ACOUSTICS

It is the science of sound which deals with the process of generation, transmission and reception of sound in a room or in a hall. Sound is a form of energy and is produced by every vibrating body.

The acoustic properties of building were studied by WC Sabine.

Sound is classified into music and noise. Musical sound produces pleasant sensation to ear. They are produced by periodic waves. Noise produces disturbing sensation to ear. They are produced by non periodic waves.

Characteristics of musical sound

(i) Pitch of Sound: Pitch of a sound depends on the frequency of the sound. High pitch means higher frequency and low pitch means lower frequency.

(ii) Intensity of sound

Intensity of sound at any point is the amount of sound energy incident on unit area held normal to the direction of propagation of sound in one second. i.e., It is the sound power on unit area. Intensity of sound is proportional to the square of the amplitude of sound wave. Its basic unit is W/m^2

I of the sound is derived as $I = \frac{1}{2}\rho_0 v\omega^2 A^2$ where ρ_0 is the mean density of the medium (air); v is the velocity of sound; ω is the angular frequency of sound wave.

i.e., Intensity of sound $I \propto A^2$ where A is the amplitude.

Threshold minimum intensity:

It is the minimum intensity which a human being can hear and it is $I_0 = 10^{-12}\ W/m^2$

Threshold pain intensity:

It is the maximum intensity which a human ear can tolerate without sensation of pain. The threshold pain intensity of sound is 10^{12} times I_0 which is equal to $1\ W/m^2$. Thus our ear has a range of sensitivity from I_0 to $10^{12}\ I_0$.

(iii) Timbre or quality: Timbre is an important property which helps the ear to distinguish musical sound which have the same pitch and loudness. Timbre is mainly characterised by the harmonic content of sound and its dynamic properties.

Loudness and its units

* **Loudness of sound** is the degree of sensation of sound. It depends on the intensity of sound and the sensitivity of ear or microphone.
* Loudness of sound is proportional to logarithm of intensity of sound.

Consider two sounds with intensities I_0 and I_1 at same frequency. Corresponding loudness is L_0 and L_1.

$L_0 = k \log_{10} I_0$ and $L_1 = k \log_{10} I_1$ where k is the constant of proportionality.

The difference in loudness ($L = L_1 - L_0$) is called sound intensity level (SIL). i.e., $\mathbf{L = \log_{10}\frac{I_1}{I_0}}$

Units

* **Bel** is a unit of loudness or sound intensity level (SIL). $L = \log_{10}\frac{I_1}{I_0}$ Bel
* **Decibel:** 1 Bel = 10 Decibel i.e., $L = 10\log_{10}\frac{I_1}{I_0}$ dB

  For threshold hearing, $I = I_0 = 10^{-12}\ W/m^2$; $L = 10\log_{10}\frac{10^{-12}}{10^{-12}}$ dB $= 10\log_{10}(1)$ dB : $L = 0$dB

  For threshold pain intensity, $I = 1 W/m^2$, $L = 10\log_{10}\frac{1}{10^{-12}} = 120$ dB
* **Phon:**

  It is found that sound of same intensity but of different frequencies has different loudness. So a separate unit called phon is used to measure the loudness.

  Loudness in dB and in phon are the same for a frequency of 1000Hz.

Absorption of sound

All materials absorb certain amount of sound energy. The degree of absorption depends on many factors. An **open window is a perfect absorber** of sound because the sound incident on it will not be reflected back. One Sabine is the amount of sound energy absorbed by one square meter of an open window.

Absorption Coefficient (α)

The absorption coefficient of sound (α) is defined as the ratio of the amount of sound energy absorbed by the surface to the amount of sound energy incident on the surface.

Since, open window is a perfect absorber, the absorption coefficient of all substances are measured in terms of open window unit (OWU). For open window, α = 1

$$\alpha = \frac{\text{Amount of sound energy absorbed by a surface}}{\text{Amount of sound energy incident on the surface}}$$

Absorption coefficient is expressed as open window unit OWU or metric sabine.

