Module 4

Ultrasonic Testing (UT)

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Ultrasonic Testing

- UT is a nondestructive method in which *high frequency sound waves* are introduced into the material being inspected.
- Most ultrasonic inspection is done at frequencies between ***0.5 and 15 MHz*** - well above the range of human hearing.
- The sound waves travel through the material with some attendant loss of energy (attenuation) due to material characteristics
- are measured after reflection at interfaces(pulse echo) or flaws, or are measured at the opposite surface (pulse transmission).

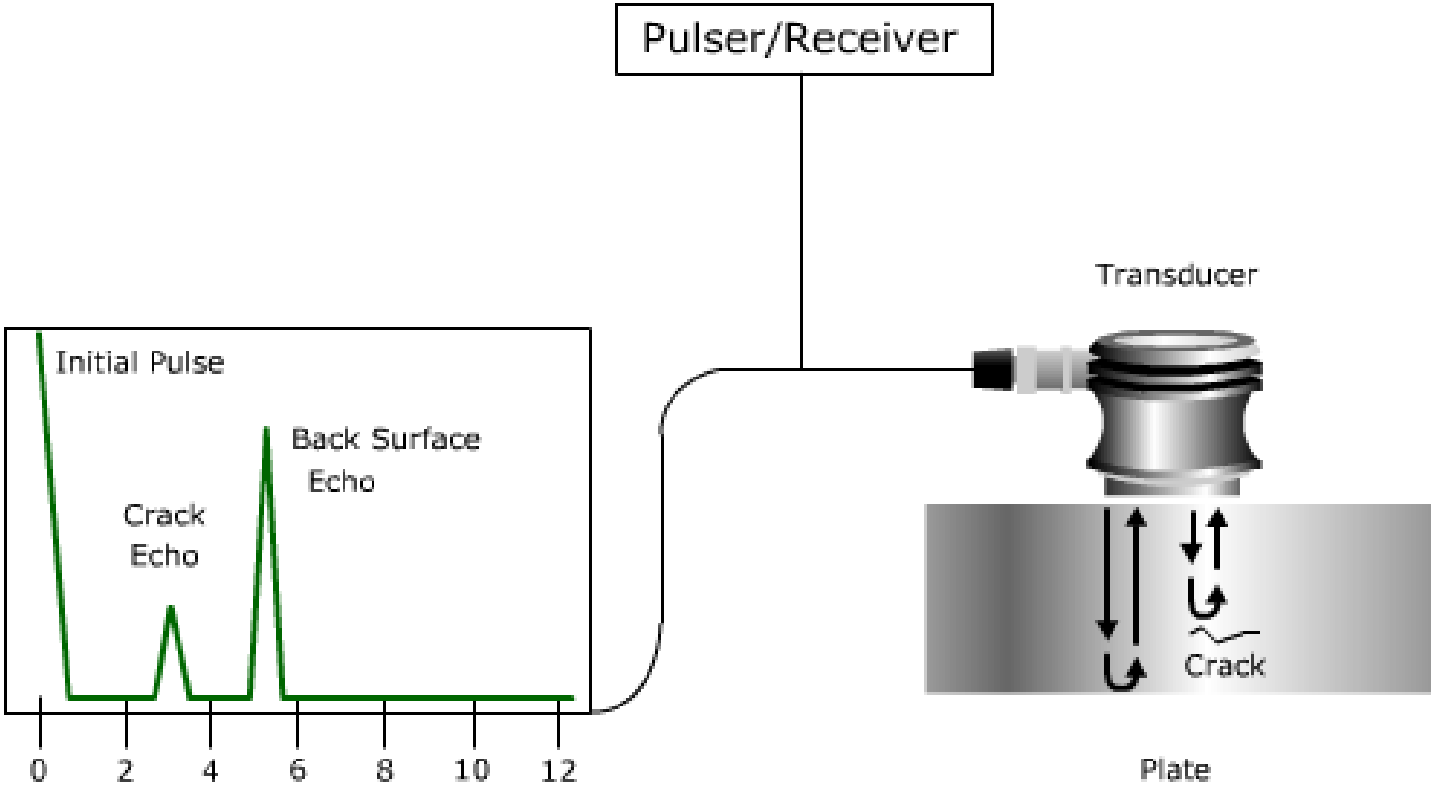
- The reflected beam is detected and analyzed to define the presence and location of flaws.
- Ultrasonic testing has a superior penetrating power to radiography and can detect flaws deep in the test specimen (up to about 6 to 7 meters of steel).
- It is quite sensitive to small flaws and allows the precise determination of the location and size of the flaws.
- Besides its wide use in engineering applications (*such as flaw detection/evaluation, dimensional measurements, material characterization, etc.), ultrasonics are also used in the medical field (such as sonography, therapeutic ultrasound, etc.).*

- In general, ultrasonic testing is based on the capture and quantification of either the reflected waves (*pulse-echo) or the transmitted waves (through-transmission).*
- *Each of the two types is used in certain applications, but generally, pulse echo systems are more useful since they require one-sided access to the object being inspected.*

Basic Principles

- A typical pulse-echo UT inspection system consists of several functional units,
- such as the pulser/receiver, transducer, and a display device.
- Pulser/receiver is an electronic device that can produce high voltage electrical pulses.
- Driven by the pulser, the transducer generates high frequency ultrasonic energy.

- The sound energy is introduced and propagates through the materials in the form of waves.
- When there is a discontinuity (*such as a crack) in the wave path, part of the energy will be reflected back from the flaw surface.*
- The reflected wave signal is transformed into an electrical signal by the transducer and is displayed on a screen.
- Knowing the velocity of the waves, travel time can be directly related to the distance that the signal traveled.
- From the signal, information about the reflector location, size, orientation and other features can sometimes be gained.


Pulser/Receiver
Transducer
Initial Pulse
Back Surface Echo
Crack Echo
0
2
4
6
8
10
12
Crack
Plate

Advantages

- It is sensitive to both surface and subsurface discontinuities.
- The depth of penetration for flaw detection or measurement is superior to other NDT methods.
- Only single-sided access is needed when the pulse-echo technique is used.
- It is highly accurate in determining reflector position and estimating size and shape.
- Minimal part preparation is required.
- It provides instantaneous results.
- Detailed images can be produced with automated systems.
- It is nonhazardous to operators or nearby personnel and does not affect the material being tested.
- It has other uses, such as thickness measurement, in addition to flaw detection.
- Its equipment can be highly portable or highly automated.

Disadvantages

- Surface must be accessible to transmit ultrasound.
- Skill and training is more extensive than with some other methods.
- It normally requires a coupling medium to promote the transfer of sound energy into the test specimen.
- Materials that are rough, irregular in shape, very small, exceptionally thin or not homogeneous are difficult to inspect.
- Cast iron and other coarse grained materials are difficult to inspect due to low sound transmission and high signal noise.
- Linear defects oriented parallel to the sound beam may go undetected.
- Reference standards are required for both equipment calibration and the characterization of flaws.

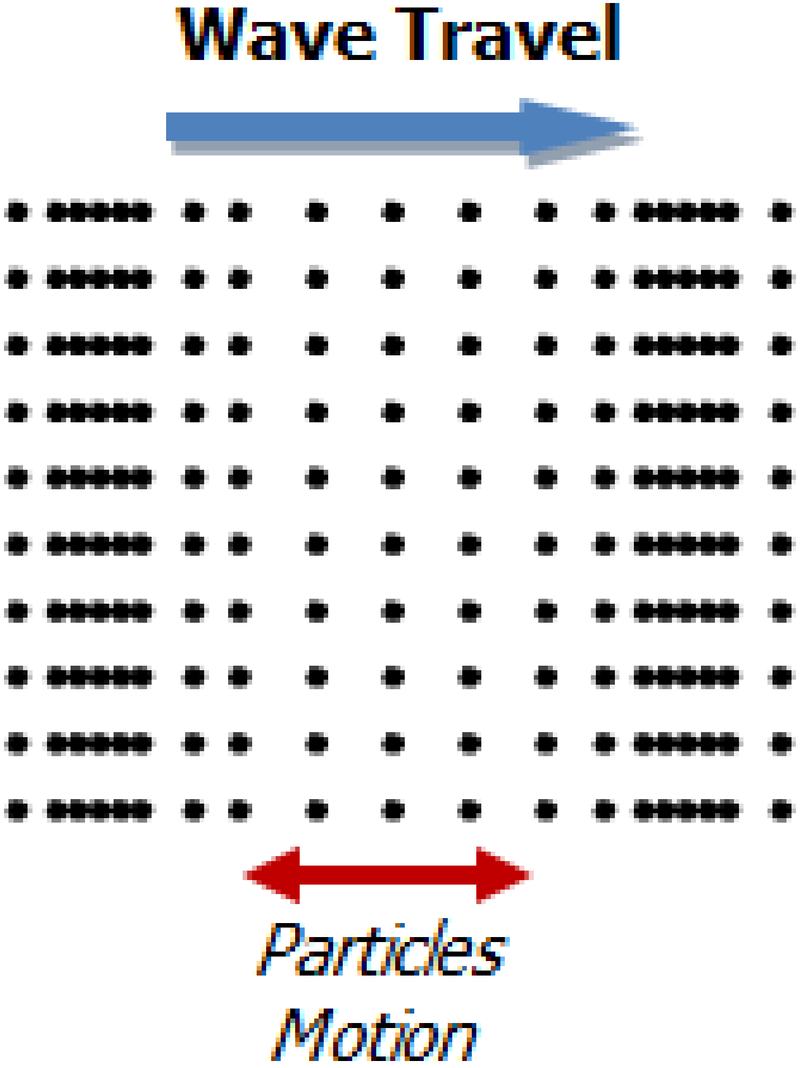
PHYSICS OF ULTRASOUND

- **Wave Propagation**
- All sound waves are mechanical vibrations involving movement of the medium in which they are travelling.
- Because of the relative movement of the particles in the medium the physical properties of the particles in the medium have to be taken into consideration.
- Ultrasonic waves are classified on the basis of the mode of vibration of the particles of the medium w.r.t. the direction of propagation of the waves:

- In solids, sound waves can propagate in four principal modes that are based on the way the particles oscillate.
- Sound can propagate as longitudinal waves, shear waves, surface waves, and in thin materials as plate waves.
- Longitudinal and shear waves are the two modes of propagation most widely used in ultrasonic testing.

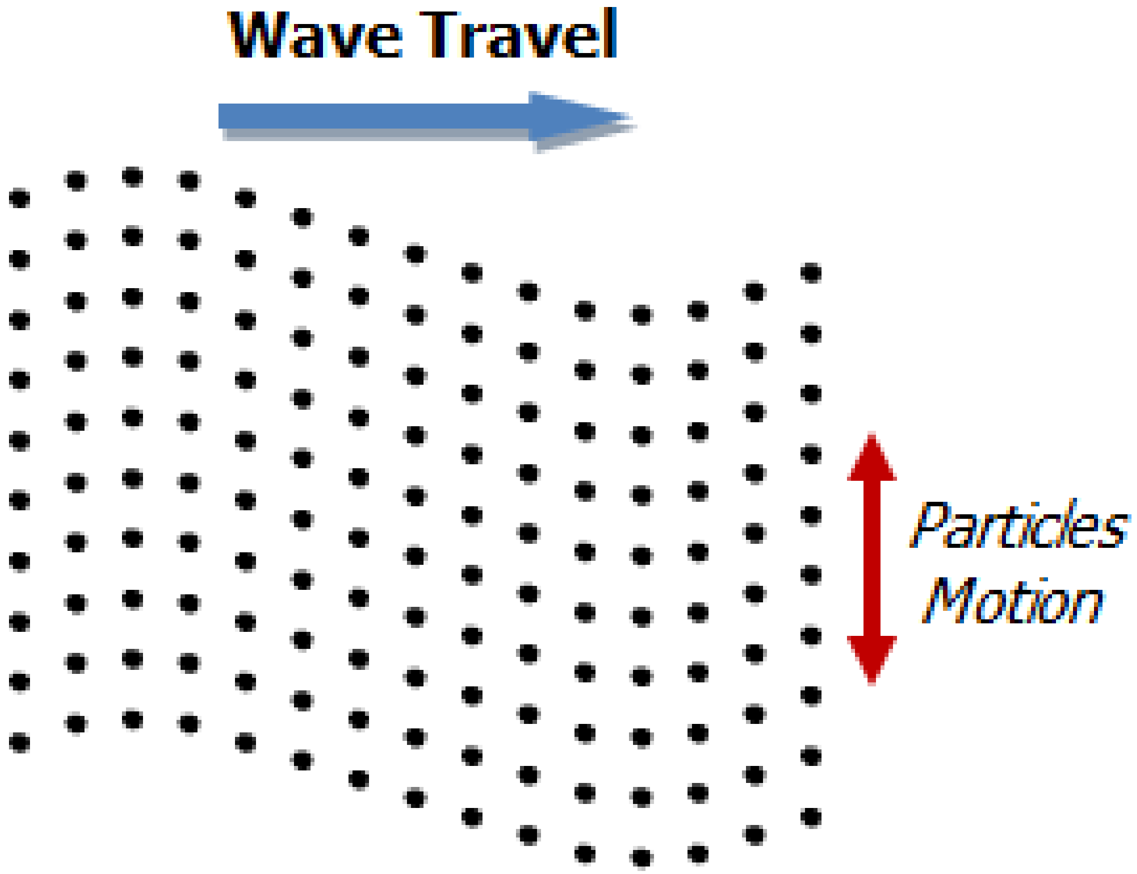
Longitudinal Waves

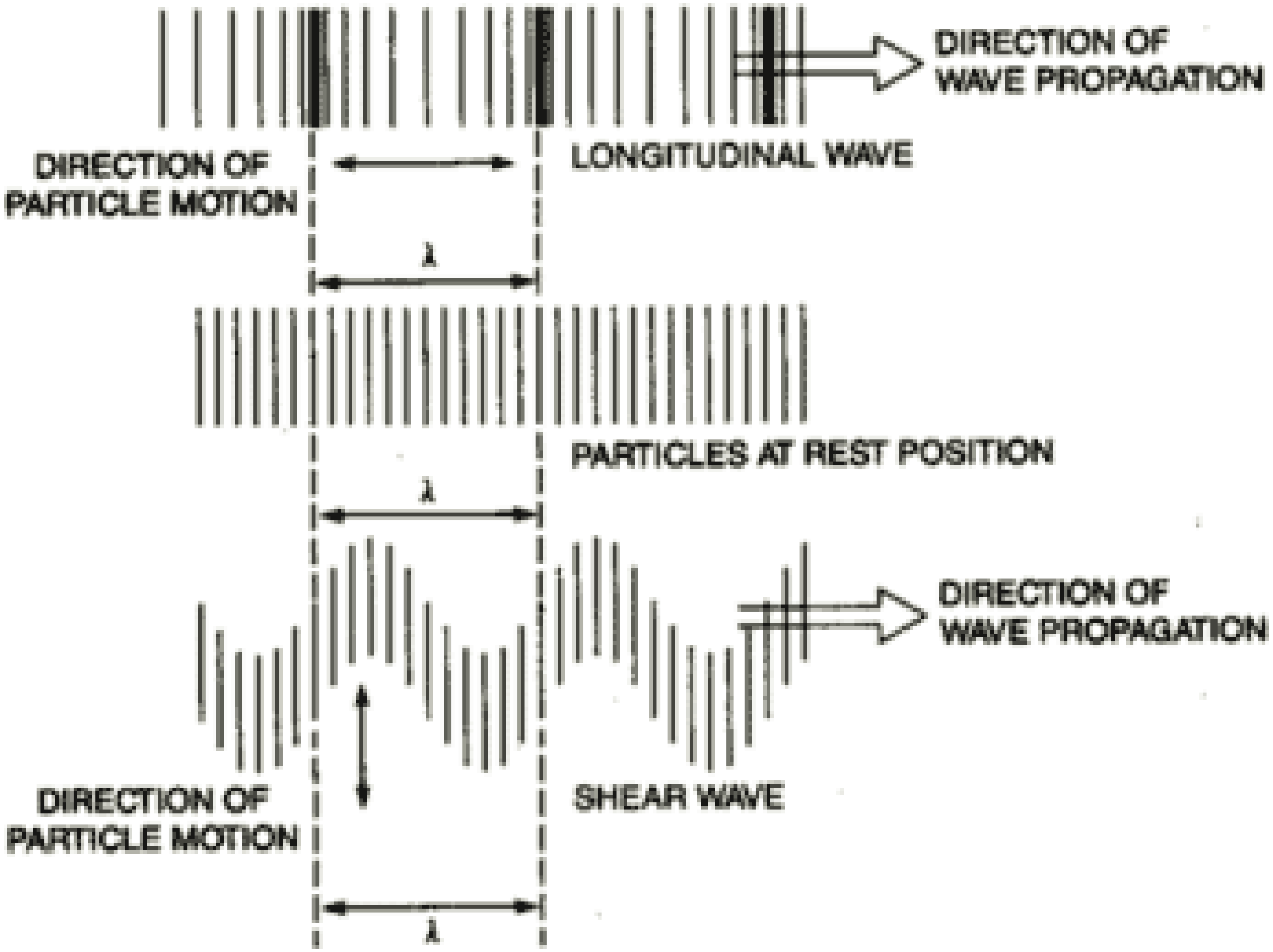
- In *longitudinal waves, the oscillations occur in the longitudinal* direction or the direction of wave propagation.
- Since compression and expansion forces are active in these waves, they are also called pressure or compression waves.
- They are also sometimes called density waves because material density fluctuates as the wave moves.
- Compression waves can be generated in gases, liquids, as well as solids because the energy travels through the atomic structure by a series of compressions and expansion movements.


Wave Travel
Particles Motion

Transverse waves

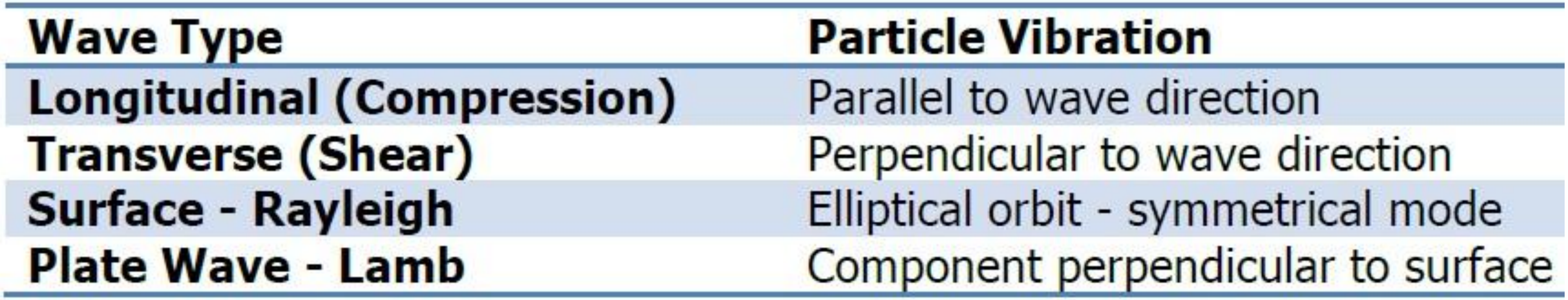
- In the *transverse or shear waves, particles* oscillate at a right angle or transverse to the direction of propagation.
- They require an acoustically solid material for effective propagation, and therefore, are not effectively propagated in materials such as liquids or gasses.
- Shear waves are relatively weak when compared to longitudinal waves.


Wave Travel
Particles Motion


DIRECTION OF WAVE PROPAGATION
DIRECTION OF PARTICLE MOTION
LONGITUDINAL WAVE
λ
PARTICLES AT REST POSITION
λ
DIRECTION OF WAVE PROPAGATION
DIRECTION OF PARTICLE MOTION
SHEAR WAVE
λ

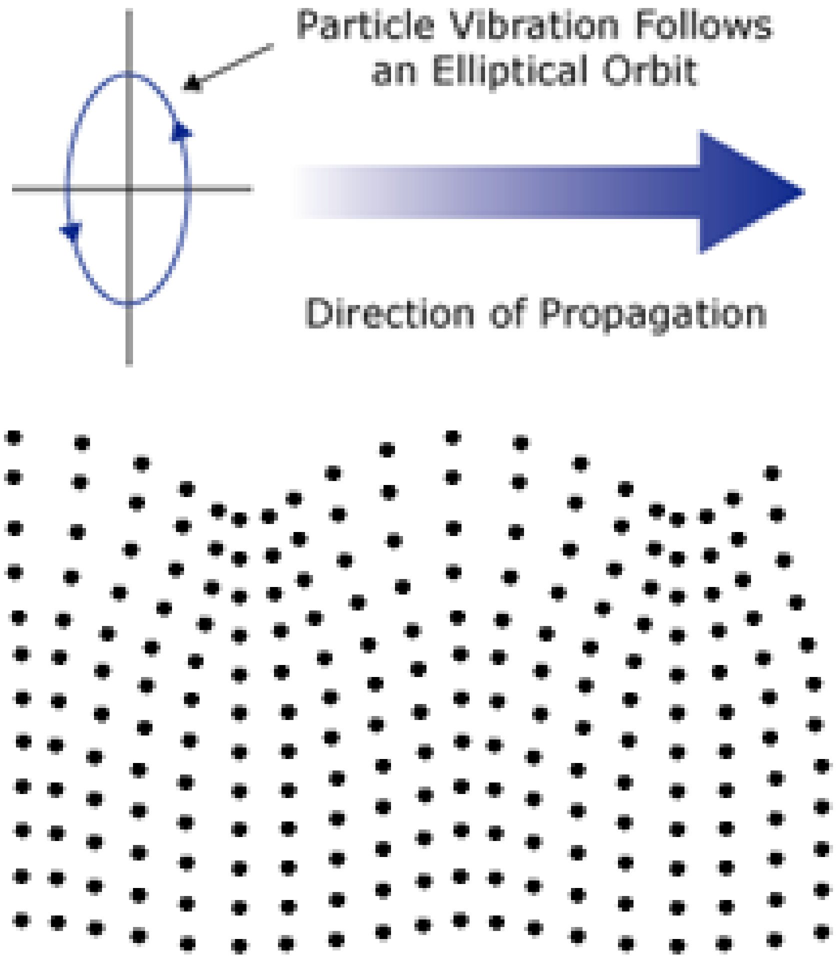
Modes of Sound Wave Propagation

- The propagation of waves is often described in terms of what are called "*wave modes*".
- longitudinal and transverse (shear) waves are most often used in ultrasonic inspection.
- However, at surfaces and interfaces, various types of elliptical or complex vibrations of the particles make other waves possible.
- Some of these wave modes such as **Rayleigh and Lamb waves** are also useful for ultrasonic inspection.



