ENGINEERING PHYSICS

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CHAPTER 1

Ultrasonics

Topics Covered

Production of ultrasonic waves; Magnetostriction effect; Magnetostriction generator; Piezoelectric effect; Piezoelectric generator; Detection of ultrasonic waves; Properties of ultrasonic waves; Cavitation; Acoustic grating; Industrial applications; SONAR; Non-destructive testing; Medical applications

Learning Objectives

After studying this chapter, a student should be able to understand

- different methods of production of ultrasonic waves
- different techniques for detection of ultrasonic waves
- the properties of ultrasonic waves
- the phenomenon of cavitation
- the concept of acoustic grating
- important industrial applications of ultrasonic waves
- the principle of operation of SONAR
- different techniques of non-destructive testing
- important medical applications of ultrasonic waves

1.1 Introduction

The human ear is capable of hearing frequencies in the range of 20 Hz to 20 kHz. This frequency range is called *audible range*. The sound waves having frequencies beyond 20 kHz are termed as *ultrasonic waves*. Ultrasonic waves are used in sound navigation and ranging (SONAR) applications to locate submerged objects like icebergs and submarines. Targets and obstructions can be located and route guidance obtained with a great degree of precision. Ultrasonic waves possess higher energy; therefore, they have a higher penetrating power. This characteristic is used in the medical field to study the functioning of internal organs of the human body by ultrasonic imaging. This chapter discusses some important aspects of the subject of ultrasonic waves. To begin with, different methods of production of ultrasonic waves are discussed. Relative merits and demerits of these technique are discussed next. The chapter then elaborates on important properties of ultrasonic waves. Finally, various industrial and medical applications of ultrasonic waves are discussed.

1.2 Production of Ultrasonic Waves

You may recall that sound waves in the audible range are produced by the vibrating diaphragm of a loudspeaker that has been fed a suitable alternating voltage. The inductance of the loudspeaker coil offers inductive reactance to any alternating current flowing through it. As the frequency of the impressed signal increases, so does the reactance offered through the inductance of this coil. Thus, the current flowing through the coil reduces with increasing frequency. In addition to this, with increasing frequency the diaphragm of a loudspeaker also loses its ability to vibrate efficiently. Both these effects prevent the loudspeaker from functioning as a useful source of ultrasonic waves. Two important methods for producing ultrasonic waves are: (i) magnetostriction method and (ii) piezoelectric method. The magnetostriction method is generally used for production of ultrasonics up to around 100 kHz, whereas generators based on piezoelectricity are generally used for producing higher frequencies. These methods are discussed in the following sections.

1.2.1 Magnetostriction Effect

When a ferromagnetic material such as iron, nickel or cobalt is placed in an alternating magnetic field, the ferromagnetic material undergoes a change in dimension. This phenomenon is known as the *magnetostriction effect*. The extent of change is independent of the sign of the magnetic field but is dependent on its magnitude and on the nature of the material. Figure 1.1 shows a schematic representation of the magnetostriction effect. A permanent

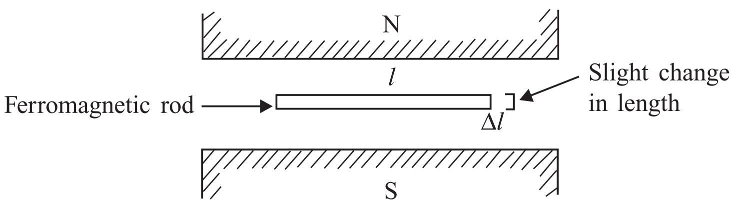

Fig. 1.1 Magnetostriction effect

magnet is used to create the magnetic field that brings about a change in length.

Suppose a ferromagnetic rod is placed inside a coil carrying an alternating current. This alternating current would give rise to a time-varying field and the rod will be put into vibration. The amplitude of this vibration is generally small. If the frequency of the alternating signal can be the same as the natural frequency of the rod, a resonance will occur. This resonance will reinforce the vibrations that would result in the rod. The ends of the rod would then emit sound waves. By ensuring a sufficiently high applied frequency, ultrasonic waves can be generated.

1.2.2 Magnetostriction Generator

Figure 1.2 is a schematic circuit diagram of a set-up for producing ultrasonic waves. A short nickel rod is clamped at the centre. The rod is magnetized by passing a direct current through it. Two other coils L_1 and L_2 are wrapped around the rod as shown in Fig. 1.2.

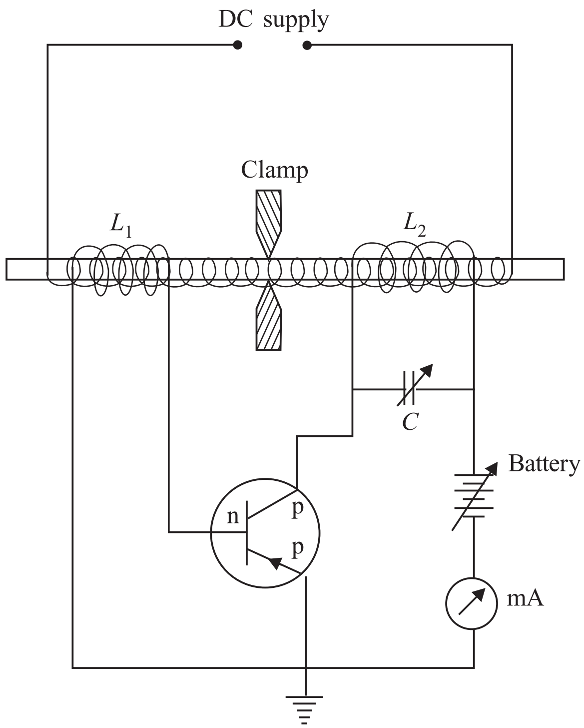

Fig. 1.2 Circuit diagram of magnetostriction method

Coil L_2 is a part of the collector circuit of the transistor circuit. Suitable biasing is provided to the transistor which is not reflected in Fig. 1.2. Coil L_1 forms a part of the base circuit. The frequency f of the alternating current set up by the resonant circuit L_2C is given by

$$f = \frac{1}{2\pi\sqrt{L_2C}}$$

The natural frequency ν of a vibrating rod is given by

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

where l represents the length of the rod, E the Young's modulus, and ρ is the density of the rod material.

1.2.3 Piezoelectric Effect

When mechanical pressure is applied along the mechanical axis of piezoelectric crystals such as quartz, tourmaline, Rochelle salt, etc., equal amount of opposite electric charges are developed along the perpendicular direction, i.e., along the electrical axis. This phenomenon is known as *piezoelectric effect*.

1.2.3.1 Inverse Piezoelectric Effect

When an emf is applied along the electrical axis of a piezoelectric crystal, the dimension of the crystal changes along the perpendicular direction, i.e., along the mechanical axis. This phenomenon is known as *inverse piezoelectric effect*.

1.2.3.2 Principle

Inverse piezoelectric effect is the principle behind the production of ultrasonics using piezoelectric crystals. In this method, ultrasound with high amplitude is produced when the natural frequency of the crystal equals the frequency of the oscillatory circuit.