Total absorption is $A = \sum \alpha_i S_i = \alpha_1 S_1 + \alpha_2 S_2 + \ldots\ldots + \alpha_n S_n$ where $\alpha_1, \alpha_2, \ldots$ are the absorption coefficients of surface of area $S_1, S_2, \ldots$

Total absorption is expressed in Sabine m^2

If 'S' is total area of a surface and α is absorption coefficient, then total absorption (A) is given as **A = α S**

* For eg: If α for plaster is 0.05. For $100m^2$ plaster, total absorption $A = 0.05\times100 = 5m^2$.

  i.e., $100m^2$ plaster absorbs same energy absorbed by $5m^2$ of an open window.
* Let a room containing different materials with surface areas S_1, S_2, ... and absorption coefficients α_1, α_2 ....

  Total amount of energy absorbed = $\alpha_1 S_1 + \alpha_2 S_2 + \ldots\ldots$

  Average absorption coefficient $\alpha = \frac{\alpha_1 S_1 + \alpha_2 S_2 + \ldots}{S_1 + S_2 + \ldots} = \frac{\alpha_1 S_1 + \alpha_2 S_2 + \ldots}{S_1 + S_2 + \ldots} = \frac{\sum \alpha_i S_i}{\sum S_i}$

Reverberation

Sound produced by a source in a hall suffers multiple reflections from various objects in the hall, like wall, floor, ceiling etc. Hence the listeners hear a series of sound in addition to the original sound. So sound persists for a time even after the source has stopped.

The phenomenon of persistence of sound in a hall due to multiple reflections from the ceiling, floor, walls, and other materials, even after the source of sound has cut off is called reverberation.

Reverberation time (T)

It is defined as the time required by the sound energy to reduce its intensity to 10^{-6} times of its original intensity (or reduce its intensity by 60dB of its original intensity) from the moment the source of sound is stopped.

Sabine's formula

Sabine derived an equation for reverberation time T. According to him,

Reverberation time is (i) directly proportional to the volume of the hall (V)

(ii) inversely proportional to the total sound absorption in the hall (A). i.e., $A = \sum \alpha S$

$\therefore\ T \ \alpha \frac{V}{A}$ or $\mathbf{T = \frac{0.163V}{A}}$ where V is volume of the hall and A is total energy absorbed ($\sum \alpha_i S_i$)

Significance of reverberation time

Reverberation time is an important factor deciding the acoustic quality of a building.

* If reverberation time is so small, sound vanishes very rapidly. This produces dead silence in the hall.
* If reverberation time is too large, there will be multiple reflections and the sound waves will overlaps one over other producing loss of clarity.
* Hence reverberation time should have an optimum value for good acoustics of a hall. Reverberation time can be adjusted according to the purpose of the hall by arranging necessary sound absorbing materials in the hall.

Halls	Reverberation time
Lecture hall	0.5 sec – 1 sec
Conference hall	1 sec – 1.5sec
Cinema theatre	1.3 sec
Music recording hall	1.5 - 2 sec
Churches	1.8 sec- 3sec

Factors Affecting Acoustics Of Buildings And Their Remedies

(1) Reverberation time: It is an important factor deciding the acoustic quality of a building.

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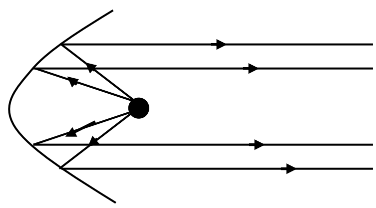
* Hence reverberation time should have an optimum value for good acoustics of a hall. Reverberation time can be adjusted according to the purpose of the hall by arranging necessary sound absorbing materials in the hall.
* Reverberation time T = $\frac{0.163V}{A}$ where V is volume of the hall and A is total energy absorbed ($\sum \alpha_i S_i$)
* **Remedies:** Reverberation time can be controlled by
  (i) by selecting suitable building materials.
  (ii) by providing proper windows and ventilators.
  (iii) by covering walls and ceilings with sound absorbing materials.
  (iv) by covering floor with carpets.
  (v) by using thick curtains.
  (vi) by furnishing with upholstered seats.

(2) Echoes: Echo is due to reflection of sound at different objects.

* Echo is produced when the time interval between the direct and reflected sound waves is about $\frac{1}{5}^{th}$ of a second.
* Long halls produce echo and almost all rooms produce reverberation.
* **Remedies:** Echoes can be controlled by
  (i) by covering distant walls and ceilings with sound absorbing materials.
  (ii) by providing thick curtains with folding.