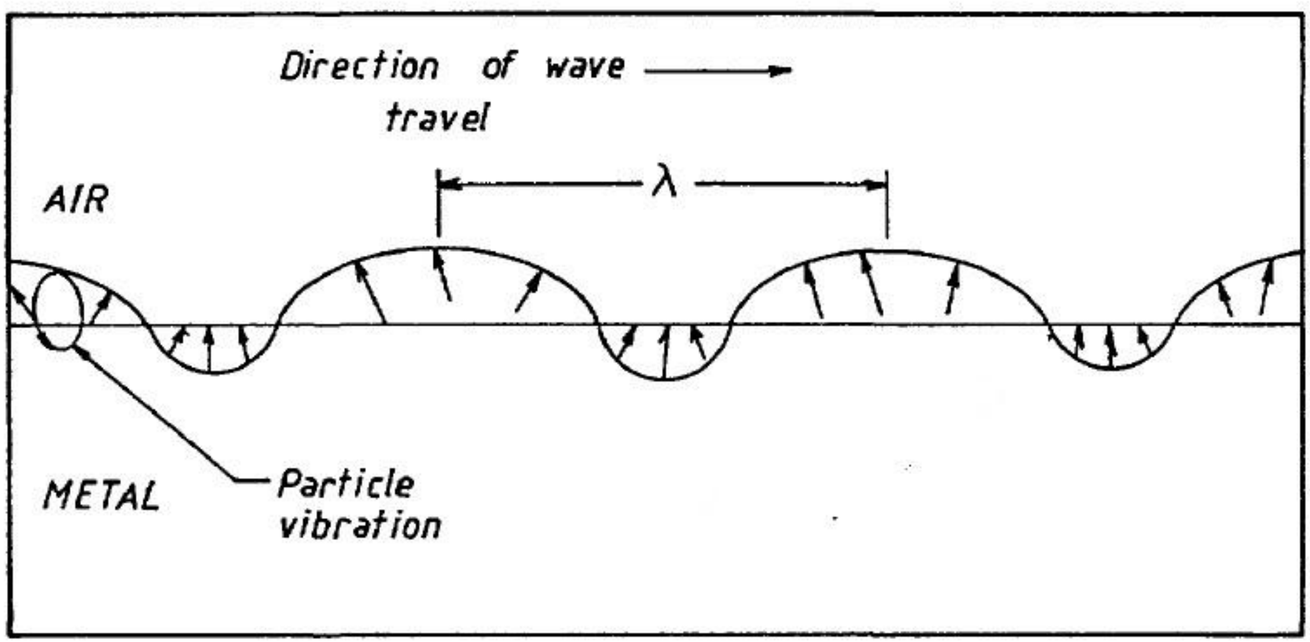
Wave Type	Particle Vibration
Longitudinal (Compression)	Parallel to wave direction
Transverse (Shear)	Perpendicular to wave direction
Surface - Rayleigh	Elliptical orbit - symmetrical mode
Plate Wave - Lamb	Component perpendicular to surface

Surface (or Rayleigh) waves



Surface (or Rayleigh) waves

- Surface waves were first described by Lord Rayleigh.
- These can only travel along a surface bounded on one side by the strong elastic forces of the solid and on the other side by the elastic forces between gas molecules.
- Surface waves, therefore, are essentially nonexistent in a solid immersed in a liquid, unless the liquid covers the solid surface only as a very thin layer.
- The waves have a velocity of approximately 90 per cent that of an equivalent shear wave in the same material,
- and they can only propagate in a region no thicker than about one wave length beneath the surface of the material.



Small arrows indicate directions of particle displacement.
Figure 2.8. Diagram of surface wave propagating at the surface of a metal along a metal - air interface.

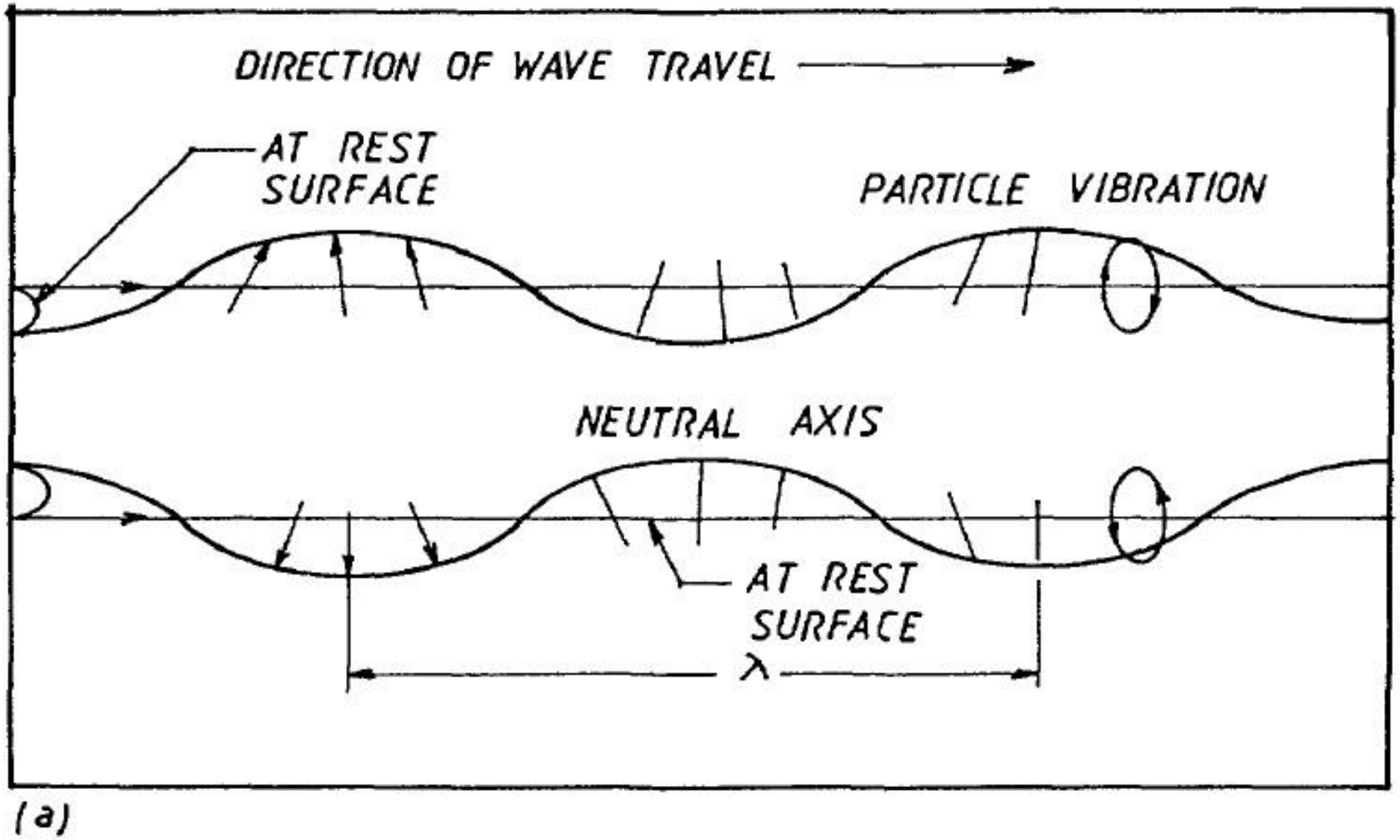
- The major axis of the ellipse is perpendicular to the surface along which the waves are travelling. The minor axis is parallel to the direction of propagation.
- Surface waves are useful for testing purposes because the attenuation they suffer for a given material is lower than for an equivalent shear or longitudinal wave,
- and because they can flow around corners and thus be used for testing quite complicated shapes.
- Only surface or near surface cracks or defects can be detected.

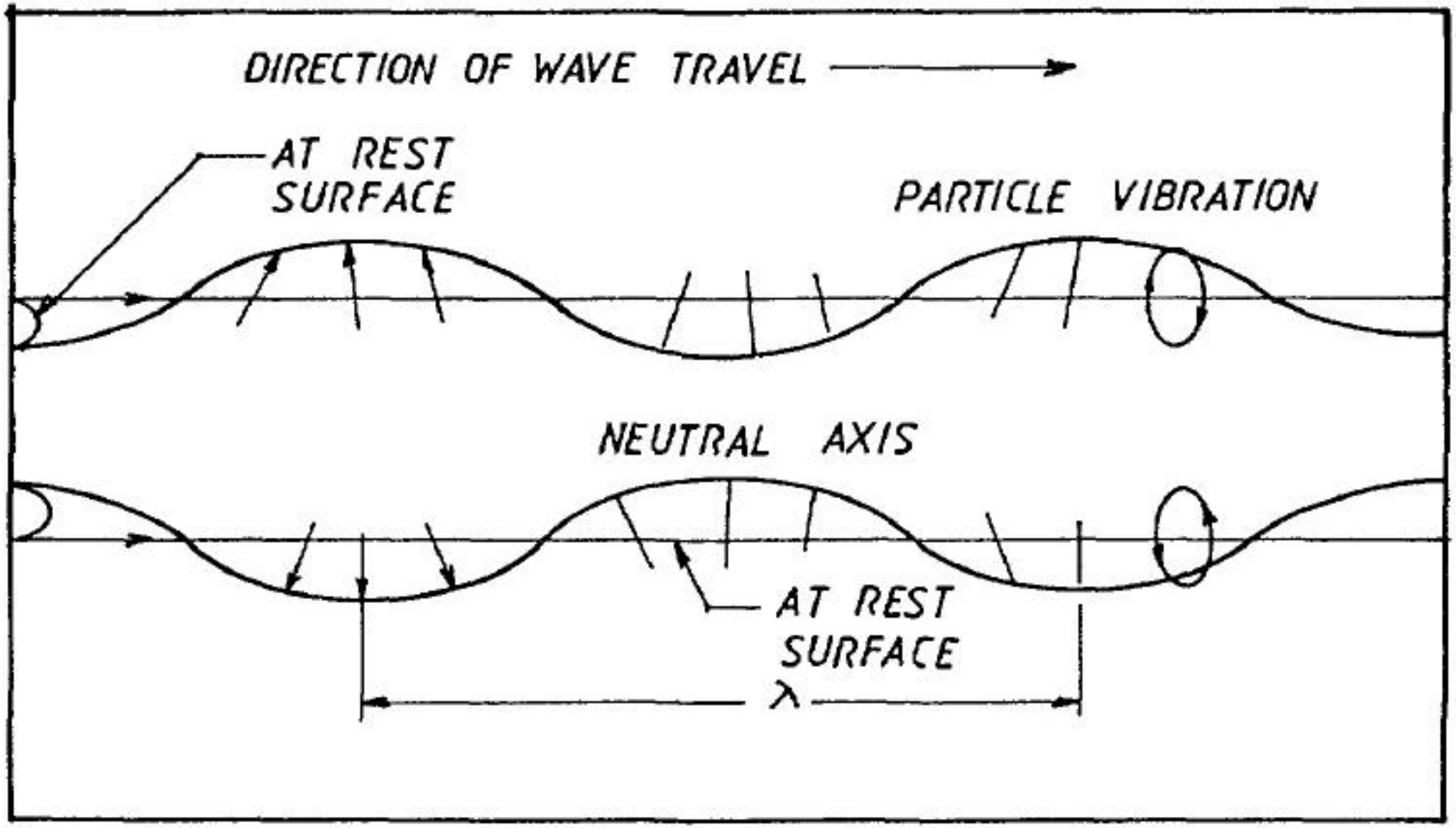
Plate (or Lamb) waves

- If a surface wave is introduced into a material that has a thickness equal to 3 wavelengths, or less, then a plate wave results.
- The material begins to vibrate as a plate i.e. the wave encompasses the entire thickness of the material.
- developed by Horace Lamb in 1916.
- Unlike longitudinal, shear or surface waves, the velocities of these waves through a material are dependent not only on the type of material,
- but also on the material thickness, the frequency and the type of wave.

- Plate or Lamb waves exist in many complex modes of particle movement.
- The two basic forms of Lamb waves are :
- (a) symmetrical or dilatational : and
- (b) asymmetrical or bending.
- The form of the wave is determined by whether the particle motion is symmetrical or asymmetrical with respect to the neutral axis of the test piece.

Symmetrical Plate wave



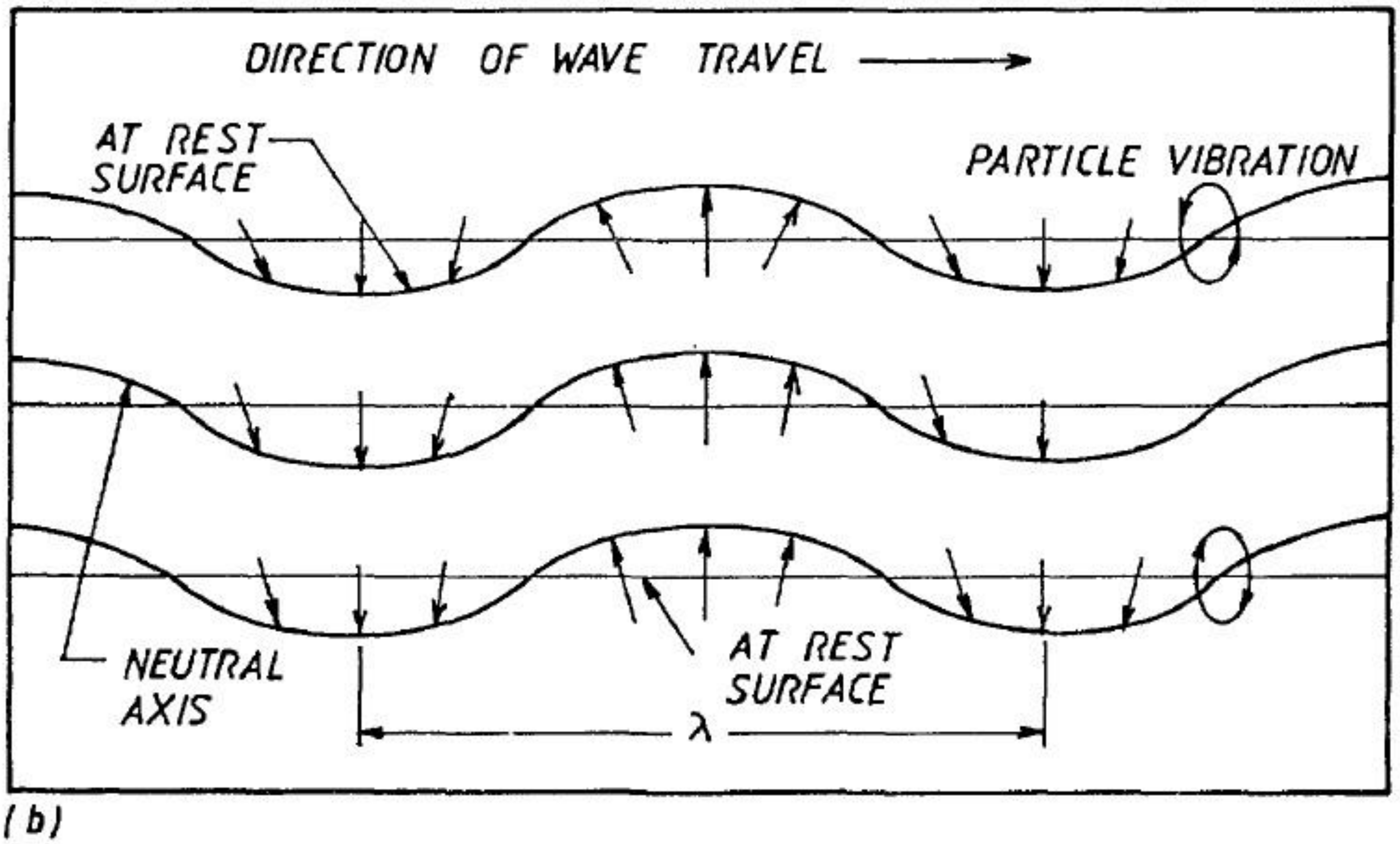


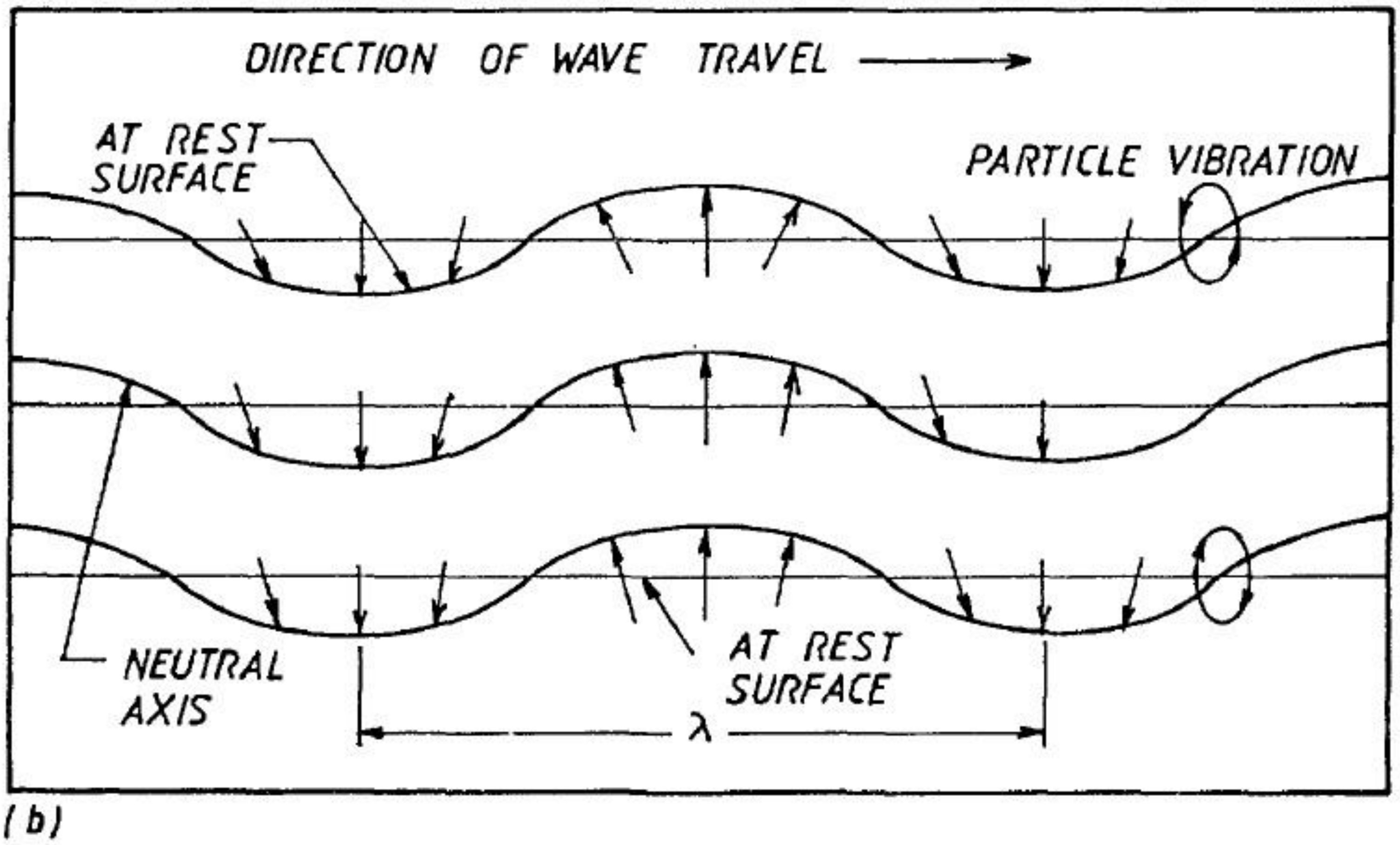
(a)

In symmetrical Lamb (dilatational) waves, there is a longitudinal particle displacement along neutral axis of the plate and an elliptical particle displacement on each surface.

Successive “thickening” and “thinning” in the plate.

Asymmetrical Plate wave





In asymmetrical(bending) Lamb waves, there is a shear particle displacement along the neutral axis of the plate and an elliptical particle displacement on each surface

Properties of Acoustic Waves:

Wave length, frequency and Velocity

- Frequency :
- The frequency of a wave is the same as that of the vibration or oscillation of the atoms of the medium in which the wave is travelling.
- It is usually denoted by the letter ‘ f ’ and is expressed as the number of cycles per second.
- The International term for a cycle per second is named Hertz (Hz).
- 1 H z =1 cycle per second
- 1 KHz = 1000 Hz = 1000 cycles per second
- 1 MHz = 1000000 Hz = 1000000 cycles per second

- Wave Length:
- During the time period of vibration T, a wave travels a certain distance in the medium.
- This distance is defined as the wavelength of the wave and is denoted by Greek letter ‘ **λ** ‘.

- Velocity:
- The speed with which energy is transported between two points in a medium by the motion of waves is known as the velocity of the waves.
- It is usually denoted by the letter ‘ V ‘.

Relation between wave length, frequency and velocity

- The wavelength is directly proportional to the velocity of the wave and inversely proportional to the frequency of the wave.
- This relationship is shown by the equation:
- $\lambda = V/f$ Where; λ : wavelength (*m),* V: velocity (*m/s) and* f: frequency (*Hz).*
- The equation is valid for all kinds of waves.

- The velocity of propagation of longitudinal, transverse and surface waves depends on the density of the material.
- Velocities of longitudinal, transverse and surface waves are given by the following equations.

For longitudinal waves, the speed of sound in a solid material can be found as:

$$\boxed{V_L = \sqrt{\frac{E(1-\upsilon)}{\rho(1+\upsilon)(1-2\upsilon)}}}$$

Where;

V_L : speed of sound for longitudinal waves (*m/s*)
E : Young’s modulus (*N/m*^{2})
υ : Poisson’s ratio

While for shear (*transverse*) waves, the speed of sound is found as:

$$\boxed{V_T = \sqrt{\frac{G}{\rho}}}$$

Where;

V_T : speed of sound for shear waves (*m/s*)

G : Shear modulus of elasticity (N/m^2); $G = E/2(1+\upsilon)$

- Velocity of surface waves, $V_s = 0.9\ V_T$
- Longitudinal waves travel faster than shear waves (longitudinal waves are approximately twice as fast as shear waves).

Acoustic Impedence

- The resistance offered to the propagation of an ultrasonic wave by a material is known as the acoustic impedence (Z).
- Z = ρV, ρ is the density of the material.
- Acoustic impedance is important in:
- the determination of acoustic transmission and reflection at the boundary of two materials having different acoustic impedances.
- the design of ultrasonic transducers.
- assessing absorption of sound in a medium.

