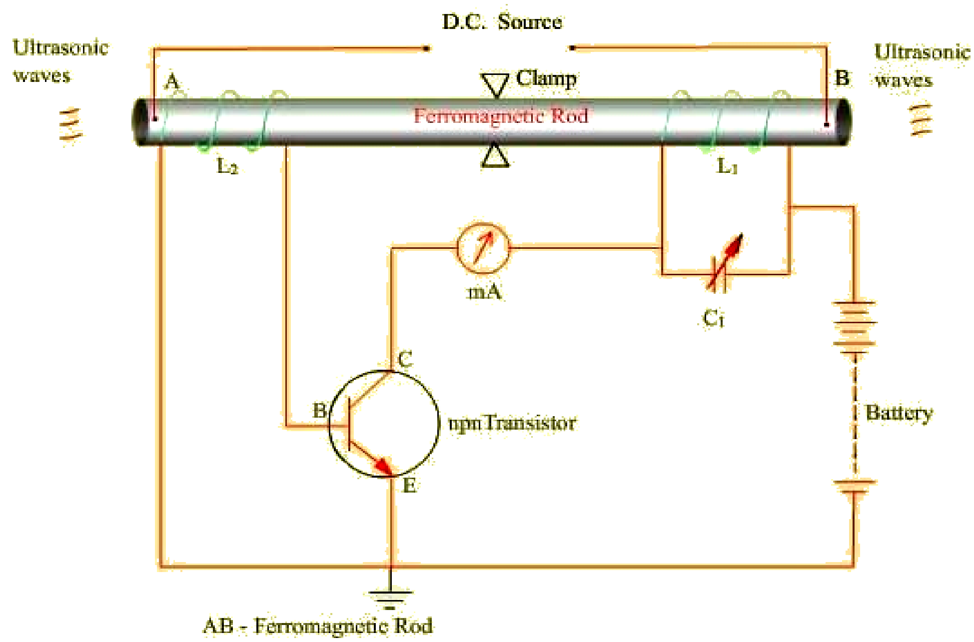


Fig. Circuit diagram for Magnetostriction oscillator method

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,

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

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:

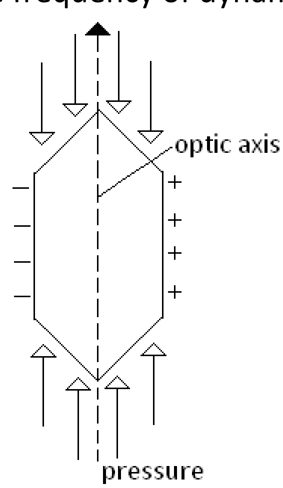
1. The design of this oscillator is very simple and production cost is low.
2. At low ultrasonic frequencies, large power output is possible without the risk of damage to the oscillatory circuit.
3. Frequency ranging from 100 Hz to 3,000 KHz can be produced.

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.

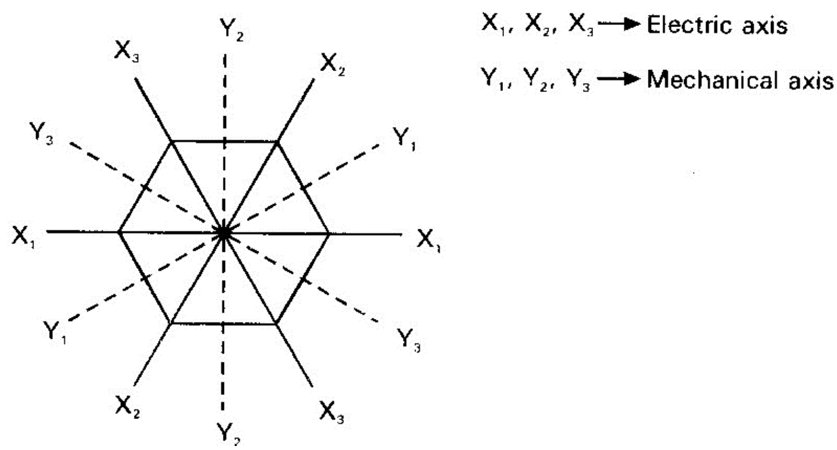


Fig. Piezoelectric crystal axis

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.

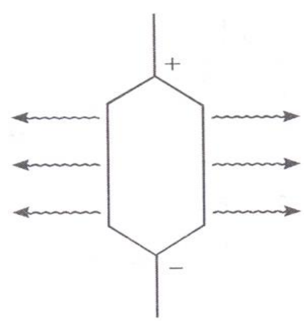


Fig. Inverse Piezoelectric effect

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.