(3) Focussing surfaces

* If there are any focussing surfaces such as concave surface, spherical, cylindrical or parabolic surfaces on the walls, floor and ceiling of the hall, the sound energy will be focussed to only certain region. This causes less sound in some other region.
* **Remedies:** For uniform distribution of sound energy throughout the hall,
  (i) There should not be any curved surfaces in the hall. If any such surfaces are present, they must be covered with sound absorbing materials.
  (ii) Ceiling must be of less height.
  (iii) A parabolic surface must be arranged with the speaker at its focus. This send out a uniform sound energy in the entire hall.



(4) Sufficient Loudness

* For satisfactory hearing, sufficient loudness throughout the hall is necessary.
* **Remedies:** For sufficient loudness,

  (i) by placing loud speakers at proper positions in the hall.

  (ii) Ceiling is kept low, so that the sound gets reflected from the ceiling and reaches the audience.

  (iii) by keeping large polished boards behind the speaker and facing the audience.

(5) Resonance Effect

* Cavities, holes, air pockets etc in the walls and ceiling of the hall will contain air columns. These air columns are set into vibrations due to resonance and as a result sound is produced.
* In some cases, section of wooden portions, window panes etc will vibrate and produce sound waves. This will also produce resonance. Sometimes, these created sounds will interfere with original sound.
* These resonance and interference produces distortion and losses the clarity of the original sound.
* **Remedies:** To avoid these,

  (i) cavities, air pockets, holes etc in the halls should be avoided or covered with sound absorbing materials.

  (ii) fixing the window panes properly.

  (iii) damping the resonant vibrations by suitable methods.

(6) Echelon effect

* Regular spacing of reflecting surfaces, or steps with equal width may produce additional musical notes due to regular repetition of echoes. This is called echelon effect. This makes original sound confusing.
* **Remedies:** This can be reduced by

  (i) making steps and pillars of unequal width.

  (ii) covering equally spaced steps with sound absorbing materials.

(7) Noise

* Unwanted sound in a hall is called noise. Noises are divided into three

  Air born noise: Noise from outside the hall through windows, door, ventilators etc are called air born noise. Eg: Vehicle moving outside produce noises. This can be eliminated by avoiding openings and holes, using double door and double windows on separate frame with an insulator between them etc.

  Structure born noise: This is caused by the vibration of the structure due to different activities going on nearer to building like drilling, working of heavy machines etc. This can be eliminated by breaking the continuity of the hall with proper sound insulators(using double walls with air in between them) etc.

  Inside noise: The noise produced inside the hall is called inside noise and this is produced by the machines like fan, engines etc. This noise can be eliminated by furnishing the floor with carpets and mats etc.

ULTRASONICS

Ultrasonic waves are sound waves whose frequency is more than 20 kHz.

They are classified into four.

(i) Transverse ultrasonic or shear waves – Particles of the medium vibrate perpendicular to the direction of propagation of the wave. It can propagate only through solids.

(ii) Longitudinal/compressional waves – These waves travel through medium as alternate compressions and rarefactions vibrating parallel to the direction of propagation of the wave.

(iii) Surface waves or Rayleigh waves - These waves are neither transverse nor longitudinal. They are analogues to water waves. They travel only through the surface layer of solids.

(iv) Lamp waves or Flexural waves or Plate waves - These waves are produced in extremely thin metal.

Properties of ultrasonic waves

* Frequency greater than 20kHz.
* They are highly energetic.
* Ultrasonic waves of high intensity produce chemical changes when passed through certain liquids. Certain chemical reactions are initiated by ultrasonic waves. In certain others, it accelerates the chemical reaction.
* When passed through substances, ultrasonic waves produce cavitation. This effect is utilized in cleaning degreasing and soldering of aluminium and its alloys.
* Exhibit reflection and interference.
* Since the wavelength is very small, there is only negligible diffraction effect. Hence, ultrasonic waves can be transmitted over long distances without much loss of energy. This property is used extensively for number of ultrasonic guided techniques.
* When passed through liquids and gases, they produce a violent agitation in a liquid which has a lot of practical applications.
* Ultrasound waves produce emulsion at the interface between two immiscible liquids and hence can be used for mixing oil and water. This property is used in the preparation of food products, paints, cosmetics and so on.
* Their speeds are different in different media.