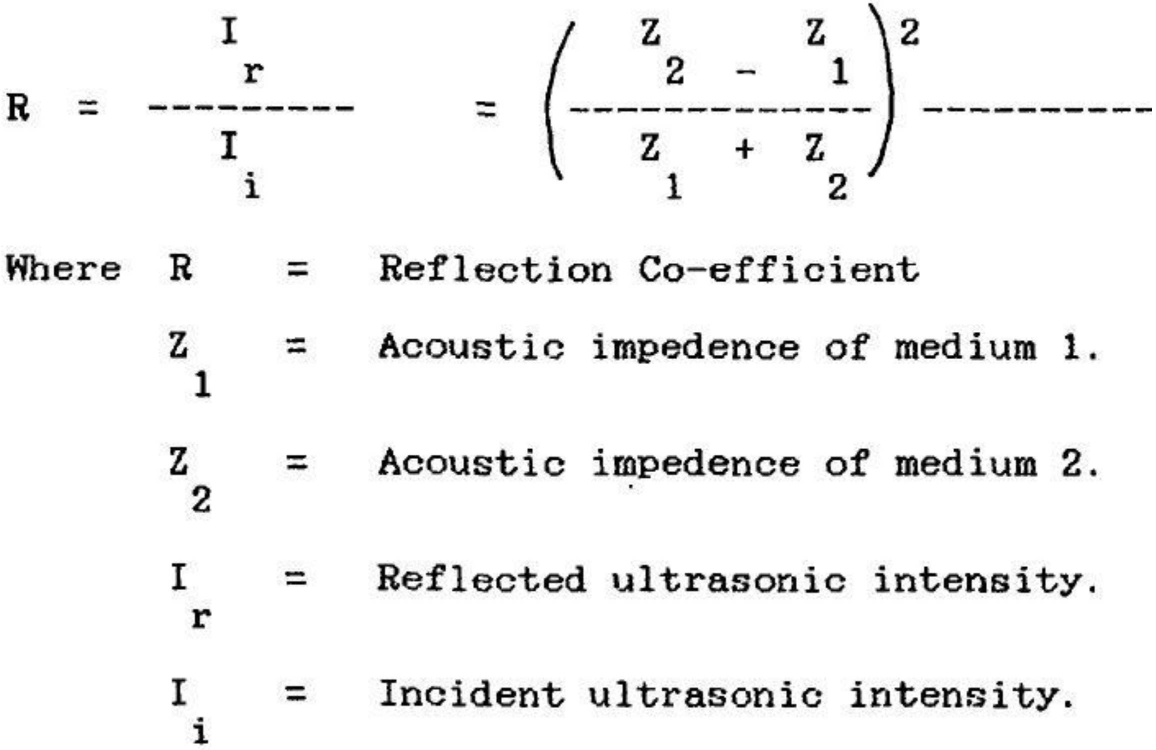
Behaviour of Ultrasonic waves

- Analysis of a wave in an extended substance is possible only theoretically because in practice every substance terminates somewhere.
- ie, it has a boundary, at the boundary the propagation of the wave is disturbed.
- If the material concerned borders on an empty space, no wave can go beyond this boundary,
- Because the transmission requires the presence of particles of a material.
- At such a free boundary, the wave will return in one form or another.
- If another material adheres to it, wave can be propagated, although in a changed direction, intensity and mode.

Reflection and Transmission at Normal Incidence

- When ultrasonic waves are incidence at right angles to the boundary {i.e normal incidence) of two media of different acoustic impedances, then some of the waves are reflected and some are transmitted across the boundary.
- The amount of ultrasonic energy that is reflected or transmitted depends on the difference between the acoustic impedances of the two media.
- If this difference is large then most of the energy is reflected and only a small portion is transmitted across the boundary.
- While for a small difference in the acoustic impedences most of the ultrasonic energy is transmitted and only a small portion is reflected back.

- Quantitatively the amount of ultrasonic energy which is reflected when ultrasonic waves are incident at the boundary of two media of different acoustic impedances is given by :-



$$R = \frac{I_r}{I_i} = \left(\frac{Z_2 - Z_1}{Z_1 + Z_2}\right)^2$$

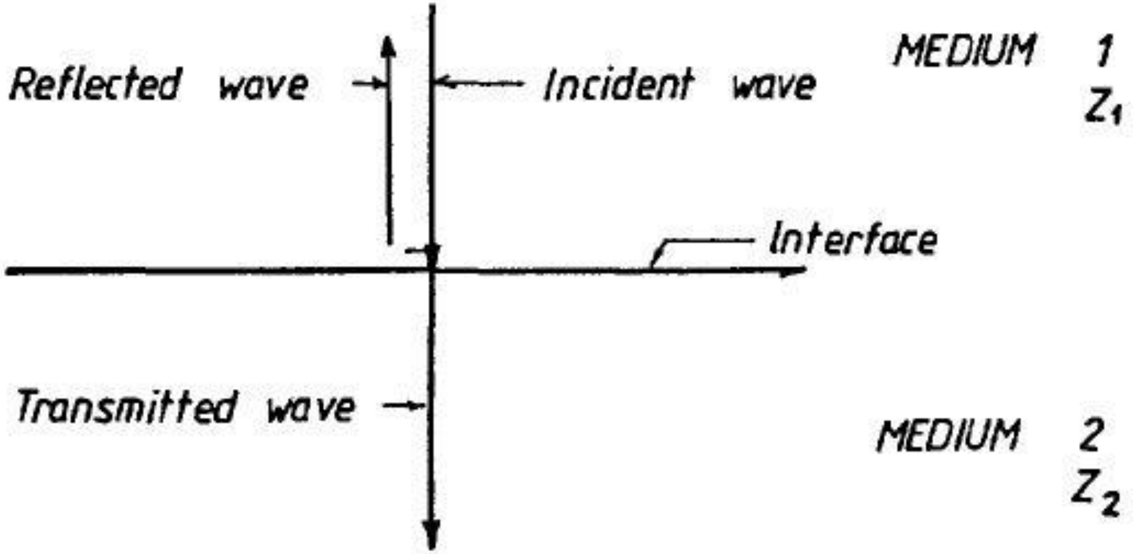
Where R = Reflection Co-efficient

Z_1 = Acoustic impedence of medium 1.

Z_2 = Acoustic impedence of medium 2.

I_r = Reflected ultrasonic intensity.

I_i = Incident ultrasonic intensity.



2.10 Reflection and Transmission at Normal Incidence.

The amount of energy that is transmitted across the boundary is given by the relation :

$$T = \frac{I_t}{I_i} = \frac{4 Z_1 Z_2}{\left(Z_1 + Z_2\right)^2} \text{ ------------- } (2.15)$$

Where

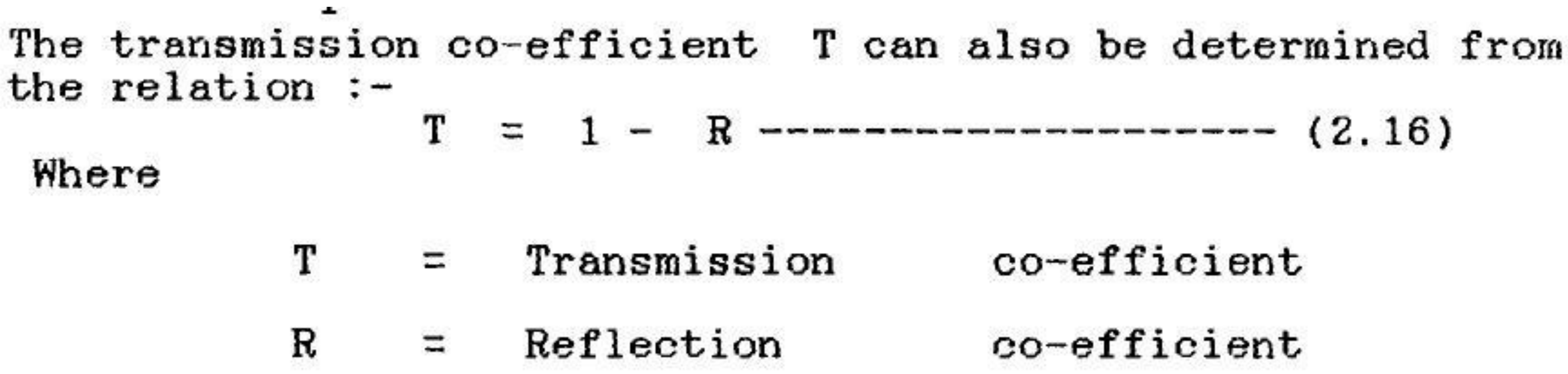
T = Transmission co-efficient.

Z_1 = Acounstic impedence of medium 1

Z_2 = Acounstic impedence of medium 2

I_t = Transmitted ultrasonic intensity.

I_i = Incident ultrasonic intensity.



The transmission co-efficient T can also be determined from the relation :-

$$T = 1 - R \quad \text{--------------------} \quad (2.16)$$

Where

T = Transmission co-efficient

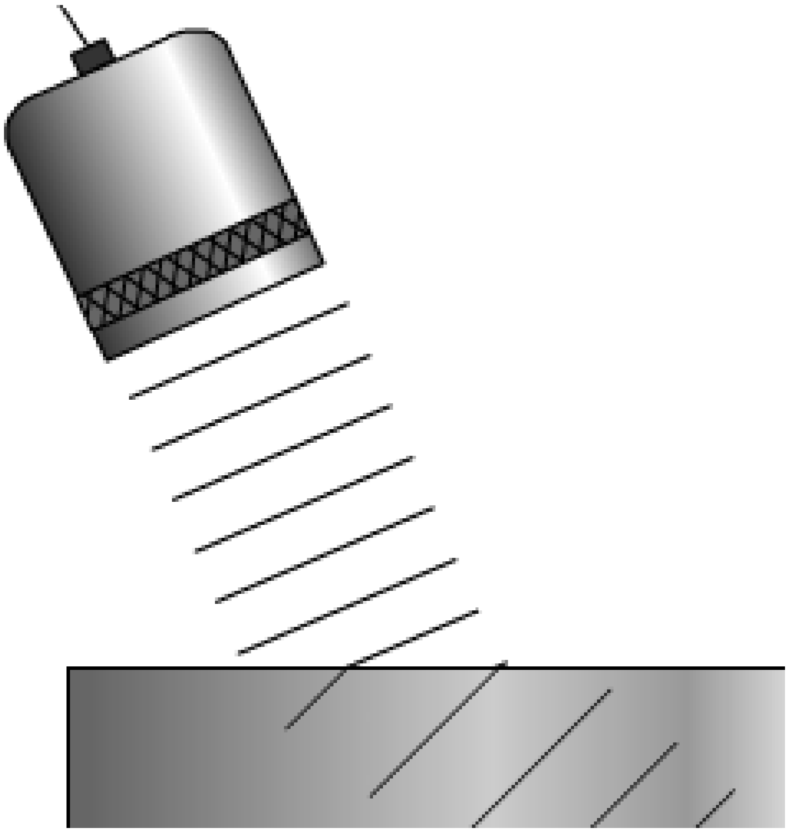
R = Reflection co-efficient

Reflection and Transmission At Oblique Incidence

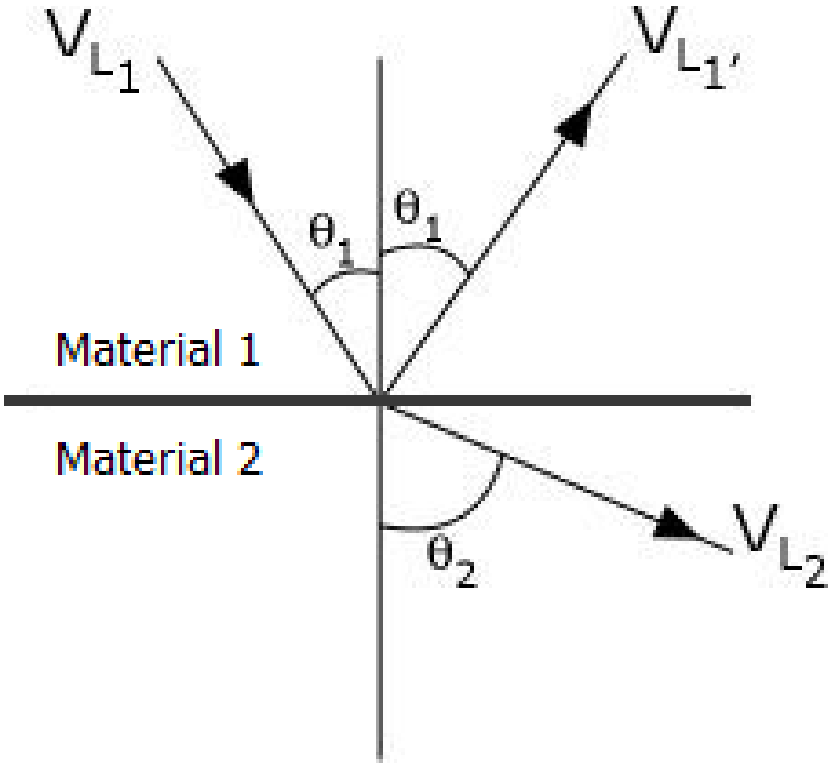
- If ultrasonic waves strike a boundary at an oblique angle, than the reflection and transmission of the waves become more complicated than that with normal incidence.
- At oblique incidence the phenomena of mode conversion (i.e a change in the nature of the wave motion) and refraction (a change in the direction of wave propagation) occur.

Refraction and Snell's Law

- When an ultrasonic wave passes through an interface between two materials at an oblique angle, both reflected and refracted waves are produced.



- Refraction takes place at an interface of two materials due to the difference in acoustic velocities between the two materials.
- When plane sound waves traveling in one material enters a second material that has a higher acoustic velocity,
- as the wave encounters the interface between these two materials, the portion of the wave in the second material is moving faster than the portion of the wave that is still in the first material.
- As a result, this causes the wave to bend and change its direction (*this is referred to as "refraction*").


V_{L_1}
$V_{L_{1'}}$
θ_1
θ_1
Material 1
Material 2
θ_2
V_{L_2}

- *Snell's Law* describes the relationship between the angles and the velocities of the waves.
- Snell's law equates the ratio of material velocities to the ratio of the sine's of incident and refracted angles, as shown in the following equation:

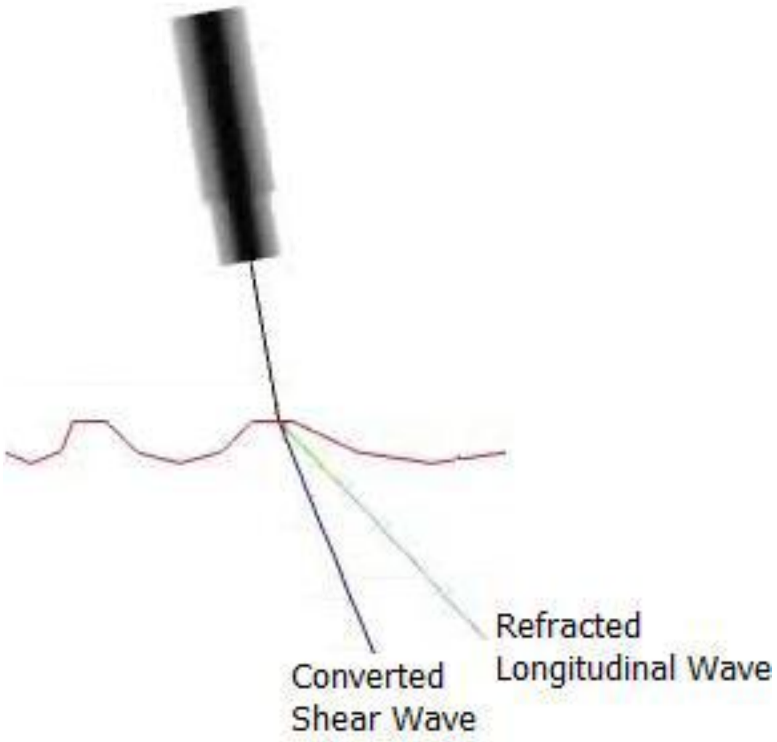
$$\boxed{\frac{\sin\theta_1}{V_{L_1}} = \frac{\sin\theta_2}{V_{L_2}}}$$

V_{L_1} & V_{L_2} : the longitudinal wave velocities in the first and second materials respectively

θ_1 & θ_2 : the angles of incident and refracted waves respectively

Mode Conversion

- When sound travels in a solid material, one form of wave energy can be transformed into another form.
- For example, when a longitudinal wave hits an interface at an angle, some of the energy can cause particle movement in the transverse direction to start a shear wave.
- *Mode conversion* occurs when a wave encounters an interface between materials of **different acoustic impedances** and the incident angle is not normal to the interface.
- It should be noted that mode conversion occurs "*every time*" a wave encounters an interface at an angle.
- This mode conversion occurs for both the portion of the wave that passes through the interface and the portion that reflects off the interface.


Refracted Longitudinal Wave
Converted Shear Wave

- when sound waves pass through an interface between materials having different acoustic velocities, **refraction** takes place at the interface.
- The larger the difference in acoustic velocities between the two materials, the more the sound is refracted.
- However, the converted shear wave is not refracted as much as the longitudinal wave because shear waves travel slower than longitudinal waves.
- Therefore, the velocity difference between the incident longitudinal wave and the shear wave is not as great as it is between the incident and refracted longitudinal waves.
- Also note that when a longitudinal wave is reflected inside the material, the reflected shear wave is reflected at a smaller angle than the reflected longitudinal wave.
- This is also due to the fact that the shear velocity is less than the longitudinal velocity within a given material.

Snell's Law holds true for shear waves as well as longitudinal waves and can be written as follows:

$$\boxed{\frac{\sin\theta_1}{V_{L_1}} = \frac{\sin\theta_2}{V_{L_2}} = \frac{\sin\theta_3}{V_{S_1}} = \frac{\sin\theta_4}{V_{S_2}}}$$

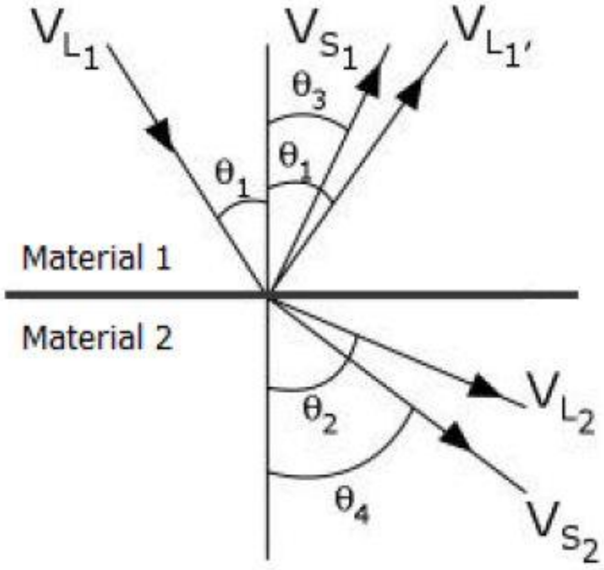
Where;

V_{L_1} & V_{L_2} : the longitudinal wave velocities in the first and second materials respectively

V_{S_1} & V_{S_2} : the shear wave velocities in the first and second materials respectively

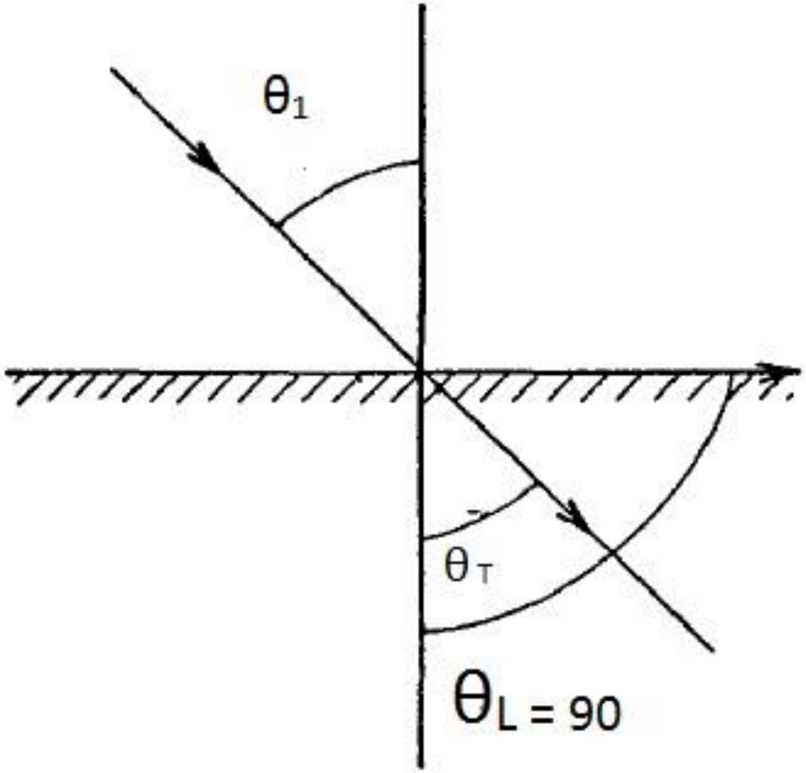
θ_1 & θ_2 : the angles of incident and refracted longitudinal waves respectively

θ_3 & θ_4 : the angles of the converted reflected and refracted shear waves respectively



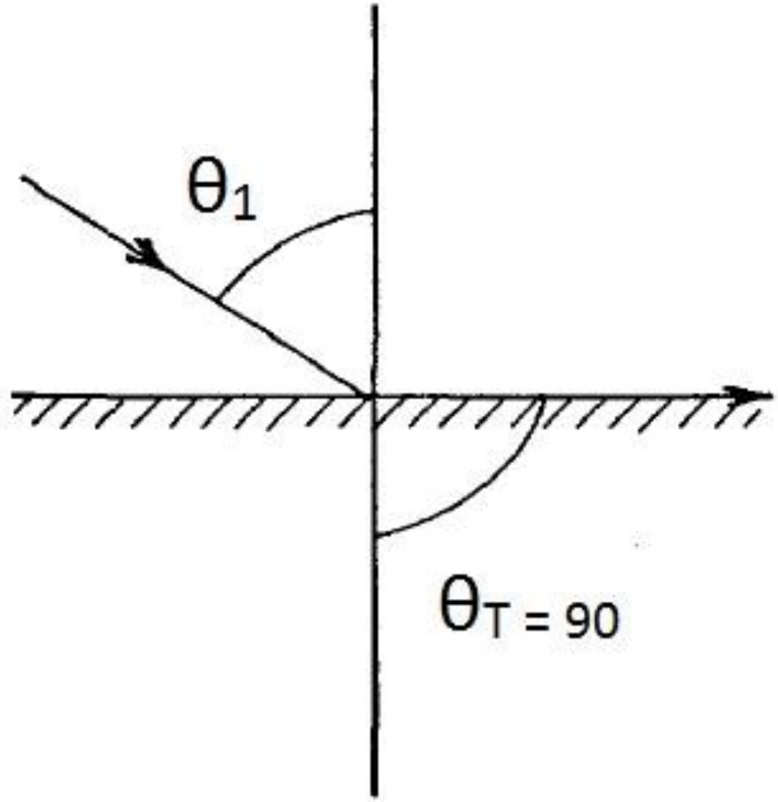
Critical Angles

- If the angle of incidence θ_1 is small, ultrasonic waves travelling in a medium undergo the phenomena of mode conversion and refraction upon encountering a boundary with another medium.
- This results in the simultaneous propagation of longitudinal and transverse waves at different angles of refraction in the second medium.
- As the angle of incidence is increased, the angle of refraction also increases.
- When the refraction angle of a longitudinal wave reaches 90° the wave emerges from the second medium and travels parallel to the boundary.
- The angle of incidence at which the refracted longitudinal wave emerges, is called the **first critical angle.**



a)· First Critical Angle

- If the angle of incidence is further increased the angle of refraction for the transverse wave also approaches 90 .
- The value of θ_1 for which the angle of refraction of the transverse wave is exactly 90 , is called the **second critical angle**.
- At the second critical angle the refracted transverse wave emerges from the medium and travels parallel to the boundary.
- The transverse wave, has become a surface or Rayleigh wave.



b).Second Critical Angle

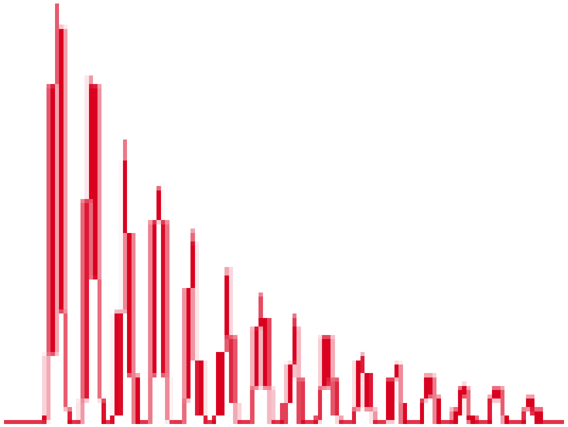
Attenuation of Sound Waves

- When sound travels through a medium, its intensity diminishes with distance.
- In idealized materials, sound pressure (signal amplitude) is reduced due to the spreading of the wave.
- In natural materials, however, the sound amplitude is further weakened due to the scattering and absorption.
- Scattering is the reflection of the sound in directions other than its original direction of propagation.
- Absorption is the conversion of the sound energy to other forms of energy.
- The combined effect of scattering and absorption is called attenuation.