1.2.3.3 Construction

Piezoelectric oscillator circuit consists of a primary and a secondary circuit. In the primary circuit L_1 and L_2 are two inductances connected with a *p-n-p* transistor through a variable source, as shown in Fig. 1.3. C_1 is a variable condenser connected parallel to L_1. This combination of L_1 and C_1 is known as *tank circuit*. L_1 and L_2 are connected inductively with the secondary

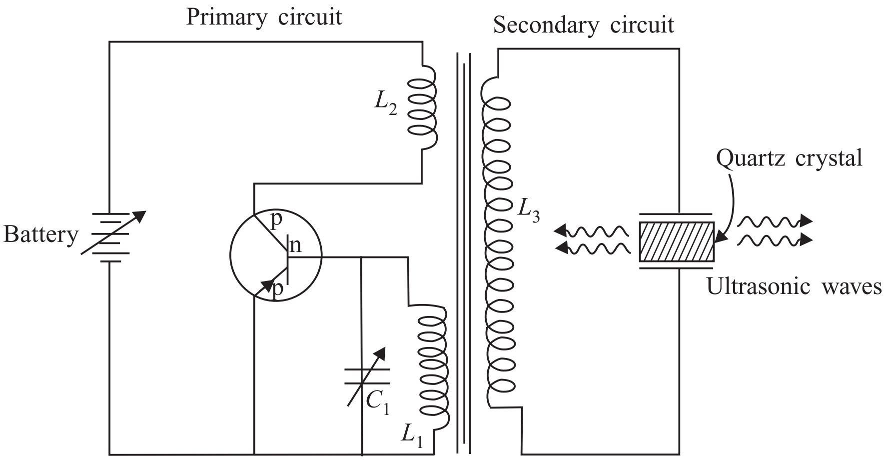

Fig. 1.3 Piezoelectric oscillator circuit

circuit. The secondary circuit consists of an inductance L_3 and a parallel-plate condenser. The quartz crystal is kept between the plates of the parallel-plate condenser.

1.2.3.4 Working

When the source is switched ON, magnetic flux lines are produced by coils L_1 and L_2; these magnetic flux lines induce current in the opposite direction in L_3. This electrical potential acts on the piezoelectric crystal placed inside the parallel-plate capacitor. When the frequency of the oscillator circuit is equal to the natural frequency of the piezoelectric crystal, the crystal vibrates with maximum amplitude, producing ultrasonic waves.

The resonant frequency of the circuit is

$$\nu = \frac{1}{2\pi\sqrt{L_1 C_1}} \tag{1.1}$$

The natural frequency of the crystal is

$$\nu = \frac{p}{2l}\sqrt{\frac{E}{\rho}} \tag{1.2}$$

where $p = 1, 2, 3\ldots$ for fundamental, first overtone, second overtone, etc.

l = length of the crystal

E = Young's modulus of the crystal

ρ = density of the crystal.

Thus, the frequency of the ultrasound produced is given by

$$\nu = \frac{p}{2l}\sqrt{\frac{E}{\rho}} \tag{1.3}$$

1.2.3.5 Advantages

- This method can produce ultrasonic waves with frequencies up to 500 MHz.
- A piezoelectric crystal is not affected by temperature and moisture. Therefore, the ultrasound produced is of constant frequency.
- The method can also be used to detect ultrasonic waves.

1.2.3.6 Disadvantages

- The piezoelectric crystal needs to be cut in a direction perpendicular to the *Y*-axis. This process is complicated.
- The cost of the crystal is high.

1.3 Detection of Ultrasonic Waves

As already mentioned, the human ear does not respond to ultrasonic waves, unlike that of some animals (e.g., bat). We, therefore, need special methods to detect ultrasonic waves. These methods are discussed in detail in this section.

1.3.1 Piezoelectric Detector

Piezoelectric crystals have the ability to develop an electric potential when a stress is applied across certain faces of the crystal. This phenomenon can be used to detect ultrasonic waves. One pair of faces of a quartz crystal (piezoelectric material) is subjected to ultrasonic waves as shown in Fig. 1.4.

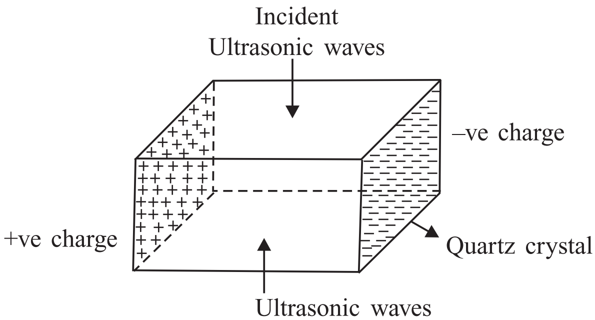

Fig. 1.4 Schematic representation of piezoelectric detector

An alternating potential then develops across the perpendicular faces. This potential can be amplified and measured to detect the presence of ultrasonic waves.

1.3.2 Kundt's Tube Method

Kundt devised an experimental technique in 1889 to study the transmission of sound in different materials. This technique is based on Kundt's tube shown schematically in Fig. 1.5.

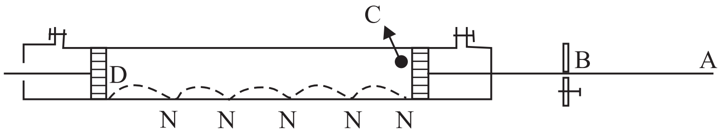

Fig. 1.5 Kundt's tube set-up for detection of ultrasonic waves

Kundt's tube consists of a horizontal glass tube about 1 m long and 5 cm in diameter. One end of the tube has an adjustable piston D, and the other end has a loosely fitted cardboard cap C that is firmly fixed to a metal rod CA. The metal rod is clamped in the middle at B on a horizontal table to ensure minimum disturbance during the use of Kundt's tube. A small amount of lycopodium powder is scattered in the portion CD of the tube. When ultrasonic waves are incident on the tube and pass through it, the lycopodium powder collects in the form of heaps at the nodal points and is blown off at the antinodal points. The distance between subsequent nodes is then equal to half the magnitude of the wavelength of ultrasonic waves. This information can then be used to determine the frequency of the waves.

1.3.3 Sensitive Flame Method

The formation of nodes and antinodes in the presence of ultrasonic waves can be exploited in another interesting way to detect and determine the frequency of the waves. If a narrow sensitive flame is moved through the medium that carries the ultrasonic waves, the flame remains stationary at antinodes and tends to flicker at nodes. The frequency of the ultrasonic wave can be found by equating the distance between subsequent nodes or antinodes to half the wavelength.

1.3.4 Thermal Detector Method

Whenever an ultrasonic wave propagates through a medium, it causes alternate compressions and rarefactions in the medium. Due to these compressions and rarefactions the temperature of the medium changes at the nodes while remaining almost constant at antinodes. A thermal detector comprises of a fine platinum wire whose resistance changes at the nodes due to these temperature variations. The complete thermal detector uses the fine platinum wire as one of the arms of a sensitive bridge arrangement. Using this bridge arrangement, changes in the resistance of the platinum wire at the nodes can be measured as a function of time. These measurements can then be used to determine the frequency of ultrasonic waves. As the detector element is moved through the medium, the bridge remains balanced at antinodes but gets off-balance at nodes.

1.4 Properties of Ultrasonic Waves

Ultrasonic waves have many characteristic properties. Some of the properties of ultrasonic waves are listed in this section.

(i) Ultrasonic waves have extremely high energy content. This is because of their high frequency. The high energy of these waves can be used in applications like drilling and cutting.

(ii) Ultrasonic waves display all characteristics of sound waves like reflection, refraction, and absorption. The properties can in turn be used to design systems based on these waves. Like sound waves, reflection is possible if the obstructing surface has dimensions much larger than the wavelength.