In solids, $v = \sqrt{\frac{Y}{\rho}}$, Y – Young's modulus ; In liquids, $v = \sqrt{\frac{K}{\rho}}$, K – Bulk modulus

In gases, $v = \sqrt{\frac{\gamma P}{\rho}}$, P – pressure and γ is $\frac{C_p}{C_v}$

Production of ultrasonic waves

(i) By Magnetostriction effect

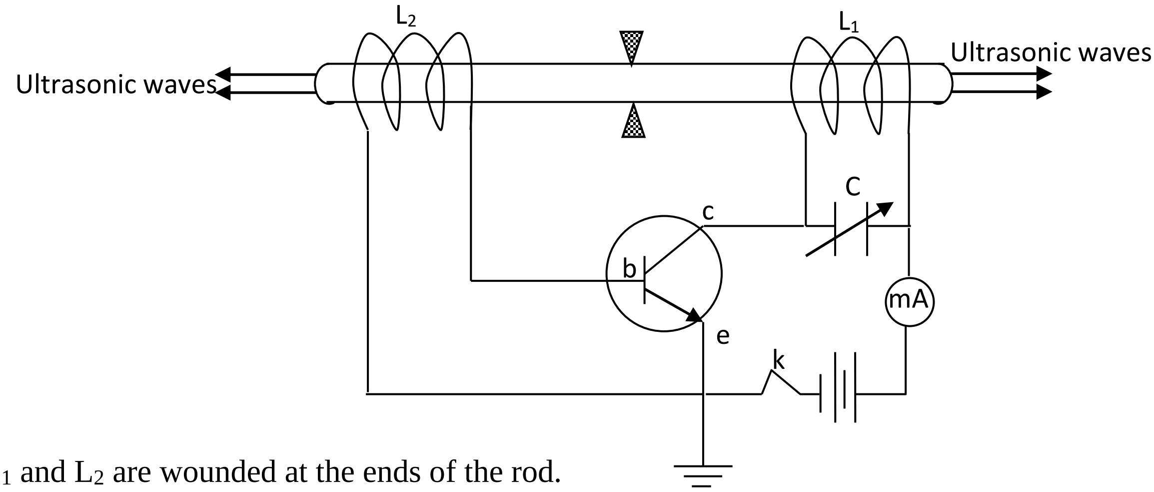
(ii) By Piezo-electric effect

(i) Production of ultrasonic waves by magnetostriction effect

* Basic principle is magnetostriction effect.
* Magnetostriction effect: When a ferromagnetic rod (iron, nickel etc) is subjected to a magnetic field parallel to its length, the length increases or decreases rapidly and a longitudinal wave is produced from both ends in the medium. This is known as magnetostriction effect.

Magnetostriction Oscillator:

A ferromagnetic rod of nickel is clamped in the middle as in the figure.



Two coils L_1 and L_2 are wounded at the ends of the rod.

The coil L_1 is connected in parallel with a variable capacitor C. The inductor L_1 and capacitor C form a tank circuit which produces electrical oscillations. Coil L_2, the second inductor is connected in between the base and emitter of an *npn* transistor T. This coil forms the feeback loop. A battery B and milliiammeter (mA) is connected as shown in the figure.

When the oscillator is switched on, the capacitor C get charged and discharged through L_1 and setting up oscillations with frequency $\mathbf{f = \frac{1}{2\pi\sqrt{L_1 C}}}$. This produces longitudinal vibrations in the rod. The rod elongates and contracts along its length and produces an emf in the coil L_2. This emf is fed to the base of the transistor and then to the tank circuit.

This positive feedback overcomes the loss of energy in the tank circuit and maintains the oscillations. The variable capacitor is adjusted so that the milliammeter shows maximum current. At this stage, the frequency of the tank circuit becomes equal to the natural frequency of longitudinal vibrations of the rod. Thus resonance is achieved. Ultrasonic waves are produced at the ends of the rod.

The frequency of vibration of the ferromagnetic rod $\mathbf{f = \frac{1}{2l}\sqrt{\frac{Y}{\rho}}}$ where l is the length of the rod, Y is Young's modulus of the material, ρ is the density of the material of the rod.