Scattering of Ultrasonic Waves

- The scattering due to the fact that the material in which the ultrasonic wave is travelling is not absolutely homogeneous.
- The inhomogeneities can be anything that will present a boundary between two materials of different acoustic impedance such as an inclusion or pores and possibly grain boundaries containing contaminants.
- Certain materials are inherently inhomogeneous, such as cast iron which is composed of a matrix of grains and graphit particles which differ greatly in density and elasticity.
- It is possible to encounter scattering in Anisotropic materials.
- Materials exhibiting these qualities not only decrease the returned ultrasonic signal because of scattering, but also often produce numerous small echoes which may mask or "camouflage" real indications.

- **Absorption Of ultrasonic Waves**
- Absorption of ultrasonic waves is the result of the conversion of a portion of the sound energy into heat.
- In any material not at absolute zero temperature the particles are in random motion as a result of the heat content of the material.
- As the temperature increases, there will be an increase in particle activity.
- As an ultrasound wave propagates through the material it excites the particles.
- As these particles collide with unexcited particles, energy is transmitted causing them to oscillate faster and through larger distances.
- This motion persists after the sound wave has passed on, so energy of the passing wave has been converted to heat in the material.



- Attenuation is generally proportional to the square of sound frequency.
- The amplitude change of a decaying plane wave can be expressed as:

$$\boxed{A = A_0 e^{-\alpha z}}$$

Where;

A_0 : initial (*unattenuated*) amplitude
α : attenuation coefficient (*Np/m*)
z : traveled distance (*m*)

Np (Neper) is a logarithmic dimensionless quantity and it can be converted to Decibels by dividing it by 0.1151.

Decibel is a more common unit when relating the amplitudes of two signals.

Ultrasonic Inspection Methods

I. <u>Contact type techniques</u>

Probes are used in direct contact with the test specimen through a film of couplant.

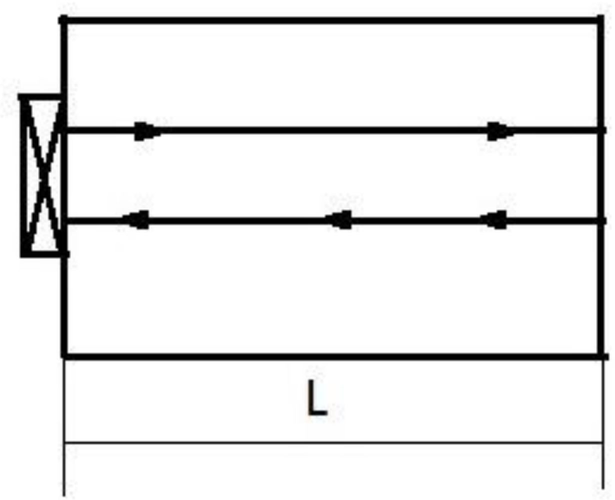
1. Normal Beam Pulse-echo
2. Normal Beam through transmission
3. Angle Beam Pulse-echo
4. Angle Beam through transmission

II. Immersion Testing Techniques

1. Immersion technique
2. Bubbler technique
3. Wheel transducer technique.

1. Normal Beam Pulse-echo testing

- The ultrasonic energy is coupled to the component being inspected through a couplant (oil, grease or glycerine).
- The couplant transmits the ultrasound between the face of the transducer and the surface of the component.
- When ultrasonic energy travels through a test sample and strikes a discontinuity, part of the energy will be reflected back and the remaining part propagates in the material.
- Ultra sonic energy that is reflected and returned to the probe is the source of defect indication shown on the instrument screen.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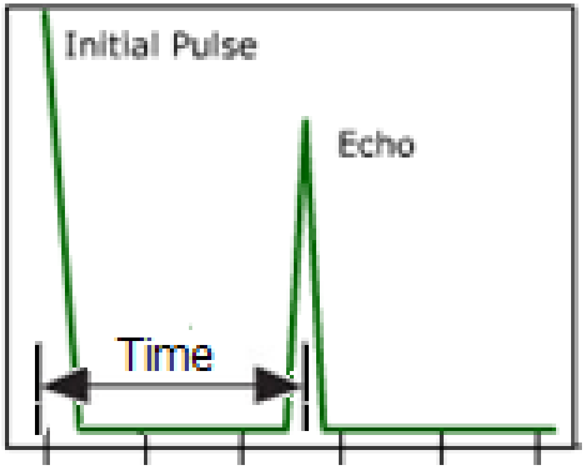
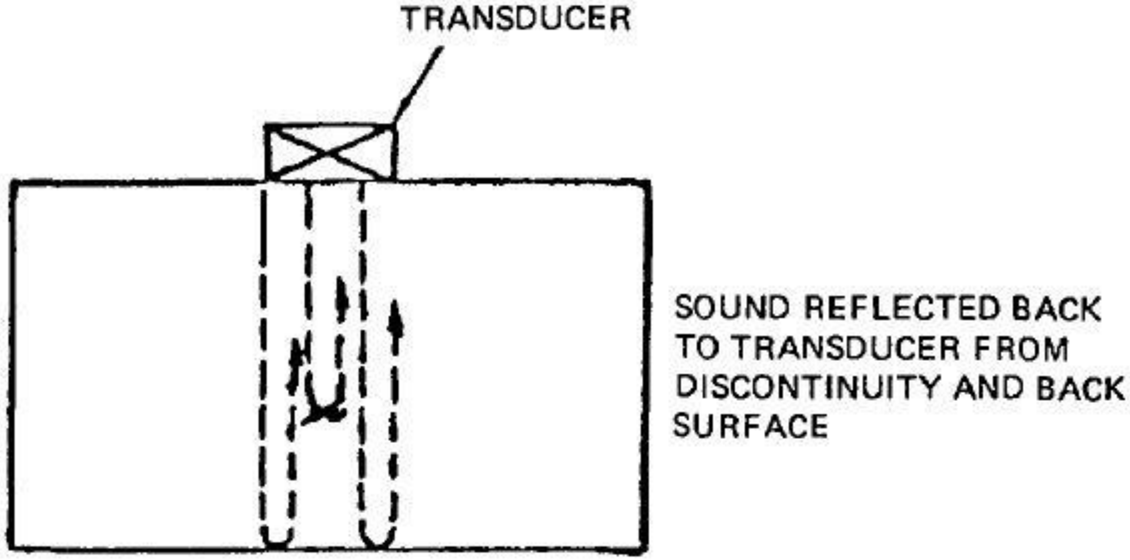

Initial Pulse
Echo
Time

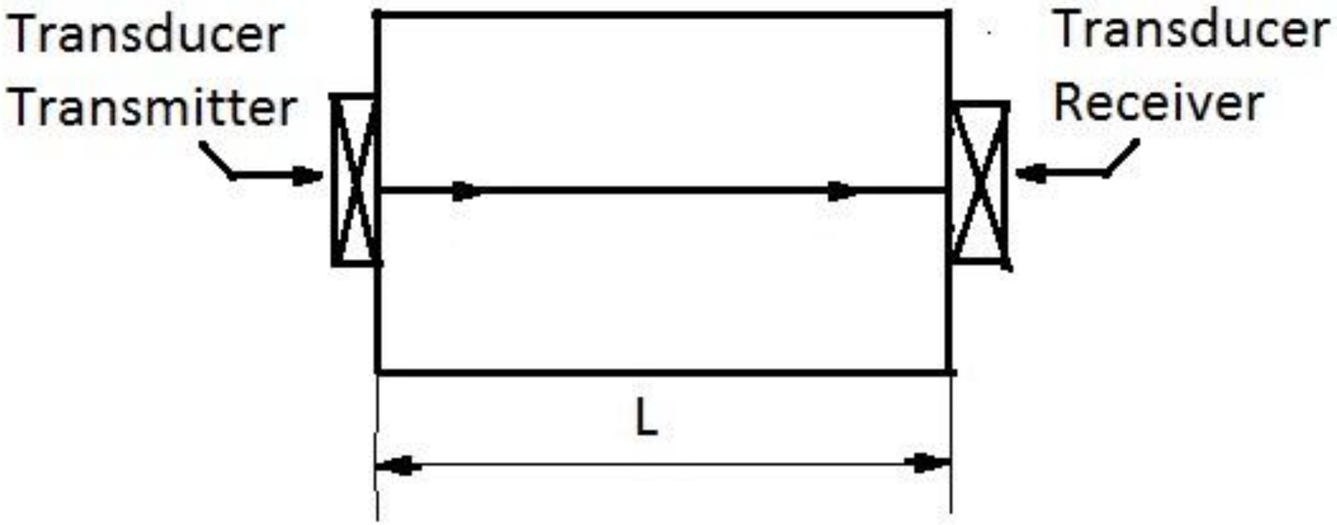


3.13 Single Transducer Pulse-Echo Technique.

- Pulse-echo ultrasonic measurements can determine the location of a discontinuity by accurately measuring the time required for an ultrasonic pulse to travel, reflect and be returned to the transducer.
- The two-way transit time measured is divided by two to account for the down-and-back travel path and multiplied by the velocity of sound in the test material.
- The result is expressed as: $d = (Vt/2)$
- Where d is the distance from the surface to the discontinuity in the test piece, V is the velocity of sound waves in the material, and t is the measured round-trip transit time.

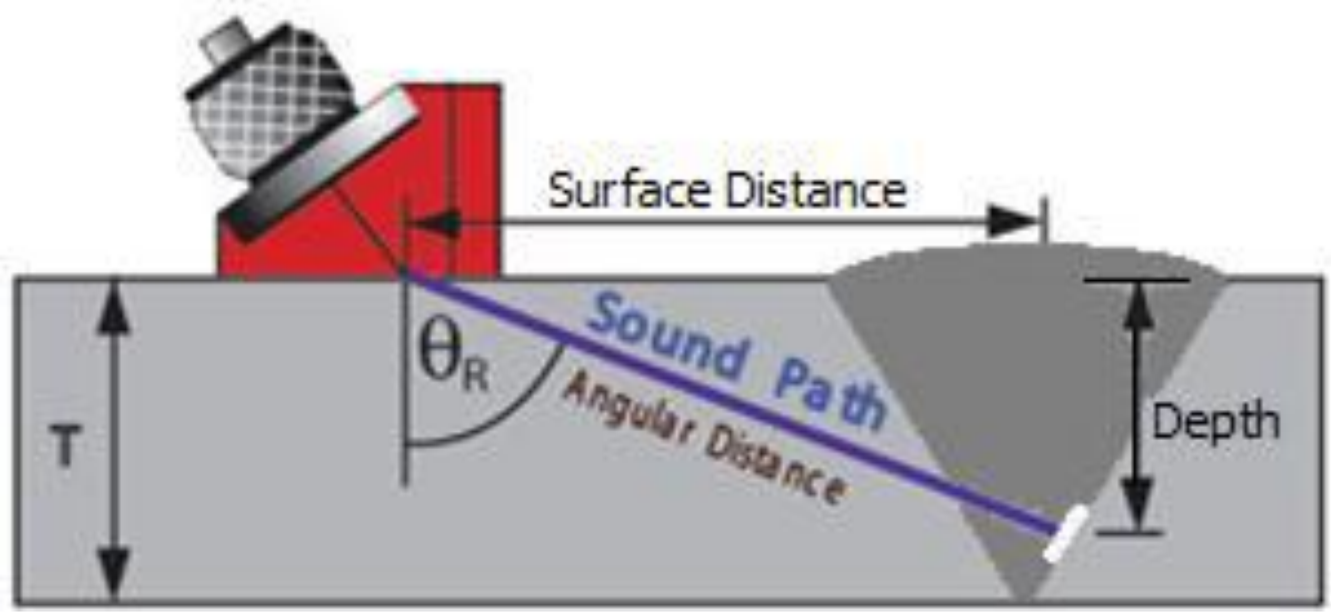
2. Normal incident Through Transmission Technique

- Many a times pulse-echo technique may not provide required test information.
- This occur when a flaw does not provide a suitable reflection surface or where the orientation or location of the flow is not favorable for detection using single probe.
- Also highly attenuating materials are tested using through transmission technique.
- The technique is often used in large castings and highly attenuating materials.


Transducer
Transmitter
Transducer
Receiver
L

3. Angle Beam Pulse-echo Testing

- Angle beam transducers provide access to areas that are inaccessible to normal beam probes.
- Angle beam inspection is accomplished with shear wave probes.
- Transverse (shear) waves at various angles of refraction between 35° and 80° are used to locate defects whose orientation is not suitable for detection by normal bea techniques.


Surface Distance
Sound Path
Angular Distance
θ_R
T
Depth

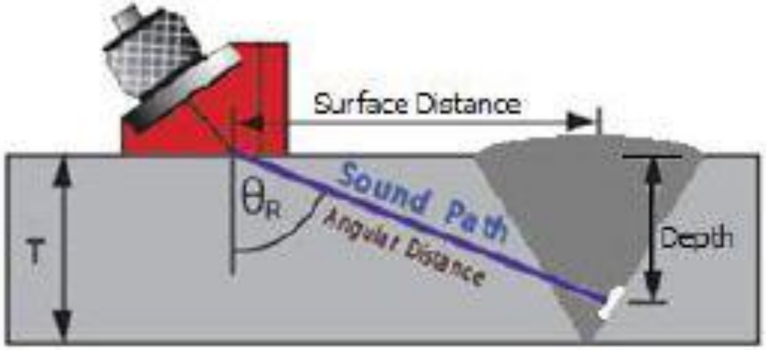
- If a reflection occurs before the sound waves reach the backwall, the reflection is usually referred to as “first leg reflection”.
- The angular distance (Sound Path) to the reflector can be calculated using the same formula used for normal beam transducers (but of course using the shear velocity instead of the longitudinal velocity) as:
- Sound path = $(V_T t)/2$, where V_T is the shear sound velocity in the material.

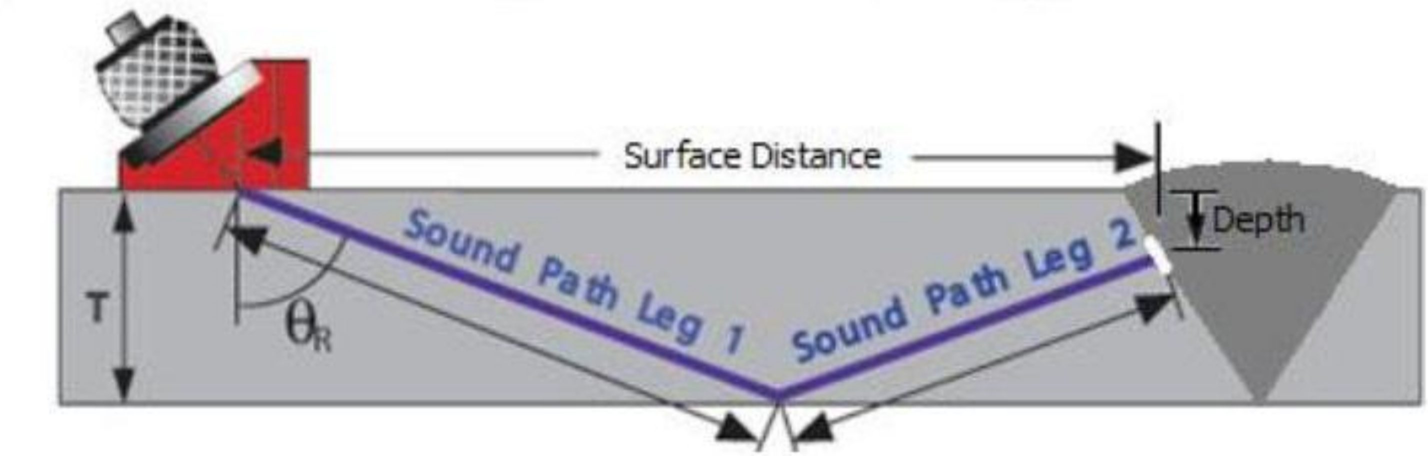
Knowing the angle of refraction for the transducer, the surface distance to the reflector and its depth can be calculated as:

$$\boxed{Surface\ Distance = Sound\ Path\ \times \sin\theta_R}$$

$$\boxed{Depth_{1^{st}\ leg} = Sound\ Path\ \times \cos\theta_R}$$

where θ_R is the angle of refraction.



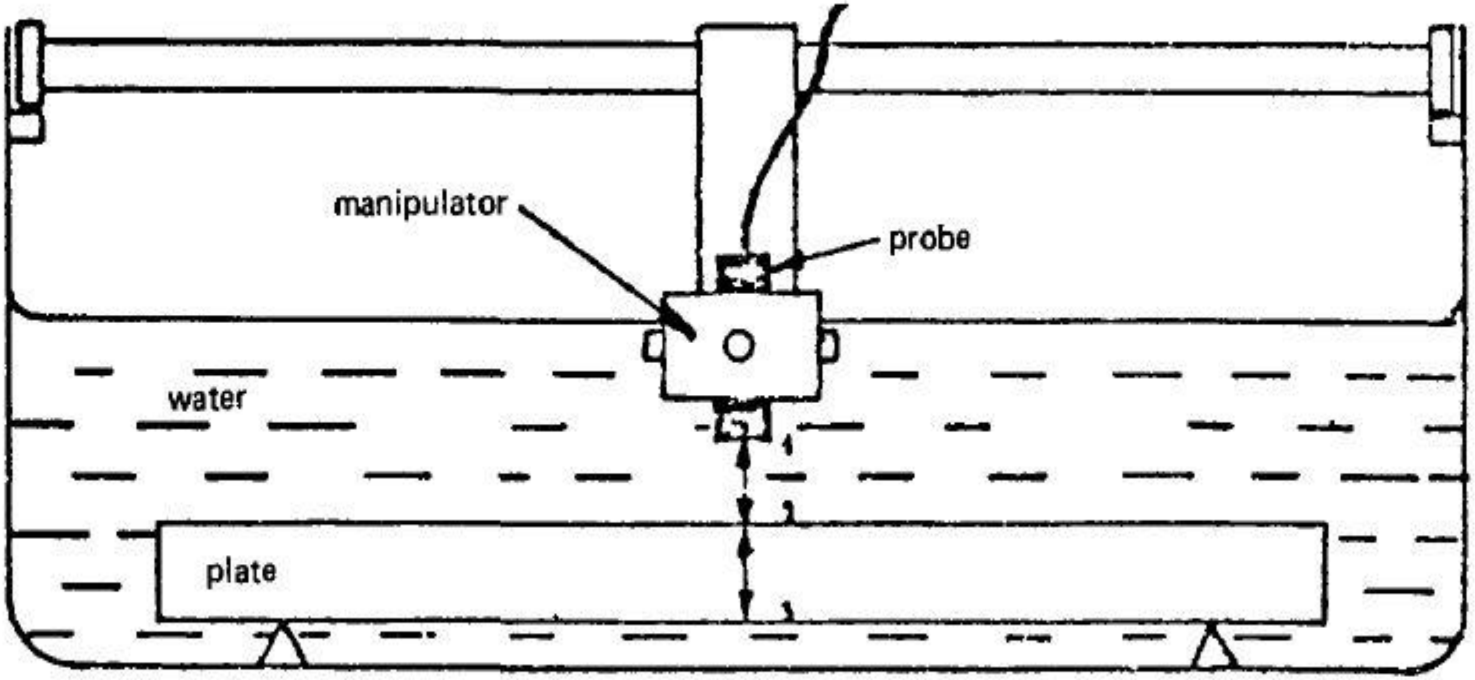
- If a reflector came across the sound beam after it has reached and reflected off the backwall, the reflection is usually referred to as “second leg reflection”.
- In this case, the “Sound Path” (the total sound path for the two legs) and the “Surface Distance” can be calculated using the same equations given above, however, the “Depth” of the reflector will be calculated as:
- 