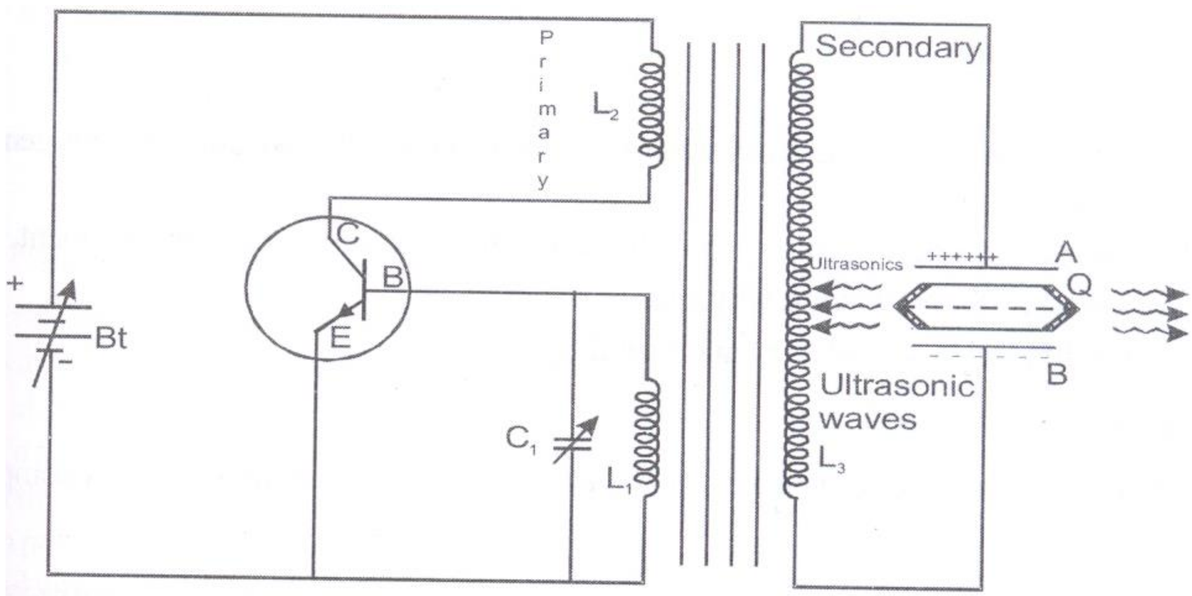


Fig. Piezoelectric oscillator method.

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

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

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

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

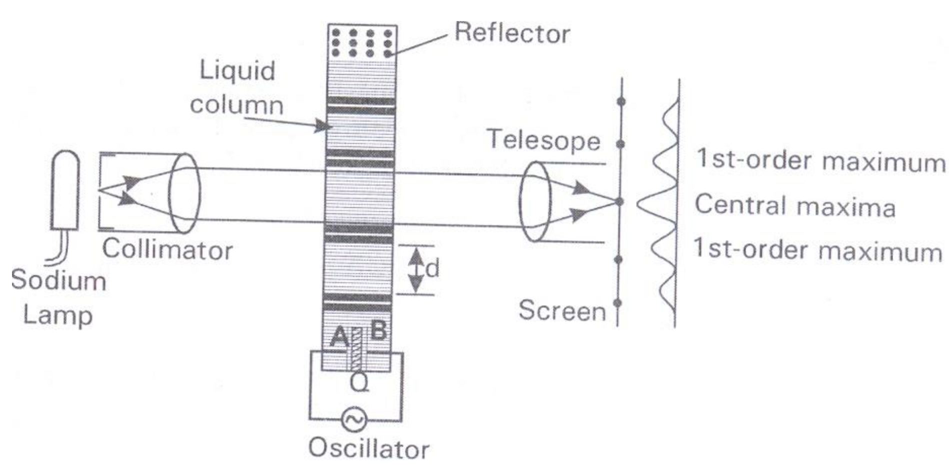


Fig. Experimental arrangement to determine the velocity of ultrasonic waves.

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?

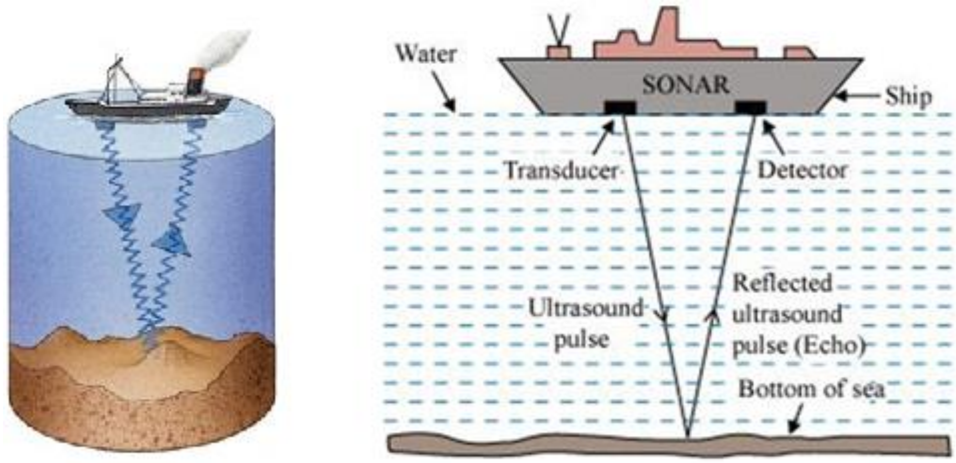


Fig. Determination of depth of sea.

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 5.5×10^3 ms^{-1}. Thickness of quartz crystal is 0.05 m.

   Given, v=5.5×10^3 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

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

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

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.