(iii) Ultrasonic waves can be transmitted over long distances with extremely low loss of energy. This is possible because of their small wavelengths, which result in negligible diffraction effects.

(iv) Ultrasonic waves can produce intense heating as they pass through materials. This is due to absorption of the energy content of the ultrasonic waves in the medium.

(v) The speed of propagation of ultrasonic waves is frequency-dependent, increasing with increase in frequency. This dependence is used in developing basic ultrasonic wave detection systems.

(vi) Ultrasonic waves passing through liquids lead to the formation of bubbles.

1.5 Cavitation

Microscopic bubbles with diameters in the range of 10^{-9} to 10^{-8} m are generally present in a liquid. A reduction of pressure in regions around these bubbles leads to evaporation and thus results in the growth of the bubbles. This growth, however, is not unlimited. Ultimately, it leads to the collapse of the bubbles. All this happens within a very short span of time, just a few milliseconds. The process of collapse of the bubbles results in the generation of shock waves and the temperature increases manifold in the region of the collapse. Ultrasonic waves passing through a liquid induce alternate regions of rarefaction and compression. Rarefaction regions are local negative pressure regions and result in the process of bubble growth and collapse. This phenomenon is called *cavitation*. The collapse of bubbles can result in local pressures reaching thousands of atmospheres and local temperatures increasing by as much as 10,000°C.

The phenomenon of cavitation can be used for the following applications:

(i) ultrasonic cleaning
(ii) exploration of minerals and oil deposits
(iii) speeding up chemical reactions
(iv) emulsification
(v) formation of stoichiometric alloys and compounds.

1.6 Acoustic Grating

When ultrasonic waves are made to propagate through a liquid, its density varies from layer to layer due to the periodic variation of pressure in the liquid. If monochromatic light is made to pass through the liquid at right angles to the direction of propagation of ultrasonic waves, the liquid then behaves like a diffraction grating. Since the grating action has been created with the help of acoustic waves, the grating is also referred to as *acoustic grating*. This set-up can be used to determine the wavelength and the velocity of ultrasonic waves.

1.6.1 Velocity Measurement

Figure 1.6 shows a schematic diagram of the experimental set-up of an acoustic grating.

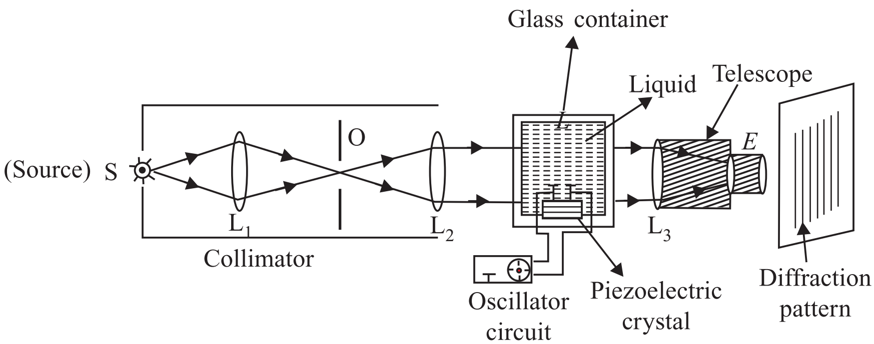

Fig. 1.6 Schematic diagram of acoustic grating

Light originating from a monochromatic source S is focussed on a narrow slit O using a focusing lens L_1. The second lens L_2 is used to produce a parallel beam of light. This parallel beam of light is then made to pass through an ultrasonic cell that consists of a tank containing the test liquid. A piezoelectric crystal forming a part of the oscillator circuit is dipped inside the liquid. Ultrasonic waves generated by the crystal travel through the liquid and get reflected from the walls of the container of the ultrasonic cell. The position of the crystal is adjusted to ensure that the resultant stationary waves are formed in a direction that is perpendicular to the direction of propagation of the ultrasonic waves. The light emerging out of the ultrasonic cell is focused onto a telescope with the help of the lens L_3.

Initially, no power is fed to the piezoelectric crystal and thus no ultrasonic waves are generated. A single image of the slit is then observed through the telescope. As the piezoelectric crystal starts generating ultrasonic waves, a complete diffraction pattern is observed to form. The angular separation θ between the direct image of the slit and the maxima of the diffraction fringe of any order n is then determined. If λ_A represents the wavelength of the generated ultrasonic waves and λ the wavelength of the incident monochromatic light, then applying the theory of diffraction grating, we can write

$$\lambda_A \sin\theta_n = n\lambda \tag{1.4}$$

The grating element for the acoustic grating is clearly the wavelength of the generated ultrasonic waves.

Equation (1.4) can be rewritten in the form

$$\lambda_A = \frac{n\lambda}{\sin\theta_n} \tag{1.5}$$

Expression (1.5) can be used to calculate λ_A. If ν represents the frequency of the generated ultrasonic waves, then the velocity V_L of ultrasonic waves in the liquid medium is given by,

$$V_L = \nu\lambda_A \tag{1.6}$$

1.7 Industrial Applications

Ultrasonic waves can be used in a variety of industrial applications. We will be discussing some important industrial applications in this section.

1.7.1 Drilling

Ultrasonics can be used to drill holes in hard materials like glass and diamond. A schematic diagram of an ultrasonic drilling system is shown in Fig. 1.7.

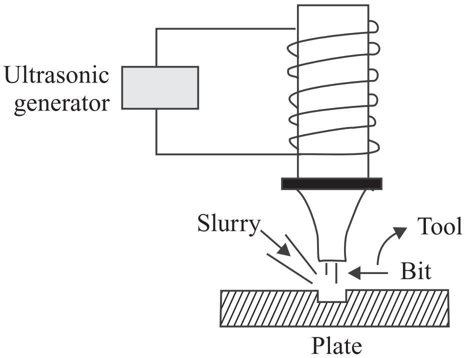

Fig. 1.7 Ultrasonic drilling system

The system consists of a tool bit connected to an ultrasonic generator. The tool bit carries out a vertical up–down motion due to the generated ultrasonic waves. Slurry (thin paste of corborundum powder and water) flows in the region between the plate of the material to be drilled and the tool bit. As the tool bit undergoes the vertical motion, the slurry removes material from the plate. Holes with a very good control of dimensions can be obtained using this technique.

1.7.2 Welding

Welding is the process of joining metals. Ultrasonics can be used to carry out welding. Figure 1.8 is a schematic representation of an ultrasonic welding system.

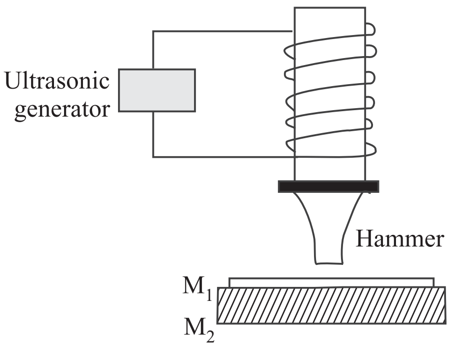

Fig. 1.8 Ultrasonic welding system

The set-up consists of a hammer connected to an ultrasonic generator. M_1 and M_2 represent two metal sheets that are to be welded together. The ultrasonic generator makes the hammer vibrate vertically at ultrasonic frequencies, generating pressure on the metal surfaces and causing the molecules of the metals to diffuse into each other. This results in welding of the two metal parts without the need for heating the plates to high temperatures. This process of welding is, therefore, also called *cold welding*.