$$\boxed{Depth_{2^{nd}\ leg} = 2\,T - (Sound\ Path\ \times \cos\theta_R)}$$

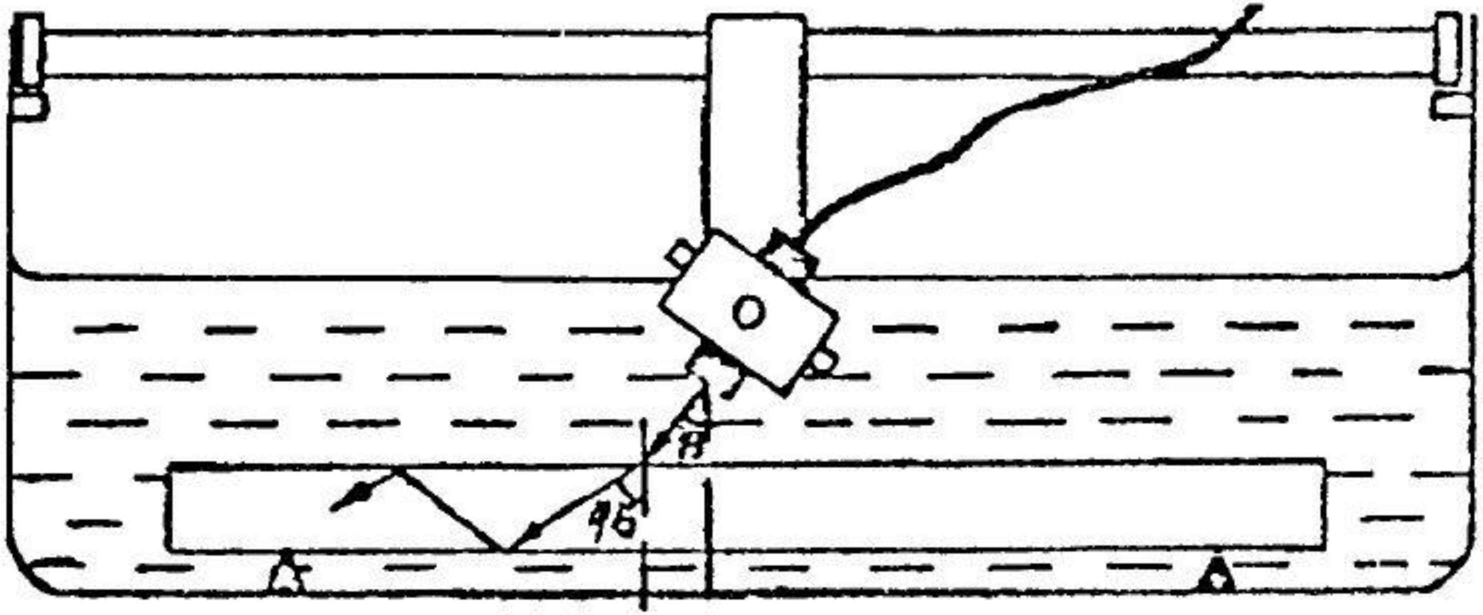
II. Immersion Testing Techniques

1. Immersion testing

- In immersion testing, a water proof probe is used with water path or column acting as a couplant.
- Both the transducer and specimen are immersed in water and the beam is transmitted through the water as medium in to the material.
- Either a normal beam technique for generating longitudinal waves or an angle beam technique for generating transverse waves can be used.
- Appropriate setting of distance between the test specimen and probe is very important.
- This distance is adjusted so that time required to send the beam through water must be greater than the time required by beam to travel through test specimen
- Mathematically, $D = (t/4) + (1/4)$ mm



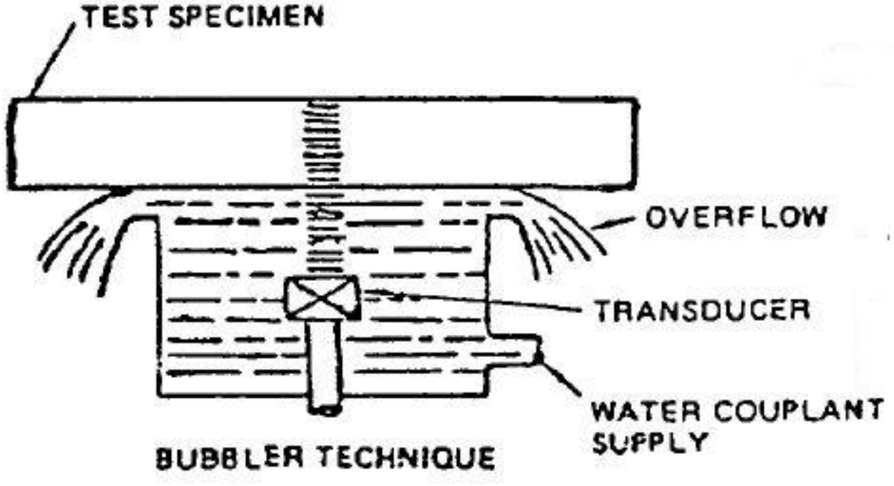
Normal beam technique



Angle beam technique

2. Bubbler or squirter technique

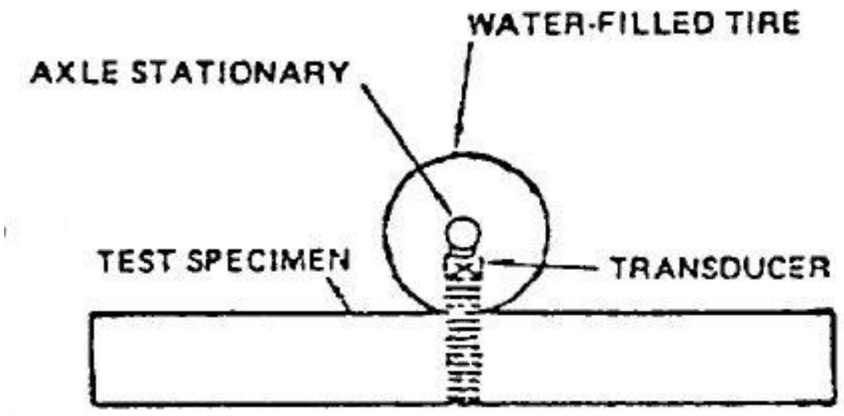
- The ultrasonic beam is directed through a water column in to the test specimen.



- This technique is usually used with an automated system for high speed scanning of plate, sheet, strip, cylindrical forms and other regularly shaped forms.
- The ultrasonic beam is either directed in a perpendicular direction (i.e. normal direction) to the test specimen to produce longitudinal waves or is adjusted at an angle to the surface of the test specimen for the production of transverse waves.

3. Wheel transducer technique

- In the wheel transducer technique the ultrasonic beam is projected through a water-filled tire in to the test specimen.



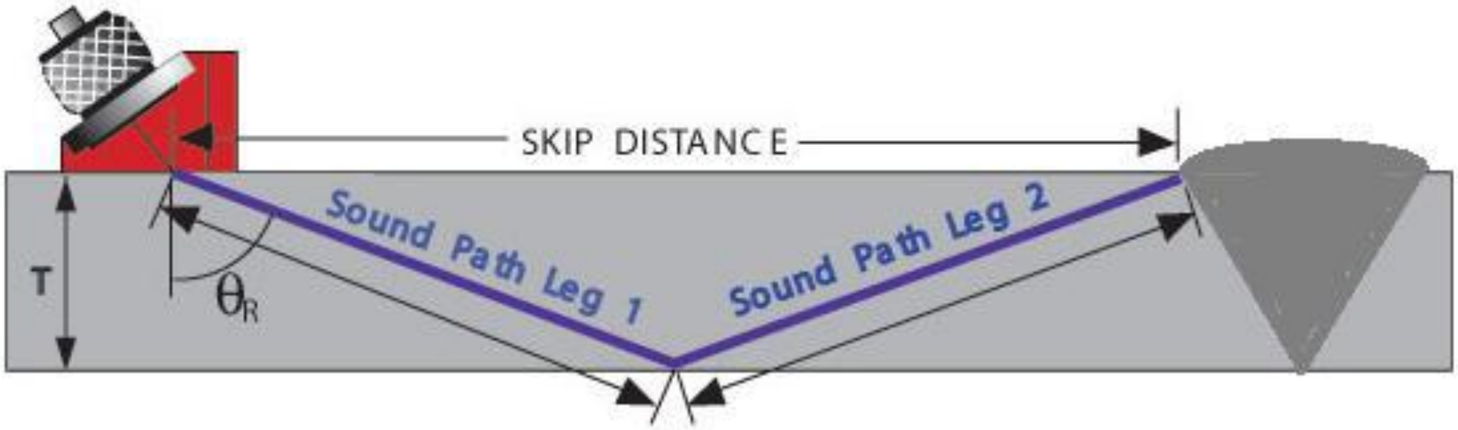
WHEEL TRANSDUCER TECHNIQUE

- The probe, mounted on the wheel axle, is held in a fixed position while the wheel and tire rotate freely.

Inspection of Welded Joints (using angle beam)

- Ultrasonic weld inspections are typically performed using straight beam transducer in conjunction with angle beam transducers.
- A straight beam transducer, producing a longitudinal wave at normal incidence into the test piece, is first used to locate any laminations in or near the heat-affected zone. This is important because an angle beam transducer may not be able to provide a return signal from a laminar flaw.
- The second step in the inspection involves using an angle beam transducer to inspect the actual weld. This inspection may include the root, sidewall, crown, and heat-affected zones of a weld.
- The process involves scanning the surface of the material around the weldment with the transducer. This refracted sound wave will bounce off a reflector (*discontinuity) in the path of the sound beam.*

- To determine the proper scanning area for both sides of the weld, the inspector must calculate the skip distance of the sound beam using the refracted angle and material thickness as: Skip distance = 2T tan θ_R



- Based on such calculations, the inspector can identify the transducer locations on the surface of the material corresponding to the face, sidewall, and root of the weld.
- The angle of refraction for the angle beam transducer used for inspection is usually chosen such that ( ). Doing so, the second leg of the beam will be normal to the side wall of the weldment such that lack of fusion can be easily detected (*the first leg will also be normal to the other wall).*

Resonance Method

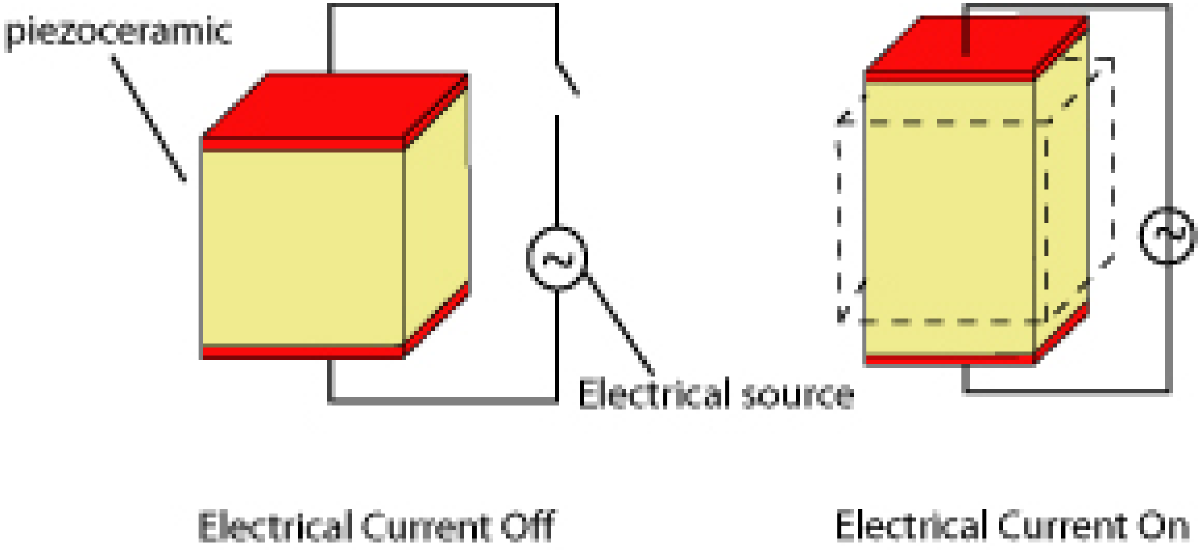
- Resonance is the tendency of a system to oscillate with greater amplitude at some frequencies than at others.
- Frequencies at which the response amplitude is a relative maximum are known as the system's **resonance frequencies**
- A condition of resonance exists whenever the thickness of a material equals half the wavelength of sound or any multiple thereof in that material.
- Control of wavelength in ultrasonics is achieved by control of frequency.
- If we have a transmitter with variable frequency control, it can be tuned to create a condition of resonance for the thickness of plate under test.

- This condition of resonance is easily recognized by the increase of received pulse amplitude.
- Knowing the resonance or fundamental frequency *f and* velocity V of ultrasound in the specimen the thickness ‘t‘ of the specimen under test can be calculated.
- $t = V/2f$
- The fundamental frequency is usually calculated from the difference of two adjacent harmonics.
- $t = V/2(f_n - f_{n-1})$, f_n=frequency at nth harmonic, f_{n-1}= frequency at (n-1) th harmonic.
- The resonance method of ultrasonics is specially suited to the measurement of thickness of thin specimens such as the cladding tubes for reactor fuel elements.

Instruments and equipments used in UT

- **Piezoelectric Transducers**
- The conversion of electrical pulses to mechanical vibrations and the conversion of returned mechanical vibrations back into electrical energy is the basis for ultrasonic testing.
- This conversion is done by the transducer using a piece of piezoelectric material (a polarized material having some parts of the molecule positively charged, while other parts of the molecule are negatively charged) with electrodes attached to two of its opposite faces.
- When an electric field is applied across the material, the polarized molecules will align themselves with the electric field causing the material to change dimensions.

- In addition, a permanently-polarized material such as quartz (SiO2) or barium titanate (BaTiO3) will produce an electric field when the material changes dimensions as a result of an imposed mechanical force.
- This phenomenon is known as the piezoelectric effect.



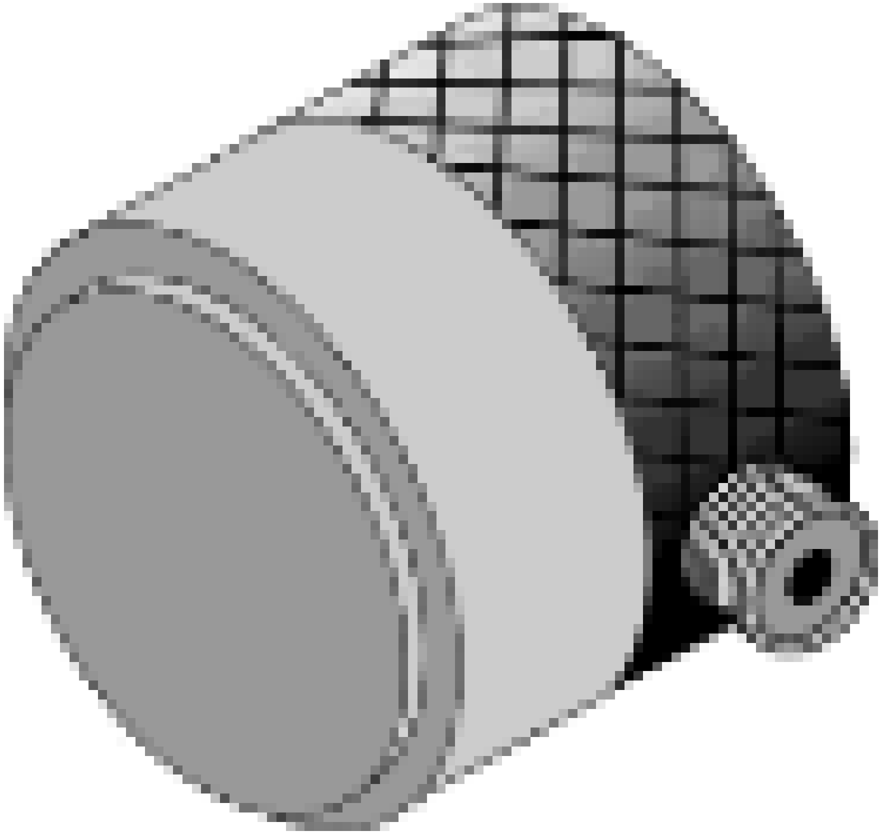
piezoceramic
Electrical source
Electrical Current Off
Electrical Current On

- The active element of most acoustic transducers used today is a piezoelectric ceramic, which can be cut in various ways to produce different wave modes.
- The most commonly employed ceramic for making transducers is lead zirconate titanate**.**
- The thickness of the active element is determined by the desired frequency of the transducer.
- A thin wafer element vibrates with a wavelength that is twice its thickness.
- Therefore, piezoelectric crystals are cut to a thickness that is 1/2 the desired radiated wavelength.
- The higher the frequency of the transducer, the thinner the active element.

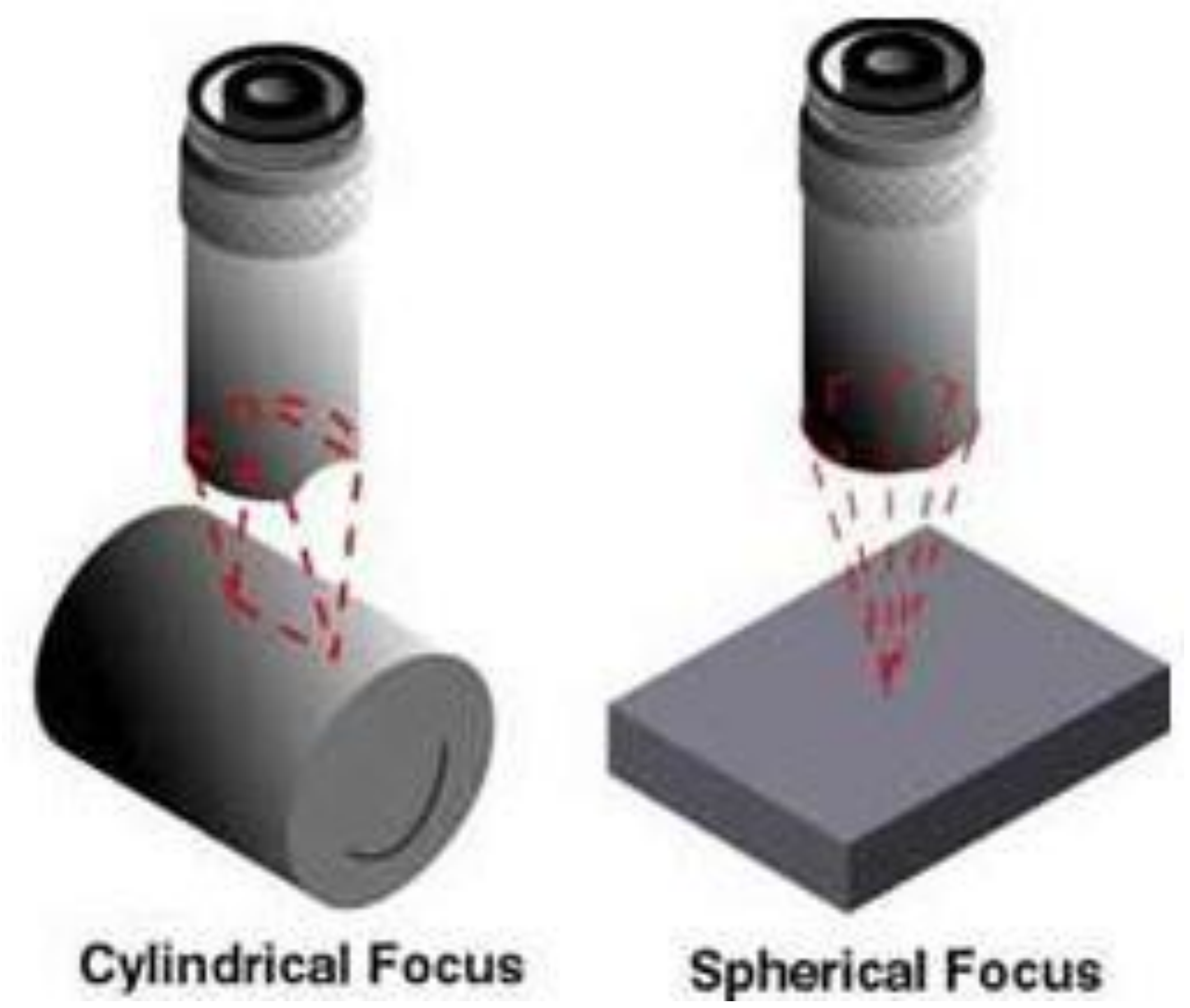
Transducer Types

- Careful attention must be paid to selecting the proper transducer for the application.
- It is important to choose transducers that have the desired frequency, bandwidth, and focusing to optimize inspection capability.

- Transducers are classified into two major groups according to the application .
- *Contact transducers* and *Immersion transducers*
- **Contact transducers** are used for direct contact inspections, and are generally hand manipulated.
- They have elements protected in a casing to withstand sliding contact with a variety of materials.
- These transducers have an ergonomic design so that they are easy to grip and move along a surface.
- They often have replaceable wear plates to lengthen their useful life.
- Coupling materials of water, grease, oils, or commercial materials are used to remove the air gap between the transducer and the component being inspected.



- **Immersion transducers** do not contact the component.
- These transducers are designed to operate in a liquid environment and all connections are watertight.
- Immersion transducers usually have an impedance matching layer that helps to get more sound energy into the water and, in turn, into the component being inspected.
- Immersion transducers can be purchased with a planar, cylindrically focused or spherically focused lens.
- A focused transducer can improve the sensitivity and axial resolution by concentrating the sound energy to a smaller area.
- Immersion transducers are typically used inside a water tank or as part of a squirter or bubbler system in scanning applications.