Ultrasonics of desired frequency can be obtained by suitable selecting the material and the length of the rod.

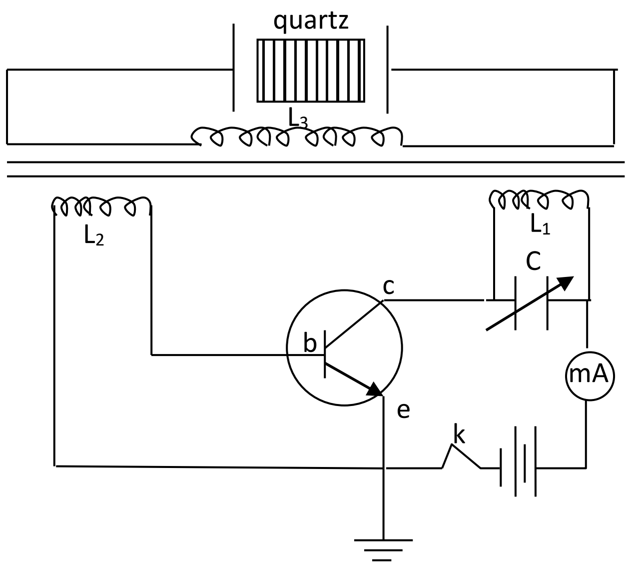
Advantages

* Ultrasonic waves up to frequency 300kHz can be produced.
* Cost of construction is low.
* Construction is simple.

(ii) Production of ultrasonic waves by piezo-electric effect

* Basic principle is piezo-electric effect.
* **Piezo-electric effect:** When certain crystals like quartz, tourmaline etc are subjected to stress or pressure along certain axis, a potential difference is produced along a perpendicular axis. This phenomenon is known as piezo-electric effect or electrostriction effect.
* **Inverse piezo-electric effect:** When an alternating voltage is applied along an axis, mechanical vibrations are produced along a perpendicular axis. This phenomenon is called Inverse **Piezoelectric effect**. If the frequency of the applied alternating voltage is equal to the natural frequency of the crystal, resonance occurs. This phenomenon is made use of in producing ultrasonic waves.

Experimental arrangement: Piezo-electric Oscillator



Connections are made as shown in figure. The coils L_1, L_2 and L_3 are coupled together by means of transformer action.

When the key is closed, the capacitor C gets charged. Then it discharges through the inductor L_1 and then again gets charged. Thus oscillations are set up in the tank circuit with frequency, $f = \frac{1}{2\pi\sqrt{L_1 C}}$.

Now an emf appears across inductor L_3 and it is fed into inductor L_2. Due to emf across L_3, the piezoelectric crystal starts vibrating producing ultrasonic waves. The emf in L_2 is amplified by the transistor and fed back to the tank circuit. Thus oscillations are maintained in the tank circuit.

At this stage, frequency of the tank circuit becomes equal to the natural frequency of the quartz crystal and resonance occurs. The vibrating quartz crystal produces longitudinal ultrasonic waves in the surrounding air.

At resonance, the natural frequency of the crystal is $\mathbf{f} = \frac{1}{2t}\sqrt{\frac{Y}{\rho}}$ where *l* is the length of the rod, Y is Young's modulus of the material, ρ is the density of the material of the rod.

Advantages

* Ultrasonic waves upto frequency 500kHz can be produced.
* More efficient than magnetostriction oscillator and compact.
* Constant and stable output frequency is produced.

Detection of ultrasonic waves

(i) Thermal detection:

* When ultrasonic waves travel through a medium, the temperature increases at the regions of compression and it decreases at the regions of rarefactions.
* When a platinum wire (which is very sensitive to change in temperature) is placed in the path of ultrasonic waves, the wire is alternately heated and cooled throughout its length.
* This change in temperature changes the resistance of the platinum wire.
* The variation in resistance can be noted with the help of a sensitive bridge arrangement. Thus ultrasonic waves are detected.

(ii) Piezoelectric detection:

* Ultrasonic waves can also be detected by employing the principle of piezoelectric effect.
* A quartz crystal is used to detect ultrasonic waves.
* When the crystal receives ultrasonic waves at one pair of faces, charges are produced on the other pair of faces.
* The corresponding voltage is very small. Hence it is suitably amplified and detected by a microvoltmeter.