1.7.3 Soldering

Aluminium has diverse industrial applications. However, using the conventional soldering technique, aluminium cannot be soldered without the use of fluxes. Ultrasonic soldering is extremely effective under such conditions. Figure 1.9 shows an ultrasonic soldering system.

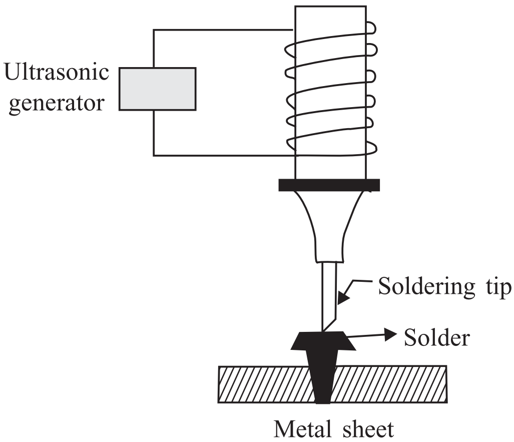

Fig. 1.9 Ultrasonic soldering system

The set-up consists of an ultrasonic soldering iron with a soldering tip at the end. Provision exists for heating the soldering tip. The heated tip melts the solder placed on aluminium and the ultrasonic vibrations of the tip remove the aluminium oxide layer. This results in excellent adhesion of the solder to the aluminium.

1.7.4 Ultrasonic Cleaning

Ultrasonic waves possess high energy and this energy can be used to clean ultensils, clothes, machine parts, etc. Ultrasonic cleaning is an important step in the processing of semiconductor wafers to realize integrated circuits and devices.

A schematic diagram of a typical ultrasonic cleaning system is shown in Fig. 1.10. The set-up consists of a transducer that converts electrical energy to mechanical energy. The ultrasonic waves so generated are coupled to the

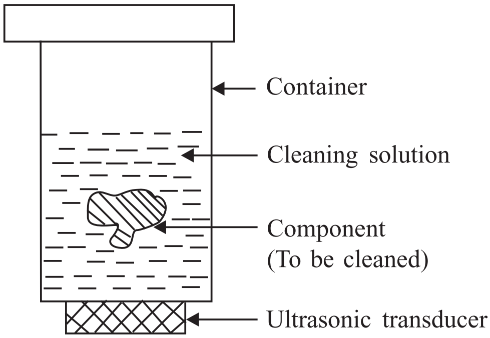

Fig. 1.10 Ultrasonic cleaning system

container vessel. This vessel contains the component requiring cleaning, in a suitable cleaning solution. The high energy of the ultrasonic waves acts on the contaminants to loosen them and thus clean the component.

1.8 SONAR

SONAR is an acronym for SOund NAvigation and Ranging. In this system, sharp beams of ultrasonic frequency are sent out in various directions in the sea. Objects like submarine, icebergs, shipwrecks, etc., result in reflections that are picked up, amplified, and displayed on suitable screens. The time lag between the incident pulse and the reflected pulse is used to estimate the location of the object that resulted in reflection. If the object producing reflection is moving, the reflected signal also incorporates a change in frequency due to the *Doppler effect*. The change in frequency is then used to determine the direction and magnitude of the velocity of the object.

1.9 Non-destructive Testing

Testing techniques that do not cause any harm or damage to the component being tested are referred to as non-destructive testing (NDT) techniques. These techniques are extremely popular in industrial and scientific applications. In this section we discuss some ultrasonics-based NDT techniques.

1.9.1 Pulse Echo Technique (Reflection Mode)

Flaws in materials can result in major changes in their characteristics like yield strength, conductivity, shine, etc. Flaws can be detected in materials using ultrasonic waves. When pulses of ultrasonic frequencies travel through a material, they encounter a change in medium at the location of flaws. This change in medium results in reflection. Reflection also takes place at extremities or back surfaces of the specimen. The presence of any reflection other than that from the back surface then is indicative of flaws in the material.

Figure 1.11 is a schematic diagram of an ultrasonic pulse-based flaw detection system.

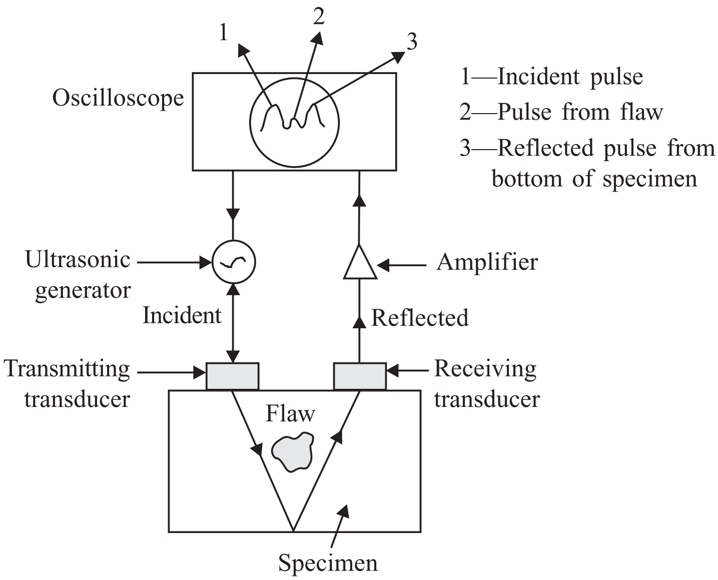

Fig. 1.11 Ultrasonic flaw detection system

An ultrasonic generator produces ultrasonic pulses that get transmitted through the test specimen using a suitable transducer. A portion of the incident ultrasonic energy is fed to an oscilloscope and produces peak 1 as shown in Fig. 1.11. A receiving transducer picks up the pulses reflected from the back surface and from any flaw existing within the material. Since the reflected signals are extremely low in strength, a suitable amplifier is used to amplify them. Peaks 2 and 3 represent the signals reflected from a flaw and from the back surface, respectively. The flaw detection system should also have a suitable arrangement to scan the entire specimen for possible flaws.

1.9.2 Transmission Technique

In this technique ultrasonic pulses are made to travel through the specimen and received as they come out. A schematic diagram of the system is shown in Fig. 1.12.

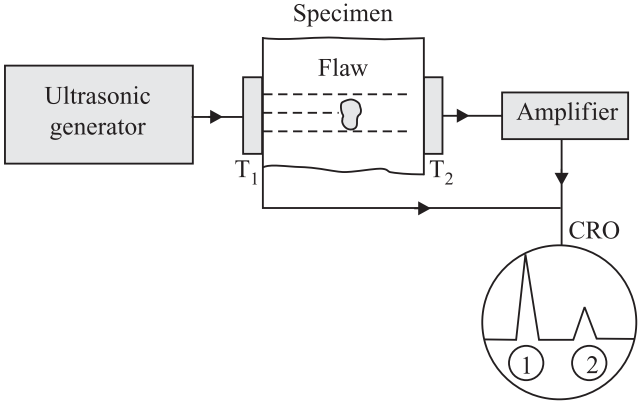

Fig. 1.12 Schematic diagram of the transmission technique

The system consists of two transducers T_1 and T_2. T_1 converts the high-frequency waves into ultrasonic pulses for transmission through the sample. A part of the input electrical signal is fed to a CRO. This is indicated by pulse 1 in Fig. 1.13. The signal received after transmission is converted into an electrical signal by transducer T_2 and fed to the CRO. This transmitted signal appears as pulse 2 in Fig. 1.13. In the presence of flaws, the transmitted signal is of lower amplitude than the direct signal, because of absorption of ultrasonic energy by the flaws. The exact size and location of a flaw is, however, difficult to predict using this technique.