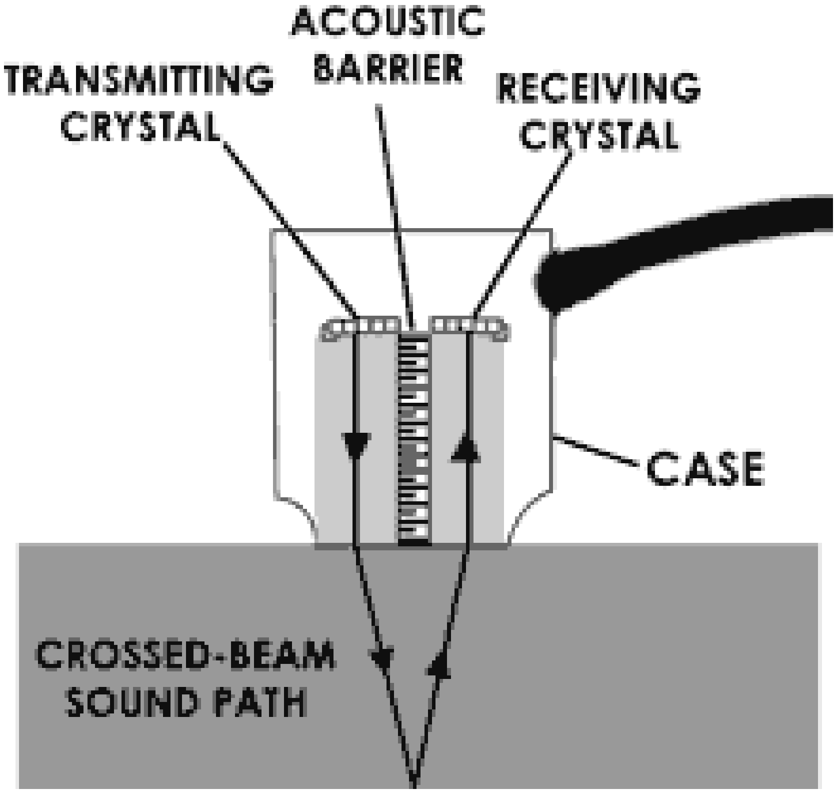

Cylindrical Focus
Spherical Focus

Types of Contact Transducers

- Contact transducers are available in a variety of configurations to improve their usefulness for a variety of applications.
- The flat contact transducer is used in normal beam inspections of relatively flat surfaces, and where near surface resolution is not critical.
- If the surface is curved, a shoe that matches the curvature of the part may need to be added to the face of the transducer.

Dual element transducers (Dual crystal Probes)

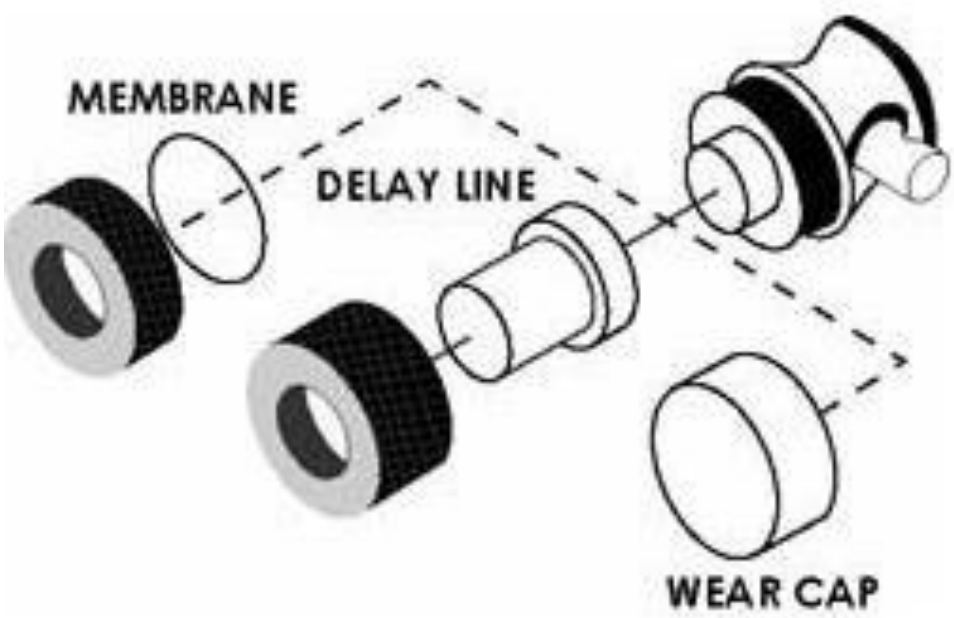
- Dual element transducers contain two independently operated elements in a single casing.
- One of the elements transmits and the other receives the ultrasonic signal.
- Dual element transducers are especially well suited for making measurements in applications where reflectors are very near the transducer, since this design eliminates the ring down effect that single-element transducers experience
- when single-element transducers are operating in pulse echo mode, the element cannot start receiving reflected signals until the element has stopped ringing from its transmit function.


ACOUSTIC
BARRIER
TRANSMITTING
CRYSTAL
RECEIVING
CRYSTAL
CASE
CROSSED-BEAM
SOUND PATH

- Dual element transducers are very useful when making thickness measurements of thin materials and when inspecting for near surface defects.
- The two elements are angled towards each other to create a crossed-beam sound path in the test material.

Delay line transducers

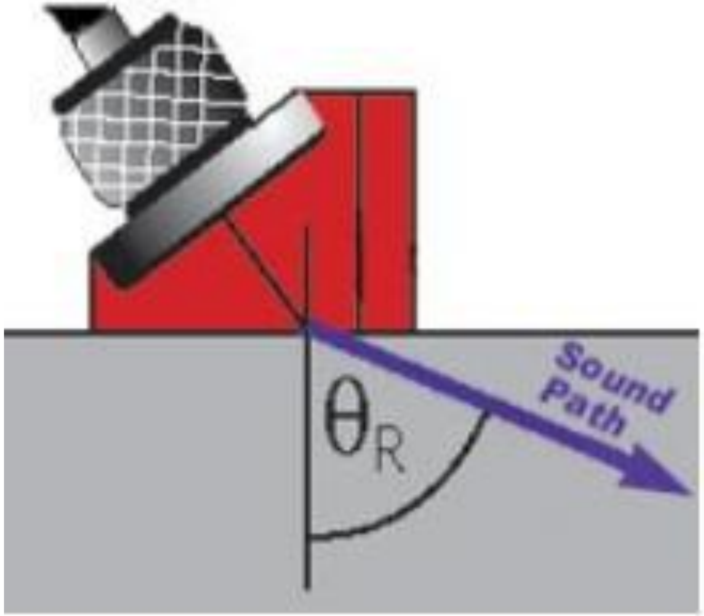
- Delay line transducers provide versatility with a variety of replaceable options.
- Removable delay line, surface conforming membrane, and protective wear cap options can make a single transducer effective for a wide range of applications.
- As the name implies, the primary function of a delay line transducer is to introduce a time delay between the generation of the sound wave and the arrival of any reflected waves.
- This allows the transducer to complete its "sending" function before it starts its "receiving" function so that near surface resolution is improved .


MEMBRANE
DELAY LINE
WEAR CAP

- They are designed for use in applications such as high precision thickness gauging of thin materials and delamination checks in composite materials.
- They are also useful in high-temperature measurement applications since the delay line provides some insulation to the piezoelectric element from the heat.

Angle beam transducers

- Angle beam transducers are typically used to introduce a refracted shear wave into the test material.
- Transducers can be purchased in a variety of fixed angles or in adjustable versions.
- In the fixed angle versions, the angle of refraction that is marked on the transducer is only accurate for a particular material, which is usually steel.
- The most commonly used refraction angles for fixed angle transducers are 45°, 60° and 70°.
- The angled sound path allows the sound beam to be reflected from the backwall to improve detectability of flaws in and around welded areas.
- They are also used to generate surface waves for use in detecting defects on the surface of a component.

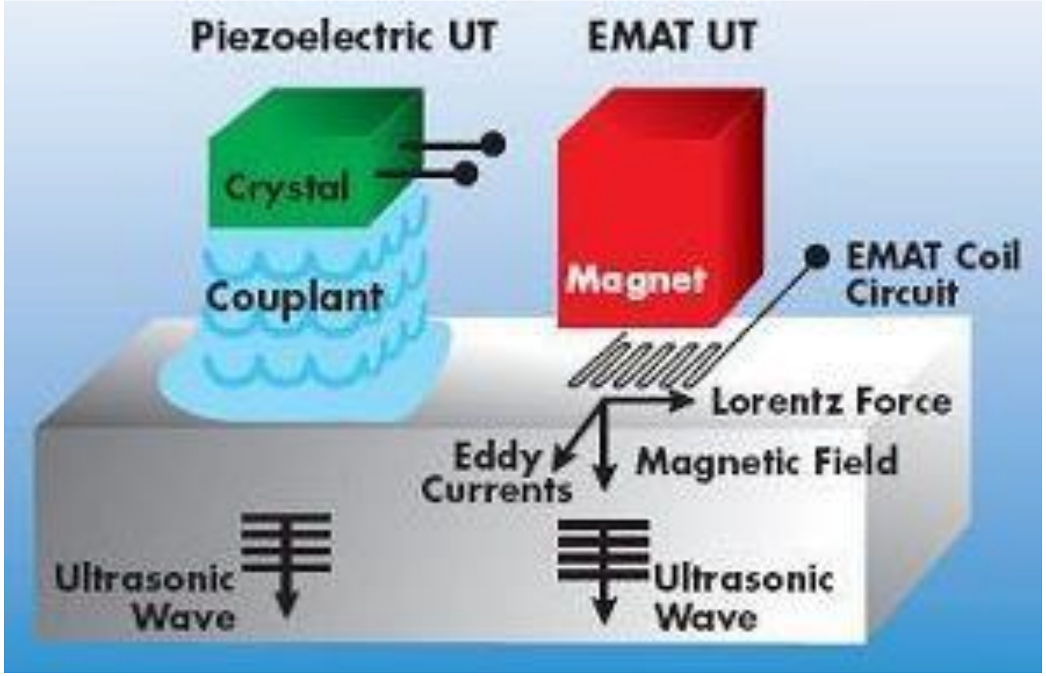

Sound Path
θR

- **Normal incidence shear wave transducers** are unique because they allow the introduction of shear waves directly into a test piece without the use of an angle beam wedge.
- Careful design has enabled manufacturing of transducers with minimal longitudinal wave contamination.

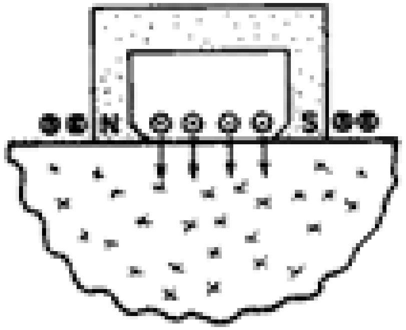
- **Paint brush transducers** are used to scan wide areas.
- These long and narrow transducers are made up of an array of small crystals and that make it possible to scan a larger area more rapidly for discontinuities.
- Smaller and more sensitive transducers are often then required to further define the details of a discontinuity.

Electromagnetic Acoustic Transducers (*EMATs)*

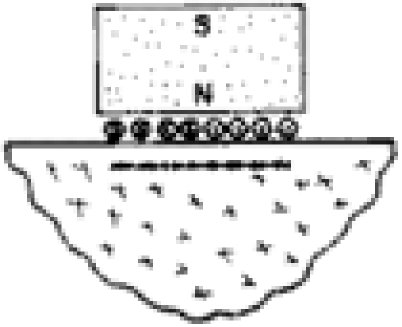
- Electromagnetic-acoustic transducers (EMAT) are a modern type of ultrasonic transducers that work based on a totally different physical principle than piezoelectric transducers and, most importantly, they do not need couplant.
- When a wire is placed near the surface of an electrically conducting object and is driven by a current at the desired ultrasonic frequency, eddy currents will be induced in a near surface region of the object.
- If a static magnetic field is also present, these eddy currents will experience forces called “Lorentz forces” which will cause pressure waves to be generated at the surface and propagate through the material.



Longitudinal Wave configration

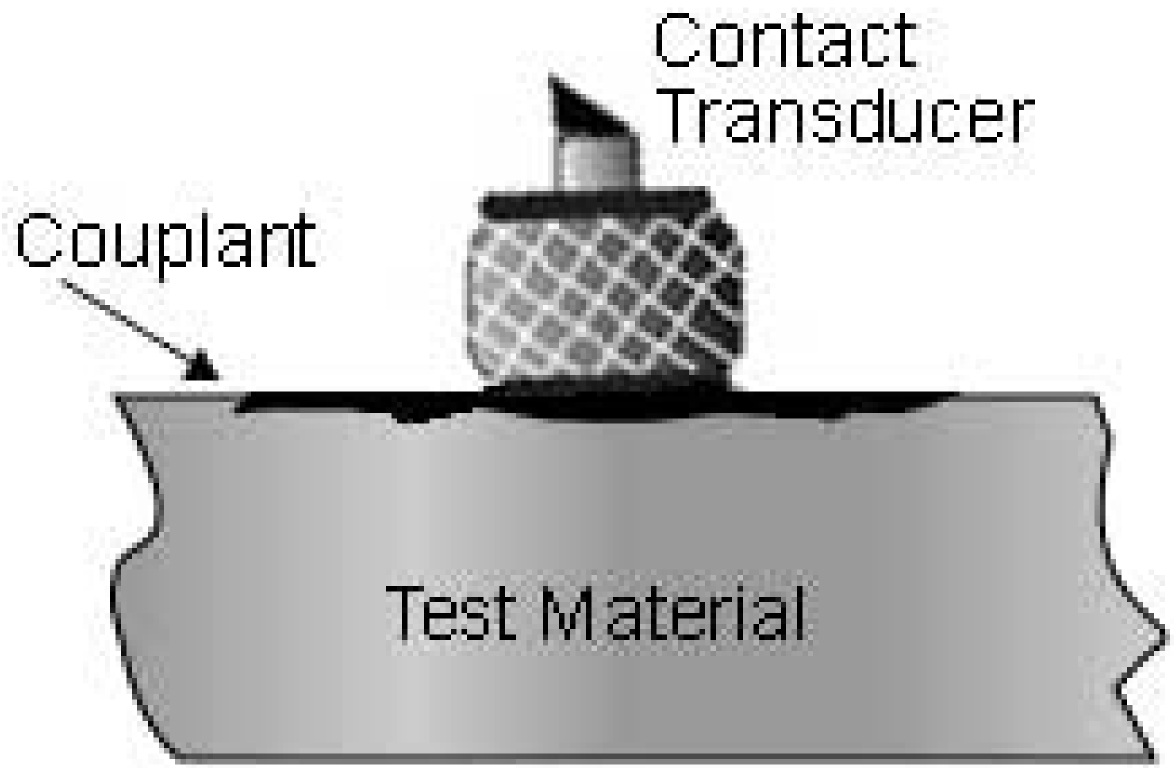


Shear Wave configration



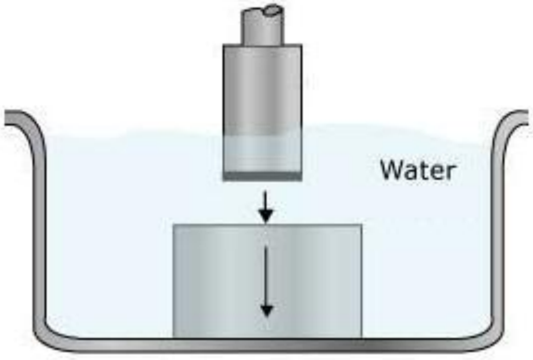
- Different types of sound waves (longitudinal, shear, lamb) can be generated using EMATs by varying the configuration of the transducer such that the orientation of the static magnetic field is changed.
- EMATs can be used for thickness measurement, flaw detection, and material property characterization.
- The EMATs offer many advantages based on its non-contact couplant-free operation.
- These advantages include the ability to operate in remote environments at elevated speeds and temperatures.

Couplant



- A couplant is a material (usually liquid) that facilitates the transmission of ultrasonic energy from the transducer into the test specimen.
- Couplant is generally necessary because the acoustic impedance mismatch between air and solids is large.
- Therefore, nearly all of the energy is reflected and very little is transmitted into the test material.
- The couplant displaces the air and makes it possible to get more sound energy into the test specimen so that a usable ultrasonic signal can be obtained.
- In contact ultrasonic testing a thin film of <u>oil, glycerin or water</u> is typically used between the transducer and the test surface.
- When shear waves are to be transmitted, the fluid is generally selected to have a significant viscosity.

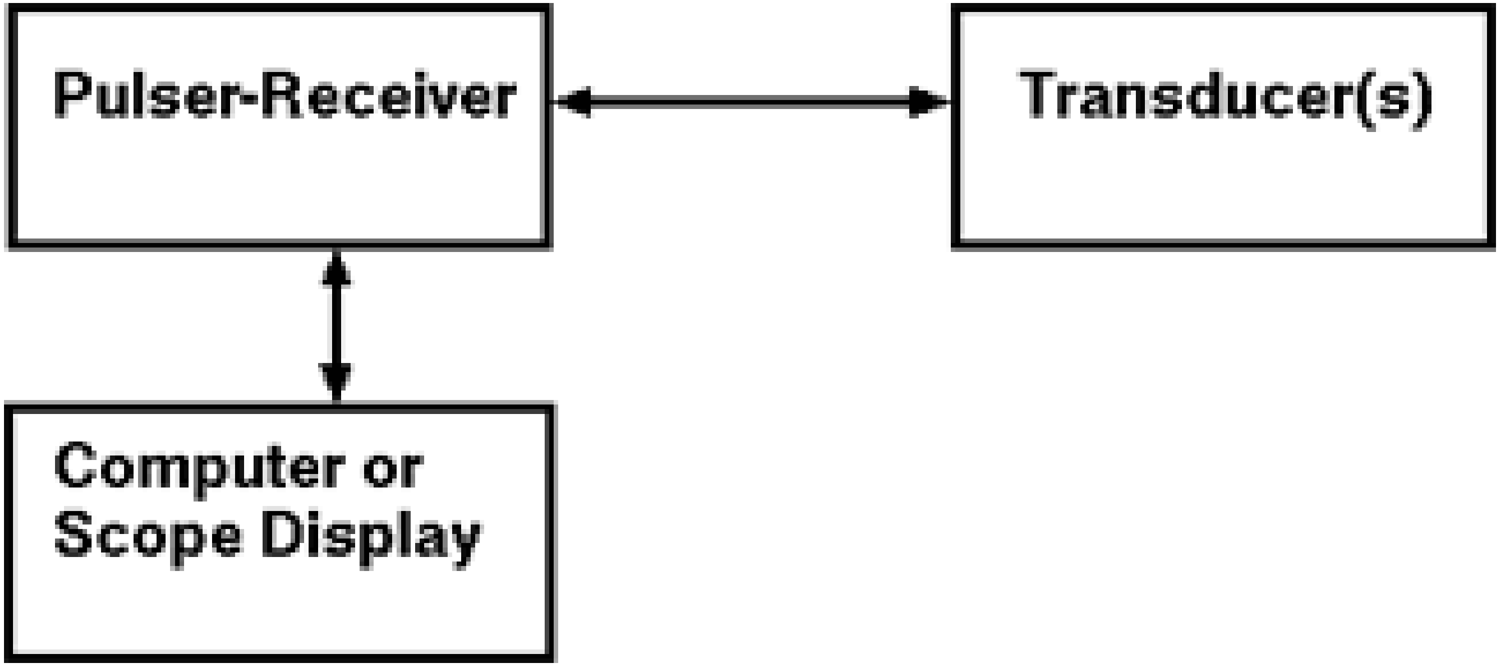
- When scanning over the part, an immersion technique is often used.



- In immersion ultrasonic testing both the transducer and the part are immersed in the couplant, which is typically water.
- This method of coupling makes it easier to maintain consistent coupling while moving and manipulating the transducer and/or the part.

Pulser-Receivers

- Ultrasonic pulser-receivers are well suited to general purpose ultrasonic testing.
- Along with appropriate transducers and an oscilloscope, they can be used for flaw detection and thickness gauging in a wide variety of metals, plastics, ceramics, and composites.
- Ultrasonic pulser-receivers provide a unique, low-cost ultrasonic measurement capability.
- Specialized portable equipment that are dedicated for ultrasonic inspection merge the pulser-receiver with the scope display in one small size battery operated unit.



Pulser-Receiver

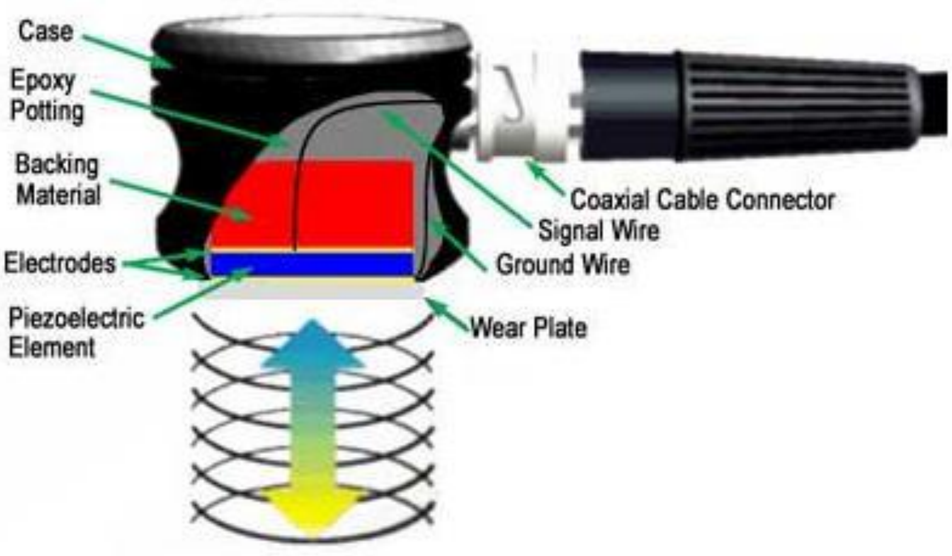
Transducer(s)

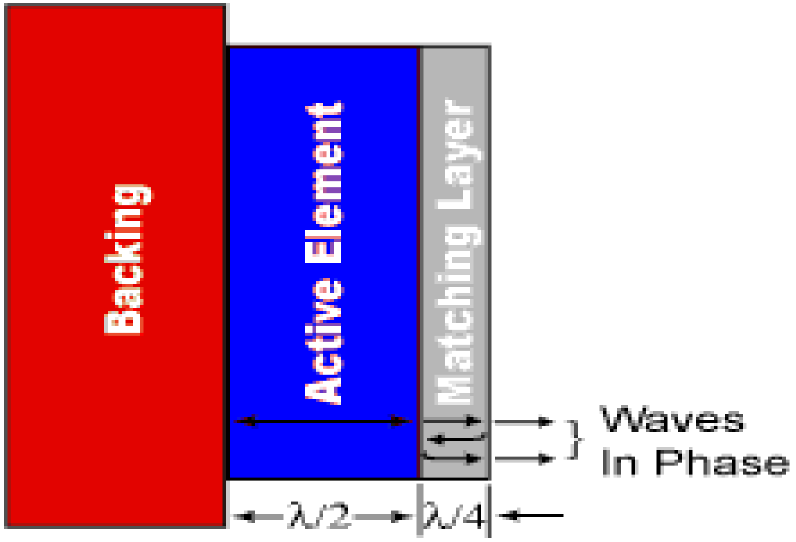
Computer or Scope Display

- The pulser section of the instrument generates short, large amplitude electric pulses of controlled energy, which are converted into short ultrasonic pulses when applied to an ultrasonic transducer.
- In the receiver section the voltage signals produced by the transducer, which represent the received ultrasonic pulses, are amplified.
- The amplified signal is available as an output for display or capture for signal processing.