Acoustic Grating

When ultrasonic waves are passed through a liquid, due to compressions and rarefactions, the density varies from layer to layer. The liquid density and consequently the refractive index is maximum at nodes and minimum at antinodes. As a result, the regions of greater and lesser refractive indices act like an **acoustic grating**.

Under this condition, if monochromatic light is passed through the liquid at right angles to the direction of propagation of ultrasonic waves, the liquid behaves like a grating, resulting in the diffraction of light.

If d is the distance between two adjacent nodal or antinodal planes, we have, $\boldsymbol{d\sin\theta = n\lambda}$ where θ is the angle of diffraction, λ is the wavelength of the monochromatic light and n is the order of diffraction.

Since d is the distance between adjacent nodes or antinodes

$$2d = \lambda_u \quad \text{or} \quad d = \frac{\lambda_u}{2}$$ where λ_u is the wavelength of ultrasonic waves.

With this value of d gives $\frac{\lambda_u}{2}\sin\theta = n\lambda$ or $\lambda_u = \frac{2n\lambda}{\sin\theta}$

Using the frequency of the ultrasonic wave, one can evaluate the velocity of the ultrasonic waves in the liquid.

Applications of ultrasonics

(a) Industrial Applications

1. Sound Navigation and Ranging:

Sound Navigation and Ranging (SONAR) is a method for the measurement of depth of oceans, locating submarines, icebergs, shoal of fish etc.

Ultrasonic waves are not much absorbed or scattered by water. In SONAR, a sharp ultrasonic beam is sent and the reflected beam is received by an ultrasonic detector. The signal is amplified and analysed by a CRO. If an object is moving, there will be a change in frequency of the echo signal. This helps to find its velocity and direction of motion.

If ‘d’ is the depth of the ocean, ‘t’ is the time taken by the ultrasonic waves for the to-and-fro motion, ‘v’ is the velocity of sound in sea water, vt =2d

Depth of the ocean, d $= \frac{\mathbf{vt}}{\mathbf{2}}$

2. Non Destructive Testing (NDT)

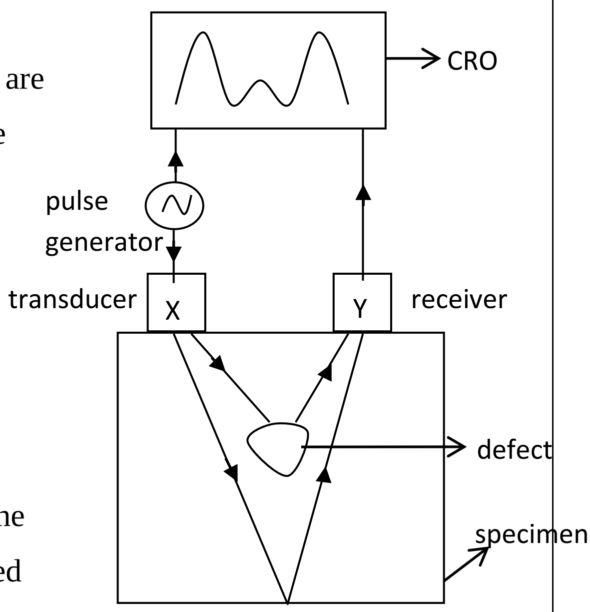
Non destructive testing (NDT) is a technique used in science and industry to detect imperfections, determine the properties or evaluate the quality of a material without causing a physical or chemical change during the process of testing. The terms Non Destructive Inspection (NDI) and Non Destructive Evaluation (NDE) are also used to describe this technology.

There are different NDT methods. The ultrasonic testing method is widely used in industries to find the size, shape and location of defects such as cracks, voids, laminations, inclusion of foreign materials etc in products. The most common ultrasonic testing system is the **pulse echo system**.

Pulse Echo System

This method is used to detect imperfections.

Ultrasonic sound waves from ultrasonic transmitting transducer are sent into the testing specimen. (Ultrasonic transducer is a device which converts electrical energy into high frequency sound energy and vice versa.)