1.9.3 Resonance Technique

In this technique, the thickness of the specimen is an integral multiple of half the wavelength of the ultrasonic pulse. This is achieved by varying the frequency of the ultrasonic waves till standing waves are formed within the sample. The resonance frequency is found to change at the location of flaws in the specimen. This change is used to detect flaws within the specimen.

1.10 Medical Applications

Some important medical applications of ultrasonic waves are discussed in this section.

1.10.1 Echocardiogram/Sonogram

An echocardiogram records the movement of the valves and other structures of the heart as a function of time. A block diagram of the basic echocardiograph unit is shown in Fig. 1.13.

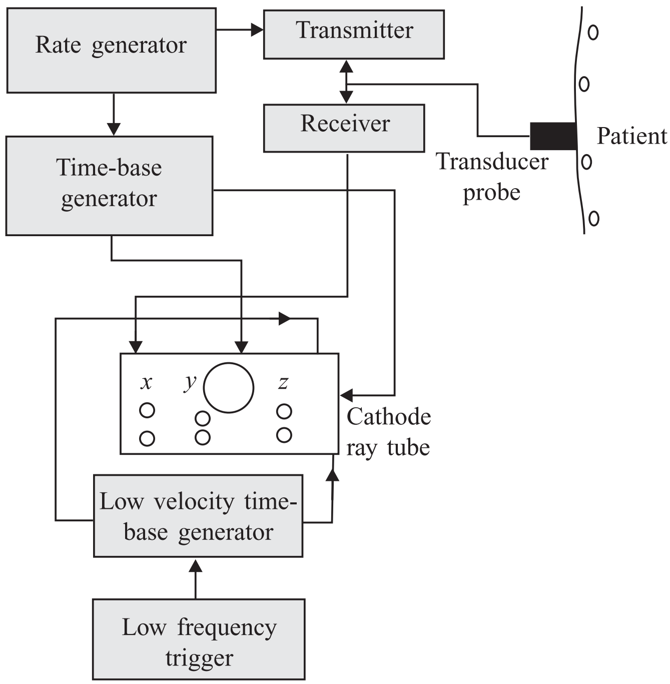

Fig. 1.13 Block diagram of an echocardiograph unit

A rate generator produces high-frequency pulses that are fed to a transmitter. The transmitter output is applied to the transducer probe as shown in Fig. 1.14. The probe sends ultrasonic waves towards the heart.

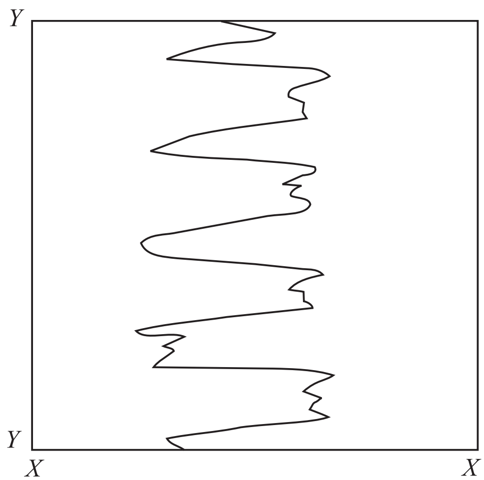

Fig. 1.14 Typical zigzag movement of the CRT spot

The reflected echo received by the probe forms the *Z*-axis input for the CRT. Pulsed output from the rate generator is also fed to the time-base generator whose output is given to the *X*-plates of the CRT. The signal applied between the *X*-plates is used to deflect the electron beam of the CRT. The vertical deflecting plates (*Y*-plates) are fed the output of a low-frequency time-base generator. This input makes a bright spot on the screen of the CRT that executes vertical motion at a slow speed.

An expansion or contraction of the heart leads to the horizontal movement of the bright spot coupled with the vertical movement of the spot. This results in a zigzag path of the spot on the CRT. A typical zigzag path of the spot is shown in Fig. 1.14.

1.10.2 Ultrasonic Imaging (Scan Displays)

Whenever an ultrasonic wave passes from one medium into another, reflection and refraction take place. The extent of reflection depends on the change in wave speed. A higher change in wave speed increases the amount of wave energy that is reflected back. An ultrasound imaging device fires a pulse of ultrasound into the body. The waves get reflected back as they meet a bone or an organ. The intensity of the reflection and the time delay from the instant when the pulse was emitted are characteristic of the nature of the reflecting medium. A picture of the bone or organ is then built up from the information about the intensity and time delay. The velocity of sound in air is much less than that in human skin. Thus, air and skin are said to be acoustically mismatched. When the ultrasound transducer that forms a part of any ultrasound imaging system is placed against the skin, a high proportion of the sound energy is immediately reflected back if there is any air gap. To eliminate the air gap, a gel is smeared on the skin and the transducer is placed on the gel. The velocity of sound in the gel is midway between that of air and skin. This helps in reducing reflection from the skin surface. In an A-scan, the information regarding the strength of the reflected signal and the time at which the sound pulse was sent are used to display a graph of distance into the body (as calculated from the time delay) against the strength of reflection. In a B-scan a sequence of dots is placed on the screen along a line, the distance between them being proportional to the distance into the body. The strength of reflection decides the relative brightness of the dots. As the transducer is moved about, many such lines are obtained which are then assembled into an image that represents a section through the body.

Figure 1.15 shows schematic representation of A-scan and B-scan displays.

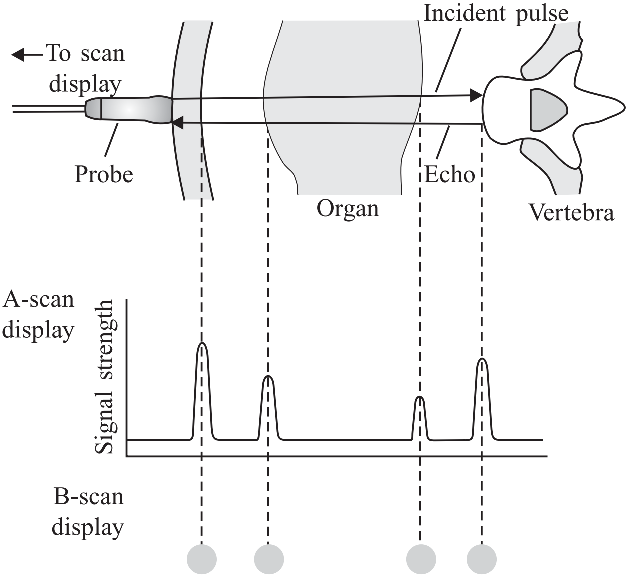

Fig. 1.15 Schematic representation of A-scan and B-scan displays

Figure 1.16 shows an image formed from a sequence of B-scan lines.