Characteristics of Piezoelectric Transducers

- The function of the transducer is to convert electrical signals into mechanical vibrations (transmit mode) and mechanical vibrations into electrical signals (receive mode).
- Many factors, including material, mechanical and electrical construction, and the external mechanical and electrical load conditions, influence the behavior of a transducer.





- To get as much energy out of the transducer as possible, an impedance matching layer is placed between the active element and the face of the transducer.
- Optimal impedance matching is achieved by sizing the matching layer so that its thickness is 1/4 of the desired wavelength.
- For contact transducers, the matching layer is made from a material that has an acoustical impedance between the active element and steel.
- Immersion transducers have a matching layer with an acoustical impedance between the active element and water.
- Contact transducers also incorporate a wear plate to protect the matching layer and active element from scratching.

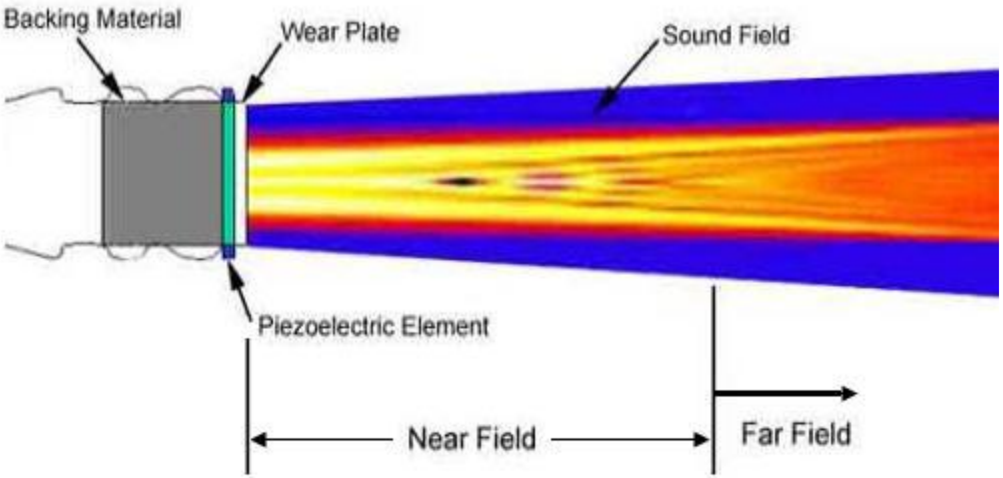
- The backing material supporting the crystal has a great influence on the damping characteristics of a transducer.
- Using a backing material with an impedance similar to that of the active element will produce the most effective damping.
- Such a transducer will have a wider bandwidth resulting in higher sensitivity and higher resolution (i.e., the ability to locate defects near the surface or in close proximity in the material).
- As the mismatch in impedance between the active element and the backing material increases, material penetration increases but transducer sensitivity is reduced.

- The bandwidth refers to the range of frequencies associated with a transducer.
- The frequency noted on a transducer is the central frequency and depends primarily on the backing material.
- Highly damped transducers will respond to frequencies above and below the central frequency.
- The broad frequency range provides a transducer with high resolving power.
- Less damped transducers will exhibit a narrower frequency range and poorer resolving power, but greater penetration.
- The central frequency will also define the capabilities of a transducer.
- Lower frequencies (0.5MHz-2.25MHz) provide greater energy and penetration in a material, while high frequency crystals (15.0MHz-25.0MHz) provide reduced penetration but greater sensitivity to small discontinuities.

Radiated Fields of Ultrasonic Transducers

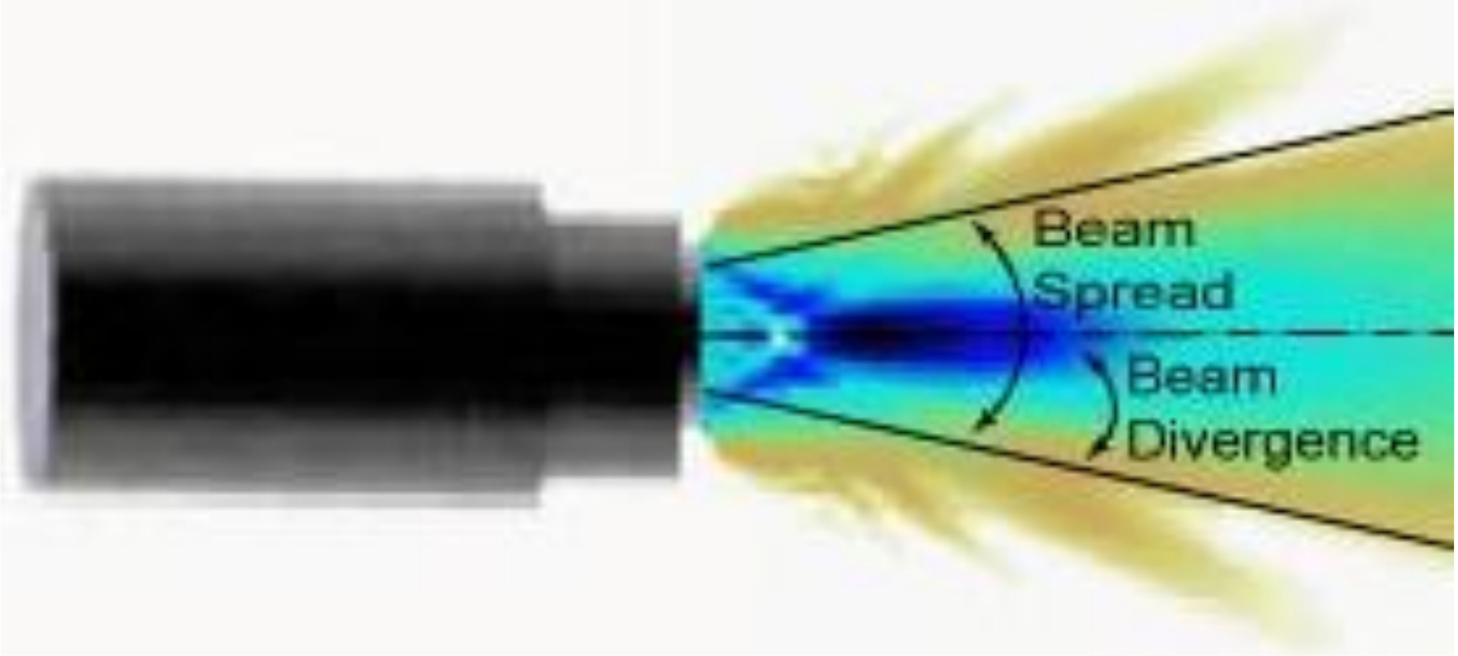
- The sound that emanates from a piezoelectric transducer does not originate from a point, but instead originates from most of the surface of the piezoelectric element.
- Since the ultrasound originates from a number of points along the transducer face, the ultrasound intensity along the beam is affected by constructive and destructive wave interference.
- This wave interference leads to extensive fluctuations in the sound intensity near the source and is known as the "*near field*".
- Because of acoustic variations within a near field, it can be extremely difficult to accurately evaluate flaws in materials when they are positioned within this area.

- The pressure waves combine to form a relatively uniform front at the end of the near field.
- The area beyond the near field where the ultrasonic beam is more uniform is called the “far field”.
- The transition between the near field and the far field occurs at a distance, , and is sometimes referred to as the "natural focus" of a flat (or unfocused) transducer.



Transducer Beam Spread

- As the sound waves exits the near field and propegate through the material, the sound beam continiously spreads out.
- This phenomenon is usually referred to as beam spread but sometimes it is also referred to as beam divergence or ultrasonic diffraction.
- It should be noted that there is actually a difference between beam spread and beam divergence.
- Beam spread is a measure of the whole angle from side to side of the beam in the far field.
- Beam divergence is a measure of the angle from one side of the sound beam to the central axis of the beam in the far field.
- Therefore, beam spread is twice the beam divergence.


Beam
Spread
Beam
Divergence

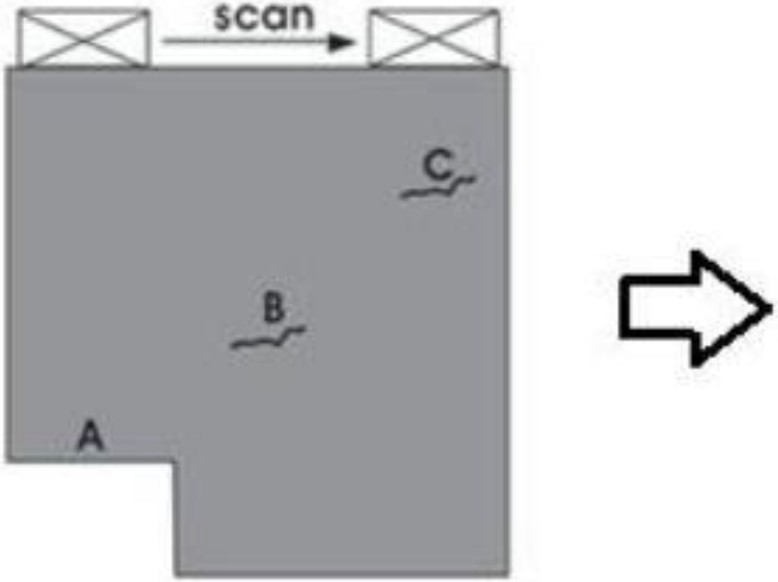
- Beam spread occurs because the vibrating particle of the material do not always transfer all of their energy in the direction of wave propagation.
- If the particles are not directly aligned in the direction of wave propagation, some of the energy will get transferred off at an angle.
- In the near field, constructive and destructive wave interference fill the sound field with fluctuation.
- At the start of the far field, however, the beam strength is always greatest at the center of the beam and diminishes as it spreads outward.

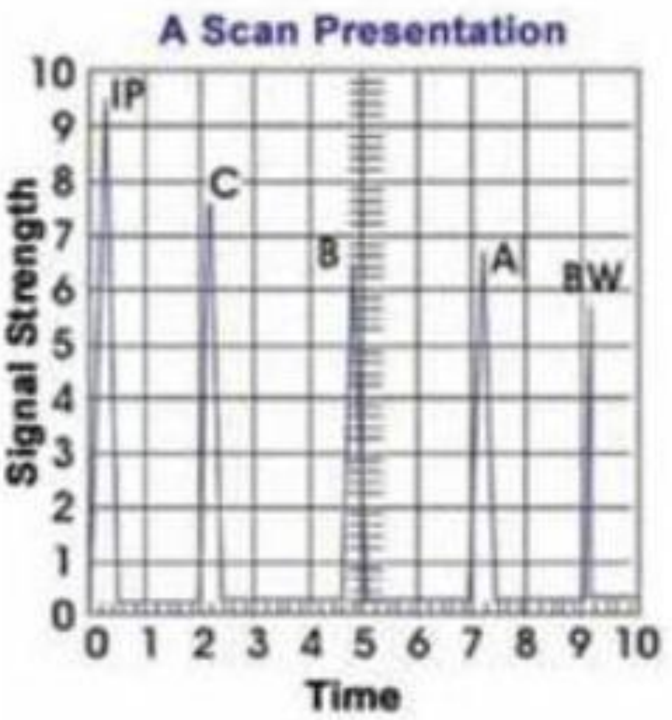
Data Presentation (Modes of display)

- Ultrasonic data can be collected and displayed in a number of different formats.
- The three most common formats are known in the NDT world as A-scan, B-scan and C-scan presentations.
- Each presentation mode provides a different way of looking at and evaluating the region of material being inspected.
- Modern computerized ultrasonic scanning systems can display data in all three presentation forms simultaneously

A-Scan Presentation

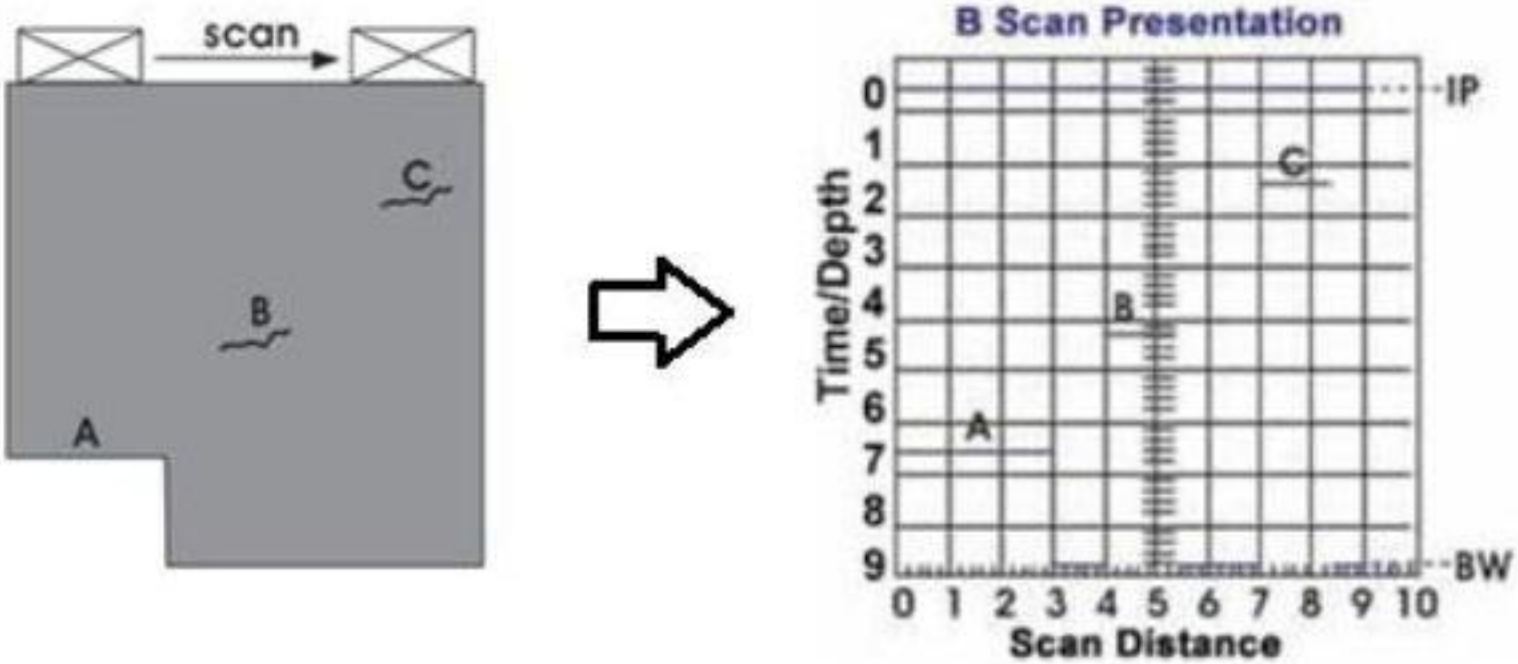
- The A-scan presentation displays the amount of received ultrasonic energy as a function of time.
- The relative amount of received energy is plotted along the vertical axis and the elapsed time (which may be related to the traveled distance within the material) is displayed along the horizontal axis.
- Most instruments with an A-scan display allow the signal to be displayed in its natural radio frequency form (RF).
- In the A-scan presentation, relative discontinuity size can be estimated by comparing the signal amplitude obtained from an unknown reflector to that from a known reflector.
- Reflector depth can be determined by the position of the signal on the horizontal time axis.


scan
C
B
A


A Scan Presentation
Signal Strength
0
1
2
3
4
5
6
7
8
9
10
Time
0 1 2 3 4 5 6 7 8 9 10
IP
C
B
A
BW

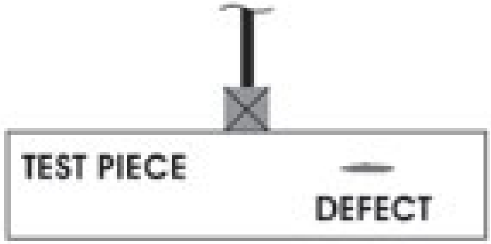
B-Scan Presentation

- The B-scan presentation is a type of presentation that is possible for automated linear scanning systems where it shows a profile (cross-sectional) view of the test specimen.
- In the B-scan, the time-of-flight (travel time) of the sound waves is displayed along the vertical axis and the linear position of the transducer is displayed along the horizontal axis.
- From the B-scan, the depth of the reflector and its approximate linear dimensions in the scan direction can be determined.
- The B-scan is typically produced by establishing a trigger gate on the A-scan. Whenever the signal intensity is great enough to trigger the gate, a point is produced on the B-scan.
- The gate is triggered by the sound reflected from the backwall of the specimen and by smaller reflectors within the material.

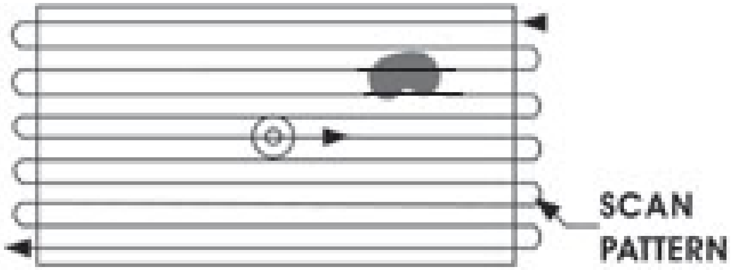

scan
C
B
A
B Scan Presentation
Time/Depth
0
1
2
3
4
5
6
7
8
9
IP
BW
C
B
A
0 1 2 3 4 5 6 7 8 9 10
Scan Distance

C-Scan Presentation

- The C-scan presentation is a type of presentation that is possible for automated two-dimensional scanning systems that provides a plan-type view of the location and size of test specimen features.
- The plane of the image is parallel to the scan pattern of the transducer.
- C-scan presentations are typically produced with an automated data acquisition system, such as a computer controlled immersion scanning system.
- The C-scan presentation provides an image of the features that reflect and scatter the sound within and on the surfaces of the test piece.



SIDE VIEW



TOP VIEW

C-SCAN PRESENTATION

Calibration and Reference Test Blocks

- In ultrasonic pulse echo testing test blocks containing notches, slots or drilled holes are used to :

i. determine the operating chacteristics of the flaw detector and probes.

ii. establish reproducible test conditions.

iii. compare the height or location of the echo from a flaw in the test specimen to that from an artificial flaw in the test block.

- The blocks used for the first two purposes are termed **calibration blocks**, while test blocks used for the third purpose, are known as **reference blocks.**
- Test blocks whose dimensions have been established and sanctioned by any of the various groups concerned with material testing standards are called **standard test blocks.**

Calibration of equipment

- The location of a discontinuity can be instantly determined using its echo if the instrument is correctly **calibrated.**
- Calibration refers to the act of evaluating and adjusting the precision and accuracy of measurement equipment.
- First, the electronics of the equipment must be calibrated to ensure that they are performing as designed.
- This operation is usually performed by the equipment manufacturer.
- It is also usually necessary for the operator to perform a "user calibration" of the equipment.
- The user must "calibrate" the system, which includes the equipment settings, the transducer, and the test setup, to validate that the desired level of precision and accuracy are achieved.

- In ultrasonic testing, reference standards are used to establish a general level of consistency in measurements and to help interpret and quantify the information contained in the received signal.
- Reference standards are used to validate that the equipment and the setup provide similar results from one day to the next and that similar results are produced by different systems.
- Reference standards also help the inspector to estimate the size of flaws.
- In a pulse-echo type setup, signal strength depends on both the size of the flaw and the distance between the flaw and the transducer.
- The inspector can use a reference standard with an artificially induced flaw of known size and at approximately the same distance away for the transducer to produce a signal.
- By comparing the signal from the reference standard to that received from the actual flaw, the inspector can estimate the flaw size.

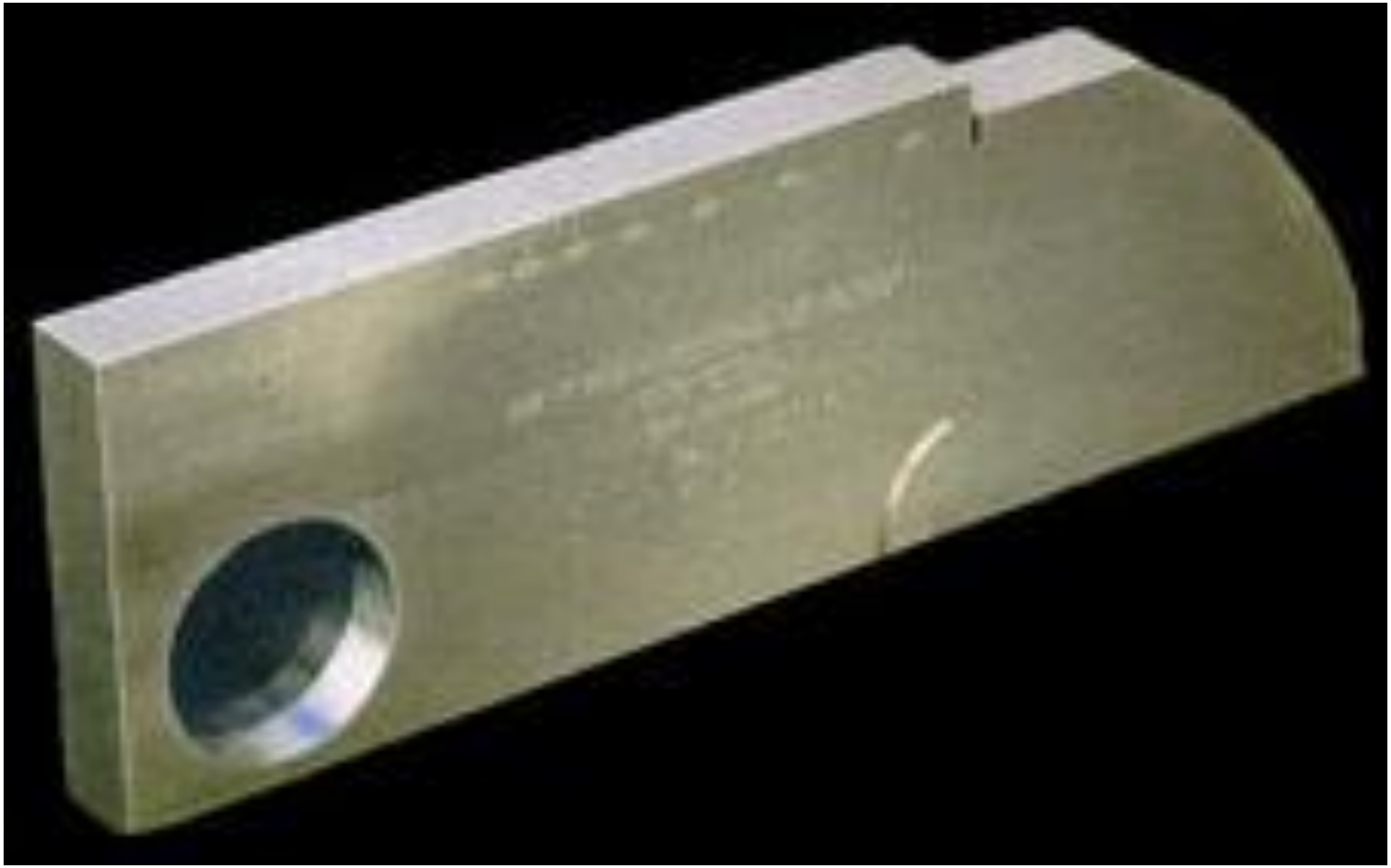
- The material of the reference standard should be the same as the material being inspected and the artificially induced flaw should closely resemble that of the actual flaw.
- This second requirement is a major limitation of most standard reference samples. Most use drilled holes and notches that do not closely represent real flaws.
- In most cases the artificially induced defects in reference standards are better reflectors of sound energy (due to their flatter and smoother surfaces) and produce indications that are larger than those that a similar sized flaw would produce.