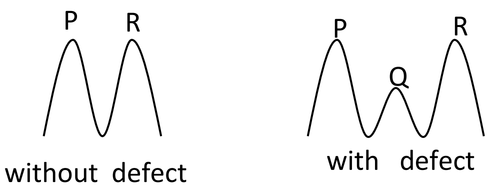
At the same time, the ultrasonic pulses passes directly to the CRO produces a high peak 'P'.

The ultrasonic waves are reflected from the other end of the specimen and are collected by the receiving transducer.

The ultrasonic waves that reflected at the imperfections inside the specimen are reflected and the corresponding pulses are collected by the receiving transducer. (receiving transducer converts the ultrasonic pulses into electrical signals.)

These signals are suitably amplified and fed to a CRO.

The ultrasonic waves reflected from the bottom end of the specimen that are fed to CRO, produces the peak 'R' and that reflected from the imperfection produces an additional peak 'Q'.



P – due to ultrasonic wave that is sent directly to the CRO
Q – due to the wave reflected from the imperfection.
R – due to the reflected wave from the bottom of the surface

From the position of the additional peak in the CRO, the exact location of the defect is estimated.

3. Other Industrial Applications

∗ Used in **ultrasonic drilling** which is very effective in brittle materials like glass, ceramics etc and also to make square or other non-circular holes.

∗ Used in **ultrasonic welding** to weld thin metal sheets and foils. This technique is used to weld plastics, aluminum, synthetic fabrics, films etc. Two pieces of metals are held in good contact and high intensity ultrasonic waves are passed through them. This increases the temperature and the two surfaces melt and join together.

∗ Used in **ultrasonic soldering** materials such as glass, ceramics etc which cannot be soldered by conventional method.

∗ Used in **ultrasonic mixing**. This method is very useful in the production of emulsions like polishes, paints, food products, pharmaceutical preparations etc.

∗ Used in **ultrasonic cleaning.** Ultrasonic cleaning is based on a process called cavitation. Ultrasonic waves are passed through cleaning fluid into which objects such as jewelry, surgical instruments or small machinery are placed for cleaning.

Cavitation is the formation of a bubble in the liquid at the region of rarefaction when ultrasonic waves passes through it. At the region of compression, these bubbles collapses and a tremendous pressure is released. The vibrations and cavitation result in turbulent cleaning action.

* Used in **signaling:** Ultrasonic waves can be concentrated into a sharp beam due to smaller wavelengths and hence can be used for signaling in a particular direction.

(b) Medical Applications of Ultrasonics

Ultrasonics have number of application in medicine. It is used both in the process of diagnosis and in various treatments. The diagnostic use involves the non invasive imaging of the internal organs or the structures of the body. Ultrasonic imaging systems use the pulse echo and pulsed Doppler techniques.

* **Ultrasound Imaging:** In pulse echo technique, an ultrasound is directed into the body and its reflection form organs and other structures are detected. In pulse Doppler technique a high frequency sound beam is send and the echo is received. When the object that reflects, the sound is in motion, there will be a change in the frequency of the reflected signal. From the change, one can estimate the direction and blood velocity. With the help of this one can find the deposition of lipid and cholesterol particles in the walls of artery, malignancy, vessel narrowing etc.

are used in examining the shape and movement of organs in human body. speed of blood flow etc.

* **Echocardiography:** It is a technique to get images of the heart with the help of ultrasound which provides many information including the size and shape of the heart, pumping capacity, the location and extent of any tissue damage etc.
* **Echoencephalography:** It is a technique to detect tumors in the brain by using ultrasound.
* In ophthalmology, ultrasound is very useful in obtaining valuable information about the deeper regions of the eye especially when the cornea or lens is opaque. Tumors, foreign bodies and detachment of the retina can be detected with ultrasound.
* In Dentistry, an ultrasound scrubber combined with a water jet is used to remove plaque from teeth.
* Ultrasound is utilized in the treatment of kidney stones. Shock wave lithotripsy is a technique to break kidney stones into small pieces without much damage to the kidney tissue.
* Ultrasonic diathermy is a method of treatment of joint disease and joint stiffness. Ultrasound is an effective deep heater of bones and joints.
* **Sonogram:** It is a computerized picture take by processing ultrasonic echoes form organs and other interior parts of the body. This technology is a medical procedure that uses ultrasound to get pictures of internal organs, bones, muscles, also used to get pictures of a developing fetus.