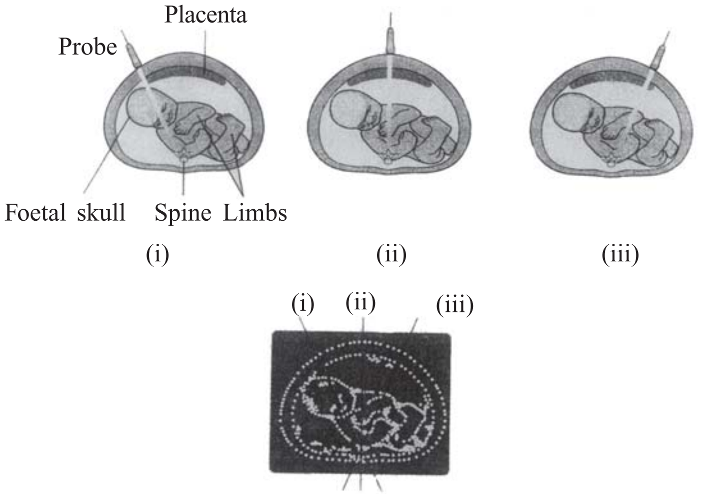

Fig. 1.16 Formation of image using a sequence of B-scan lines

1.10.2.1 C-Scan Display

In the C-scan display, the energy or frequency of ultrasonics from the probe is so adjusted that the ultrasonic pulse can reach a particular depth from the surface of the specimen and the cross-section of the specimen at that depth is scanned. The depth information of the scan is not recorded. For this purpose the ultrasonic probe, which is connected to an *x–y* plotter, is moved over the surface of the specimen either in a zigzag manner or in parallel-lines manner. The intensity of the echo received from the section of the specimen is recorded either as 'variation in line shading' or as 'a shading with blank spaces corresponding to defect regions'. We can get both the position and the cross-sectional area of the defect across the section studied. The depth of the defect is, in general, not recorded in this method. However, with a number of 2D observations made as explained, it could be possible to get a 3D image of the defect. Normally, C-scan procedure is adopted in automatic testing.

Advantages

- The testing method is automatic.
- Position and cross-sectional area of the defect are recorded.

Disadvantages

- Cost of the technique is very high.
- Depth information is not obtained.

Compared to conventional B-mode ultrasound, C-mode has the following advantages:

- Much easier for non-specialists to interpret.
- Cost is lower in comparison to B-mode.
- C-scan is free from speckle, an unwanted artefact seen on B-scan.
- C-scan is free from geometric distortion seen on B-scan.
- C-scan has far greater spatial resolution.
- It takes multiple round trips to generate one B-scan image. Sending more and more pulses improves image quality, but it sacrifices the refresh rate. C-scan requires only one round trip to generate a full field image. There is no technical need to image at less than 30 fps.
- C-scan images appear more naturally illuminated than B-scan images.
- C-scan, therefore, does not include the shadows that normally streak across B-scans.
- Structures in C-scan appear to reflect ultrasound the way they would reflect light.

Figure 1.17 shows the difference between a B-scan and a C-scan.

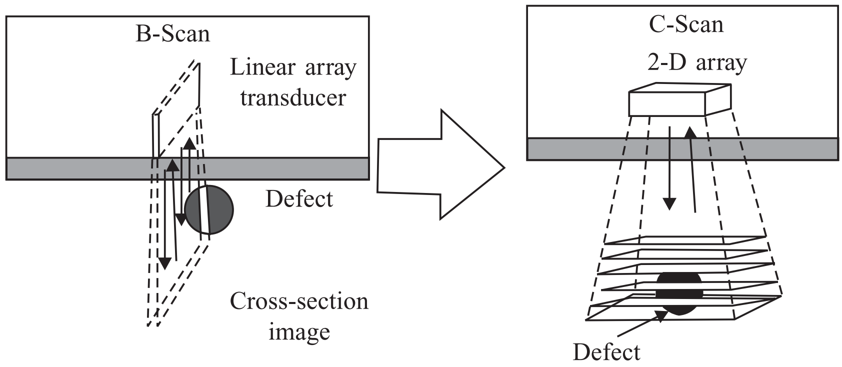

Fig. 1.17 Difference between a B-scan and a C-scan

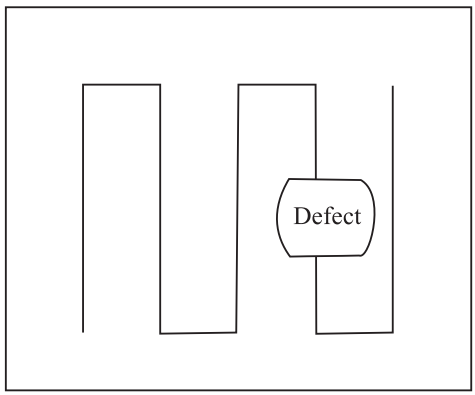

Fig. 1.18 Top view of scans or plane view

Solved Problems

1.1 Given that the velocity of ultrasonic waves in sea water is equal to 1440 m/s. Find the depth of a submerged submarine if an ultrasonic pulse reflected from the submarine is received 0.33 s after being sent out.

Solution:

Distance d travelled by the ultrasonic waves is given by

$$d = v \times t \tag{1.1.1}$$

where v is the velocity of the ultrasonic waves and t is the time lapsed. Substituting the given values in Eqn (1.1.1) leads to

$$d = 1440 \times 0.33 = 475.2 \text{ m} \tag{1.1.2}$$

Now, the total distance travelled by the ultrasonic waves is twice the depth of the submarine. Hence, the depth d_1 of the submarine is

$$d_1 = \frac{d}{2} = \frac{475.2}{2} = 237.6 \text{ m}$$

1.2 Calculate the natural frequency of a pure iron rod of 40 mm length. The density of pure iron is 7.25×10^3 kg/m^3 and its Young's modulus is 115×10^9 N/m^2. Can you use it in magnetostriction oscillator to produce ultrasonic waves?

Solution:

Natural frequency ν of the rod is given by

$$\nu = \frac{1}{2l}\sqrt{\frac{E}{\rho}} \tag{1.2.1}$$

where l represents the length of the rod, E represents Young's modulus, and ρ the density of iron.

Substituting the given values in Eqn (1.2.1) leads to

$$\nu = \frac{1}{2 \times 40 \times 10^{-3}}\left[\frac{115 \times 10^9}{7.25 \times 10^3}\right]^{1/2}$$

or

$$\nu = (12.5)\ (15.86 \times 10^6)^{1/2}$$

$$= 49{,}780 \text{ Hz} = 49.78 \text{ kHz}$$

Yes, the rod can be used for producing ultrasonic waves because its frequency lies in the ultrasonic range.

1.3 A quartz crystal of length 1 mm is vibrating at resonance. Calculate its fundamental frequency. (Assume that for quartz $E = 7.9 \times 10^{10}$ N/m^2 and $\rho = 2650$ kg/m^3).

Solution:

The frequency ν of vibration is given by

$$\nu = \frac{p}{2l}\sqrt{\frac{E}{\rho}} \tag{1.3.1}$$

For the fundamental mode, $p = 1$, giving

$$\nu = \frac{1}{2l}\sqrt{\frac{E}{\rho}} \tag{1.3.2}$$

Putting the given values is Eqn (1.3.2) leads to

$$\nu = \frac{1}{2\times 0.001}\sqrt{\frac{7.9\times 10^{10}}{2650}} = 2.73\times 10^{6}\ \text{Hz}$$

1.4 An ultrasonic interferometer is used to measure the velocity of ultrasonic waves in sea water. If the distance between two constructive antinodes is 0.55 mm, compute the velocity of the waves in sea water. The frequency of the crystal is 1.45 MHz.

Solution:

The distance between two antinodes is given by $\lambda/2$, where λ is the wavelength of the ultrasonic waves. Thus,

$$\lambda/2 = 0.55\times 10^{-3}$$

or $$\lambda = 1.1\times 10^{-3}\ \text{m} \tag{1.4.1}$$

Also, $$v = \nu\lambda \tag{1.4.2}$$

where v represents the velocity of the ultrasonic waves and ν the frequency. Using Eqn (1.4.1) in Eqn (1.4.2) leads to

$$v = 1.5\times 10^{6}\times 1.1\times 10^{-3} = 1650\ \text{m/s}$$

1.5 Calculate the natural frequency of a 50 mm long ferromagnetic rod whose density is 7250 kg/m^3 and Young's modulus of the material is 11.5×10^{10} N/m^2.

Solution:

Length of the rod, $l = 50\times 10^{-3}$ m

Density of the rod, $\rho = 7250$ kg/m^3

Young's modulus of the material, $E = 11.5\times 10^{10}$ N/m^2

The natural frequency of the rod

$$\nu = \frac{1}{2l}\left[\frac{E}{\rho}\right]^{1/2}$$

$$= \frac{1}{2\times 50\times 10^{-3}}\left[\frac{11.5\times 10^{10}}{50\times 10^{-3}}\right]^{1/2}$$

or $$\nu = 39.83\ \text{kHz}$$

1.6 A quartz crystal of length 2 mm is vibrating at resonance frequency. The density of quartz is 2650 kg/m^3 and its Young's modulus is 7.9×10^{10} N/m^2. Calculate the frequency of the ultrasound produced by the piezoelectric method.

Solution:

Length of the crystal, $l = 2\times 10^{-3}$ m
Density of the crystal, $\rho = 2650$ kg/m^3
Young's modulus of the crystal, $E = 7.9\times 10^{10}$ N/m^2

The frequency of the crystal

$$\nu = \frac{p}{2l}\left[\frac{E}{\rho}\right]^{1/2}$$

Here $p = 1$, so

$$\nu = \frac{1}{2\times 2\times 10^{-3}}\left[\frac{7.9\times 10^{10}}{2650}\right]^{1/2}$$

or $\nu = 1.365$ MHz

1.7 A quartz crystal of length 3 mm is vibrating at resonance frequency. The density of the material is 2500 kg/m^3 and its Young's modulus is 8×10^{10} N/m^2. Calculate the frequency of the ultrasound produced by the piezoelectric method.

Solution:

Length of the crystal, $l = 3\times 10^{-3}$ m
Density of the crystal, $\rho = 2500$ kg/m^3
Young's modulus of the crystal, $E = 8\times 10^{10}$ N/m^2

The frequency of the crystal

$$\nu = \frac{p}{2l}\left[\frac{E}{\rho}\right]^{1/2}$$

Here $p = 1$, so

$$\nu = \frac{1}{2\times 3\times 10^{-3}}\left[\frac{8\times 10^{10}}{2500}\right]^{1/2}$$

or $\nu = 942.80$ kHz

1.8 A quartz crystal of length 1.5 mm is vibrating at resonance frequency. The density of the material is 2650 kg/m^3 and its Young's modulus is 7.9×10^{10} N/m^2. Calculate the frequency of the ultrasound produced by the piezoelectric method.

Solution:

Length of the crystal, $l = 1.5\times 10^{-3}$ m
Density of the crystal, $\rho = 2650$ kg/m^3

Young's modulus of the crystal, $E = 7.9\times10^{10}$ N/m^2

The frequency of the crystal

$$\nu = \frac{p}{2l}\left[\frac{E}{\rho}\right]^{1/2}$$

Here $p = 1$, so

$$\nu = \frac{1}{2\times1.5\times10^{-3}}\left[\frac{7.9\times10^{10}}{2650}\right]^{1/2}$$

$$\nu = 1.82 \text{ MHz}$$

1.9 An ultrasonic source generating waves of frequency 800 kHz is used to find the depth of the sea. The velocity v of sound in sea water is 1440 m/s and the time t taken by the sound to reach the source after reflection from the sea bed is 0.95 s.

Solution:

Depth of the sea is given by half the total distance d traversed by the ultrasonic pulse

$$d = vt$$

$$= 1440\times0.95 \text{ m}$$

Hence, the depth of the sea

$$= \frac{1440\times0.95}{2} \text{ m}$$

$$= 684 \text{ m}$$

1.10 Find the depth of the submerged submarine if the ultrasound pulse reflected from the submarine reaches the source after 0.83 s and the velocity of sound in sea water is 1400 m/s.

Solution:

Total distance d travelled by sound in sea = $v\times t$

$$= 1440\times0.83 = 1195 \text{ m}$$

Hence, the depth at which the submarine is detected

$$= 1195/2 = 597.5 \text{ m}$$

$$= 597.50 \text{ m}$$

1.11 A cinema hall has a volume of 9000 m^3. The total absorption inside the hall is 1050 Sabine. Calculate the reverberation time of the hall.

Solution:

Total absorption inside the hall

$$aS = 1050 \text{ Sabine}$$

where a is the average absorption coefficient and S the area of the interior surface.

Volume of the cinema hall, $V = 9000\ m^3$

Reverberation time T of the hall $= (0.165 \times V)/aS$

$$= 0.165 \times 9000/1050$$

Reverberation time of the hall = 1.4143 s.

1.12 The volume of an auditorium is 13,500 m^3 and its reverberation time is 1.2 s. If the average absorption coefficient of the interior surface is 0.65 Sabine/m^2, find the area of the interior surface.

Solution:

Volume of the cinema hall, $V = 13{,}500\ m^3$

Reverberation time of the hall, $T = 1.2$ s

Total absorption inside the hall

$$aS = 0.65S \text{ Sabine}$$

We know that reverberation time of the hall

$$T = (0.165 \times V)/aS$$

Hence, total area of the interior surface is

$$S = (0.165 \times V)/aT$$

$$= 0.165 \times 13{,}500/0.65 \times 1.2$$

Total area of the interior surface, $S = 2855\ m^2$.

1.13 A cinema hall has a volume of 15,000 m^3 and its reverberation time is 1.3 s. If 300 cushioned chairs are additionally placed inside the hall, calculate the new reverberation time of the hall. The absorption of each chair is 1 Sabine.

Solution:

Volume of the cinema hall, $V = 15{,}000\ m^3$

Initial reverberation time of the hall, $T_1 = 1.3$ s

We know

$$T_1 = (0.165 \times V)/aS$$

Total absorption of the hall, $aS = (0.165 \times V)/T_1$

$$= 0.165 \times 15000/1.3$$

$$= 1904 \text{ Sabine}$$

Therefore, reverberation time of the hall after adding 300 chairs, each having absorption of 1 Sabine, is

$$T_2 = (0.165 \times V)/(aS + a_1S_1)$$

$$= (0.165 \times 15{,}000)/(1904 + 300) = 1123 \text{ s}$$

Reverberation time of the hall after adding 300 chairs, $T_2 = 1.123$ s

1.14 The velocity of ultrasonic waves in sea water is equal to 1440 m/s. Find the depth of a submerged submarine if an ultrasonic pulse reflected from the submarine is received 0.5 s after being sent out.

Solution:

Distance d travelled by the ultrasonic waves is given by

$$d = v \times t \tag{1.14.1}$$

where v is the velocity of the ultrasonic waves and t is the time lapsed.

Substituting the given values in Eqn (1.14.1) yields

$$d = 1440 \times 0.5 = 720 \text{ m} \tag{1.14.2}$$

Now, the total distance travelled by the ultrasonic waves is twice the depth of the submarine. Hence, the depth d_1 of the submarine is

$$d_1 = \frac{d}{2} = \frac{720}{2} = 360 \text{ m}$$

1.15 An ultrasonic interferometer-based system is used to measure the velocity of ultrasonic waves in sea water. The distance between two consecutive antinodes is found to be 0.4 mm. Calculate the velocity of the waves in sea water. Frequency of the waves generated by the crystal is 1.5 MHz.

Solution:

The distance between two antinodes gives $\lambda/2$, where λ is the wavelength of the ultrasonic waves. Thus,

$$\lambda/2 = 0.4 \times 10^{-3} \text{ m}$$

or

$$\lambda = 0.8 \times 10^{-3} \text{ m} \tag{1.15.1}$$

We know that

$$v = \nu\lambda \tag{1.15.2}$$

where v represents the velocity of the ultrasonic waves and ν the frequency. Using Eqn (1.15.1) in Eqn (1.15.2) yields

$$v = 1.5 \times 10^{6} \times 0.8 \times 10^{-3} = 1200 \text{ m/s}$$

1.16 A ferromagnetic rod has a length of 40 mm and the density of the material is 7250 kg/m^3. Evaluate the natural frequency of the rod if Young's modulus of the material is 11.5×10^{10} N/m^2.

Solution:

Length of the rod, $l = 40 \times 10^{-3}$ m
Density of the rod, $\rho = 7250$ kg/m^3
Young's modulus of the material, $E = 11.5 \times 10^{10}$ N/m^2

The natural frequency of the rod, v, is given by

$$v = \frac{p}{2l}\left[\frac{E}{\rho}\right]^{1/2}$$

which yields

$$v = \frac{1}{2 \times 40 \times 10^{-3}}\left[\frac{11.5 \times 10^{10}}{7250}\right]^{1/2}$$

or $$v = 49.78 \text{ kHz}$$

Recapitulation

- The frequency f of the alternating current set up by a resonant LC circuit is

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

- The natural frequency ν of a vibrating rod is

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

- An x-cut crystal plate of length l of a piezoelectric crystal has a frequency

$$\nu = \frac{p}{2l}\sqrt{\frac{E}{\rho}}$$

- For an acoustic grating,

$$\lambda_A \sin\theta_n = n\lambda$$

Short-Answer Questions

1.1 What are the properties of ultrasonics?

Ans: (i) They have high energy.
(ii) They have high penetration depth in solids and fluid.

(iii) They can undergo reflection, refraction, interference, and diffraction, like light.

(iv) They produce heat when incident on materials.

(v) They produce standing-wave patterns while passing through liquids.

1.2 What are the various methods of producing ultrasonic waves?

Ans: The two methods are:

(i) Magnetostriction method

(ii) Piezoelectric method

1.3 What is meant by magnetostriction effect?

Ans: When a ferromagnetic material such as iron, nickel or cobalt is kept in an alternating magnetic field, a change occurs in its dimension. This is known as magnetostriction effect.

1.4 What is meant by piezoelectric effect?

Ans: When pressure is applied along the mechanical axis of a piezoelectric crystal such as quartz, calcite or Rochelle salt, opposite electric charges develop along the electrical axis of the crystal. This is known as piezoelectric effect.

1.5 What are the methods used for detection of ultrasonics?

Ans: (i) Kundt's tube method

(ii) Sensitive flame method

(iii) Thermal detector method

(iv) Piezoelectric method

1.6 What is meant by SONAR?

Ans: SONAR is a device used to detect submerged objects such as icebergs and submarines in the sea. It is an acronym for SOund NAvigation and Ranging.

1.7 Mention some applications of ultrasonic waves.

Ans: Ultrasonic waves find applications in

(i) drilling holes in glass and iron sheets

(ii) welding and soldering

(iii) cleaning clothes and tiny mechanical/electronic components, as in watches

(iv) forming alloys of uniform compositions
(v) signalling
(vi) measuring the depth of the sea
(vii) detecting submerged objects in the sea water
(viii) conducting seismic surveys
(ix) relieving body pain
(x) detecting tumours and other defects in human body
(xi) removing kidney stones and brain tumours without surgery

1.8 What is Doppler effect?

Ans: There is an apparent change in frequency of the sound waves emitted from the source when there is a relative motion between the source and the observer. This is known as Doppler effect and the change in frequency is called Doppler frequency.

Review Questions

1.1 What is magnetostriction effect?

1.2 Give the principle of magnetostriction method of producing ultrasonics.

1.3 What is piezoelectric effect?

1.4 What is inverse piezoelectric effect?

1.5 Give the principle of piezoelectric method of producing ultrasonics.

1.6 Mention the methods of detection of ultrasonic waves.

1.7 What are the properties of ultrasonics?

1.8 Mention a few medical applications of ultrasonic waves.

1.9 What are the industrial applications of ultrasonics?

1.10 Show a schematic representation of magnetostriction effect.

1.11 Give an expression for the natural frequency of vibration of a rod.

1.12 Explain the Kundt's tube method for determination of frequency of sound waves.

1.13 Explain the sensitive flame method for the determination of frequency of ultrasonic waves.

1.14 Describe the phenomenon of cavitation.

1.15 Give some applications of the phenomenon of cavitation.

1.16 What is an acoustic grating?

1.17 How can one use an acoustic grating to determine the velocity of ultrasonic waves?

1.18 Explain the principle of SONAR.

1.19 Differentiate between A-scan and B-scan.

Numerical Problems

1.1 Velocity of ultrasonic waves in sea water is 1440 m/s. Find the depth of a submerged submarine if a reflected ultrasonic pulse is received 0.25 s after being sent out.
[**Hint:** $d = v \times t$]

(**Ans:** 180 m)

1.2 The submarine indicated in Problem 1.1 relocates itself to a depth of 200 m. What will be the new time internal between the received and sent ultrasonic pulse?
[**Hint:** $d = v \times t$]

(**Ans:** 0.28 s)

1.3 Calculate the natural frequency of a 30 mm length of pure iron rod. Given the density of pure iron is 7.25×10^3 kg/m^3 and its Young's modulus is 115×10^9 N/m^2.

$$\left[\textbf{Hint:}\ v = \frac{1}{2l}\sqrt{\frac{E}{\rho}}\right]$$

(**Ans:** 66.37 kHz)

1.4 The length of rod indicated in Problem 1.3 is changed to 33 mm. Calculate the change in natural frequency.

$$\left[\textbf{Hint:}\ v = \frac{1}{2l}\sqrt{\frac{E}{\rho}}\right]$$

(**Ans:** $\Delta\nu = -6.03$ kHz)

1.5 A quartz crystal of length 0.8 mm is vibrating at resonance. Determine the fundamental frequency. (Assuming E for quartz = 7.9×10^{10} N/m^2 and ρ for quartz = 2650 kg/m^3.)

$$\left[\textbf{Hint:}\ v = \frac{p}{2l}\sqrt{\frac{E}{\rho}}\right]$$

(**Ans:** 3.41×10^6 Hz)

1.6 What should be the length of the quartz crystal that resonates at 6 MHz. Use the data given in Problem 1.5.

$$\left[\textbf{Hint:}\ v = \frac{1}{2v}\sqrt{\frac{E}{\rho}}\right]$$

(**Ans:** 0.46 mm)

1.7 An ultrasonic interferometer is being used to measure the velocity in sea water. If the distance between two constructive antinodes is 0.6 mm, compute the velocity of the waves in the sea water. The frequency of the crystal is 2 MHz.
[**Hint:** $v = \nu\lambda$]

(**Ans:** 2400 m/s)