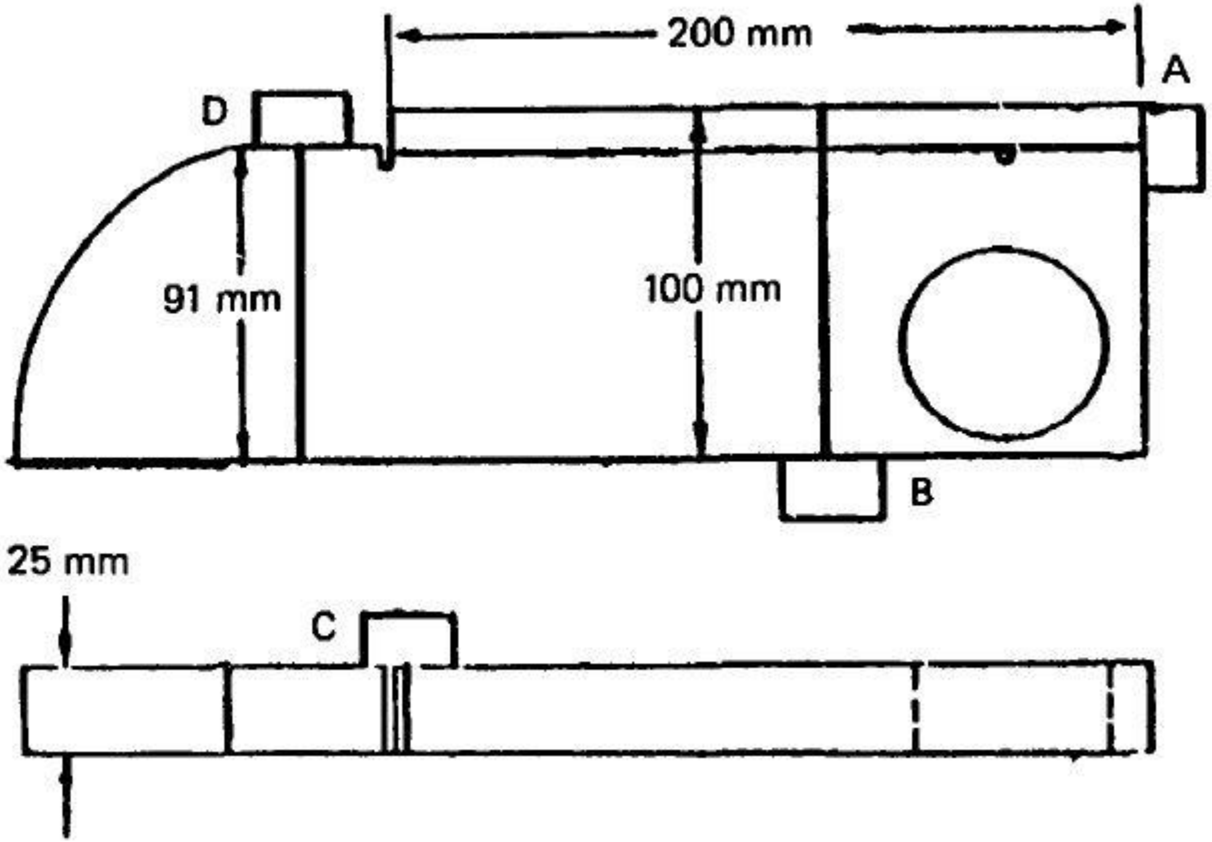
Introduction to Some of the Common Standards

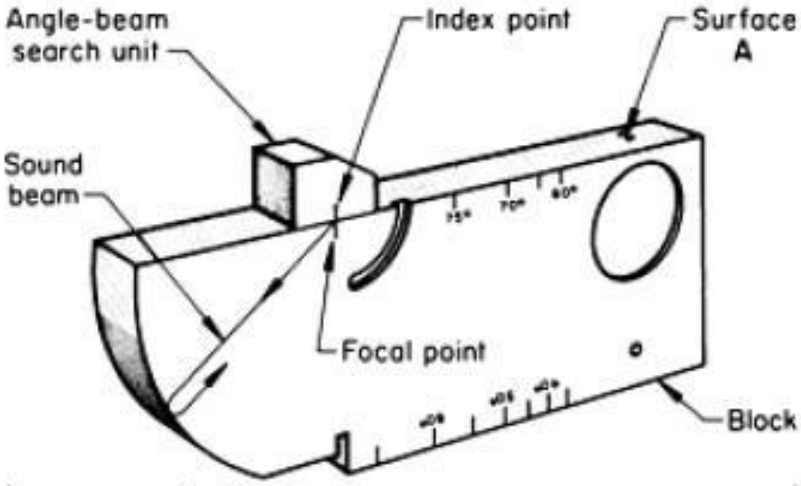
- A wide variety of standard calibration blocks of different designs, sizes and systems of units (mm or inch) are available.
- The type of standard calibration block used is dependent on the NDT application and the form and shape of the object being evaluated.
- The most commonly used standard calibration blocks are those of the; International Institute of Welding (IIW), American Welding Society (AWS) and American Society of Testing and Materials (ASTM).

IIW Type US-1 Calibration Block

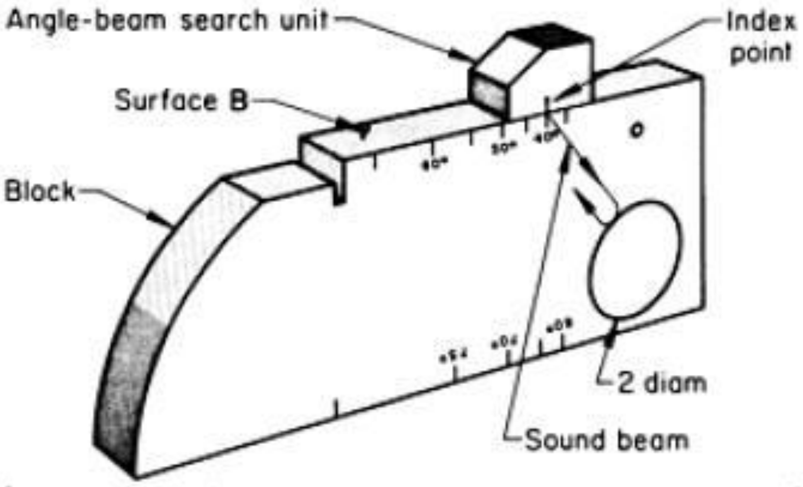
- This block is a general purpose calibration block that can be used for calibrating angle-beam transducers as well as normal beam transducers.
- The material from which IIW blocks are prepared is specified as killed, open hearth or electric furnace, low-carbon steel in the normalized condition.
- Official IIW blocks are dimensioned in the metric system of units.
- The block has several features that facilitate checking and calibrating many of the parameters and functions of the transducer as well as the instrument where that includes; angle-beam exit (index) point, beam angle, beam spared, time base, linearity, resolution, sensitivity and range setting.



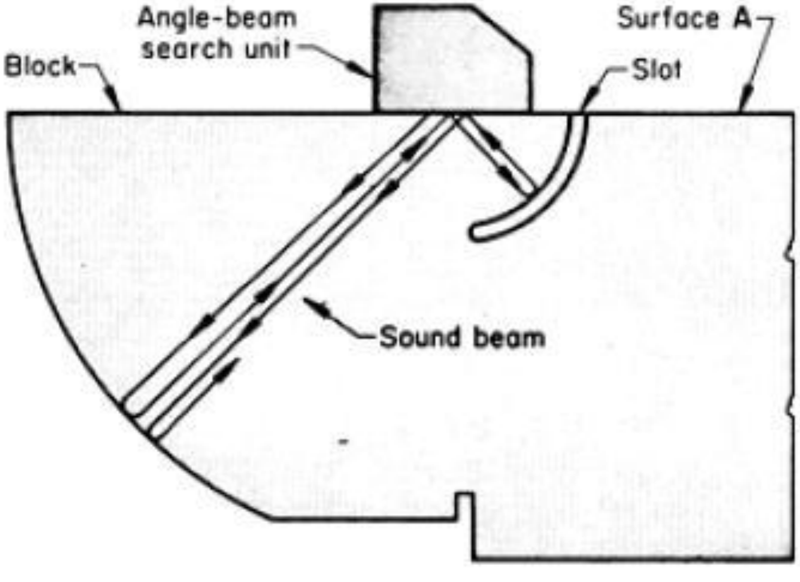

200 mm
A
D
91 mm
100 mm
B
25 mm
C



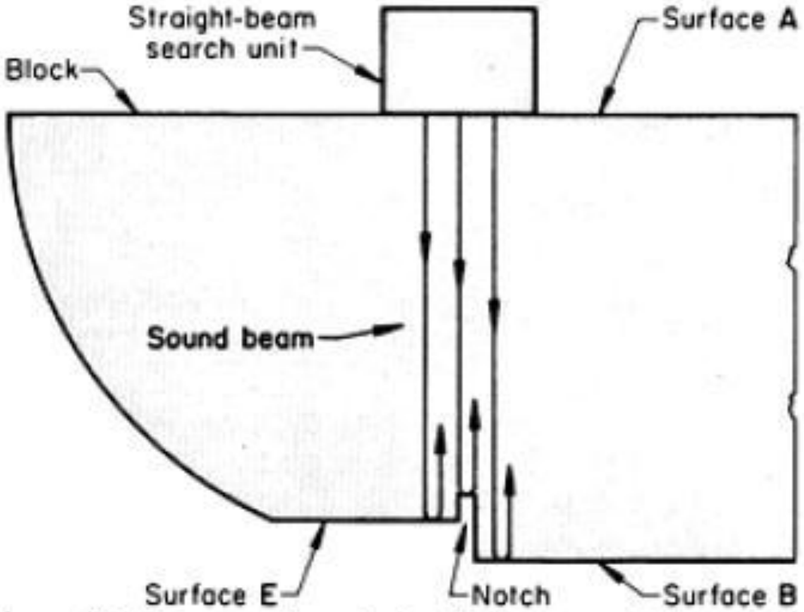
(a) Determination of index point



(b) Determination of beam angle



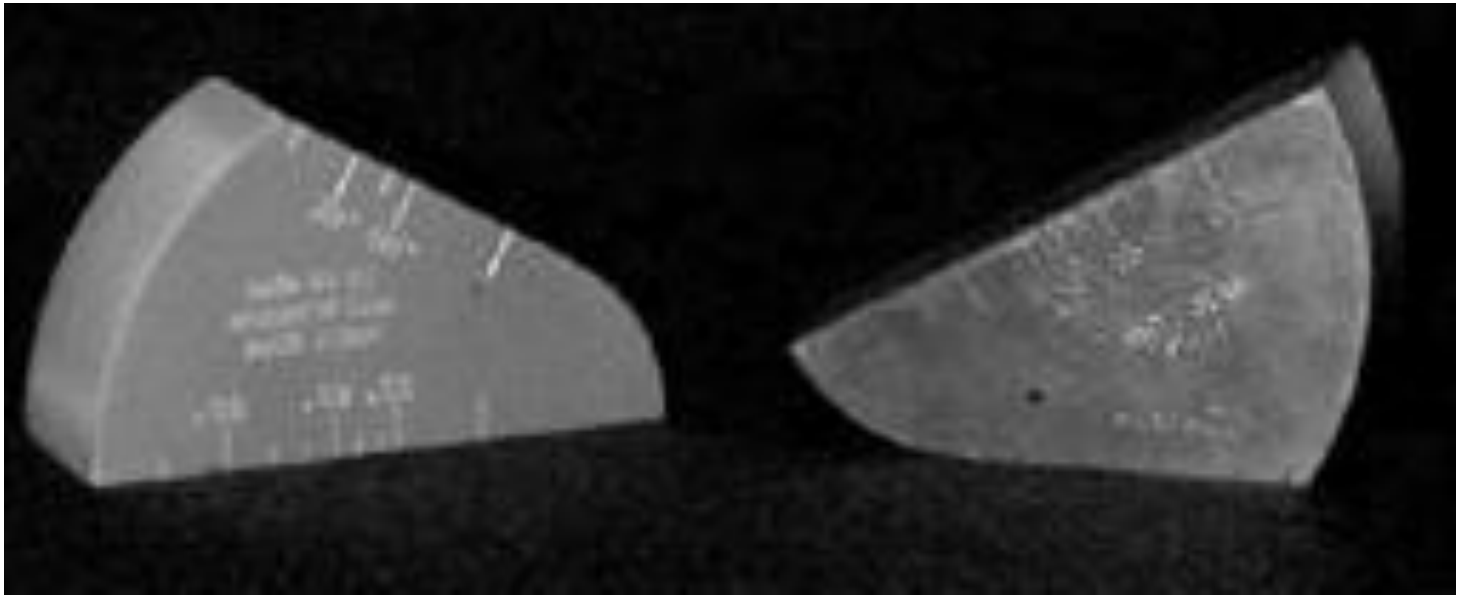
(c) Calibration of instrument time base



(d) Determination of straight-beam resolution

ASTM - Miniature Angle-Beam Calibration Block (V2)

- The miniature angle-beam block is used in a somewhat similar manner as the as the IIW block, but is smaller and lighter.
- The miniature angle-beam block is primarily used in the field for checking the characteristics of angle-beam transducers.

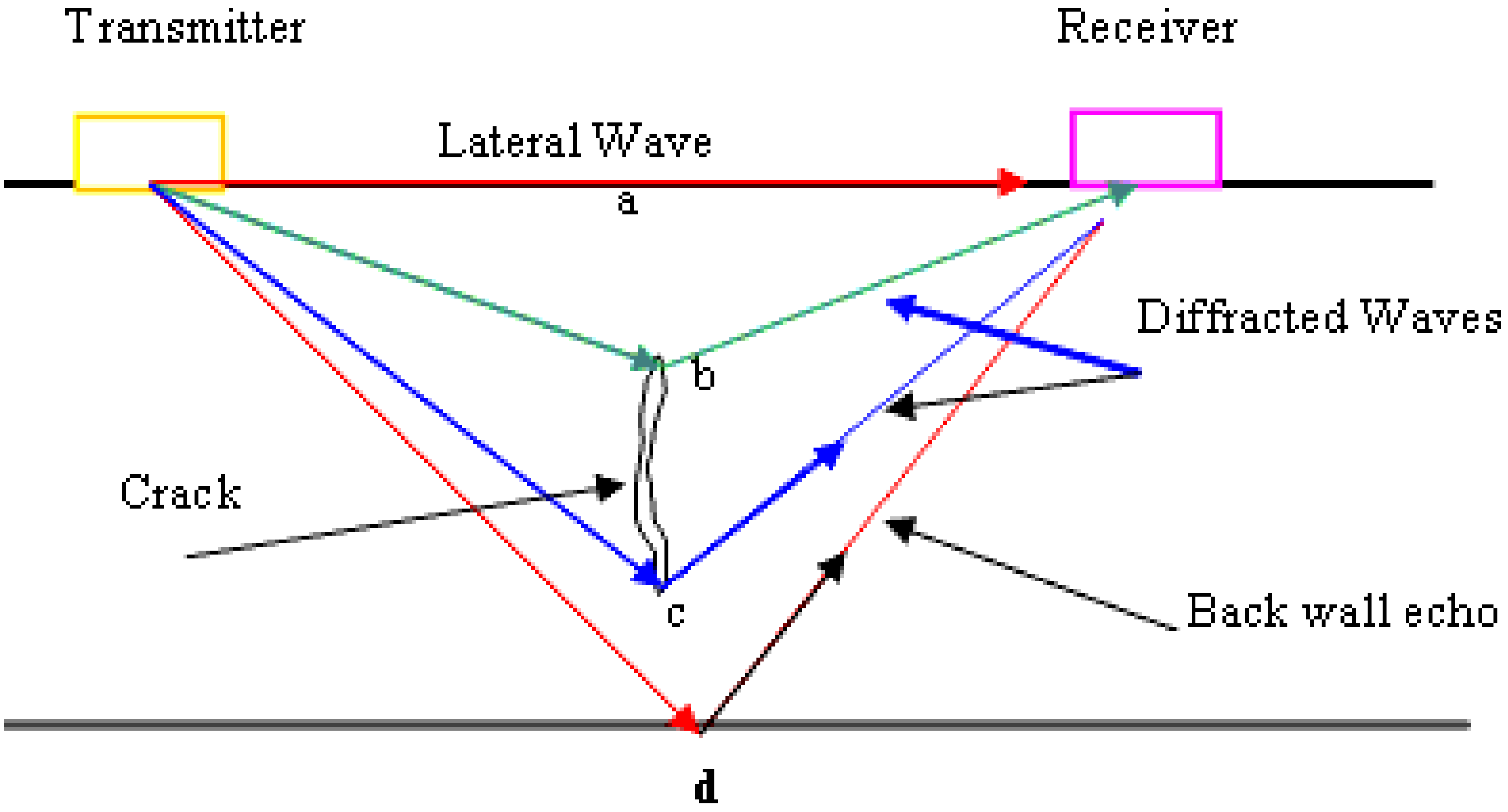


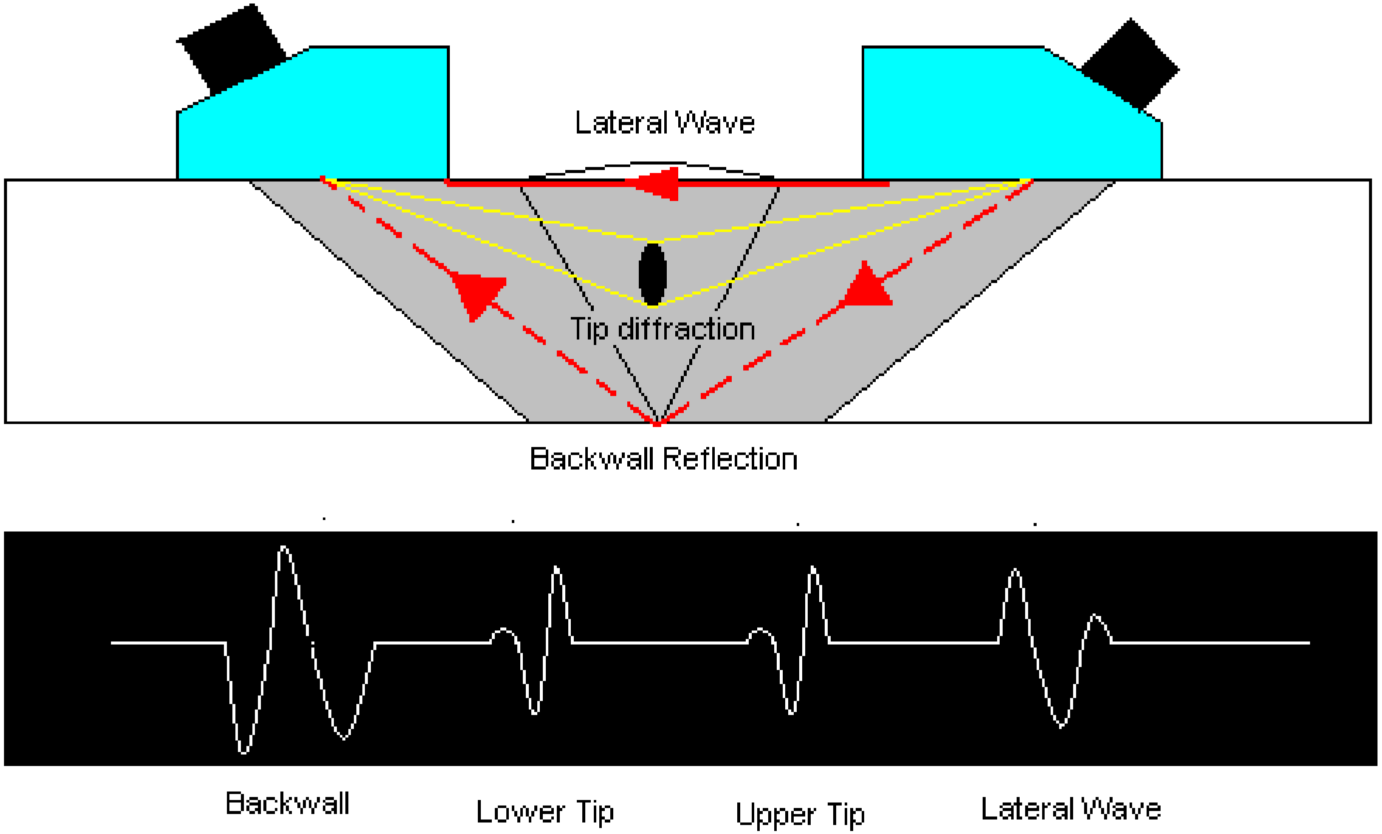
- With the miniature block, beam angle and exit point can be checked for an angle-beam transducer.
- Both the 25 and 50 mm radius surfaces provide ways for checking the location of the exit point of the transducer and for calibrating the time base of the instrument in terms of metal distance.
- The small hole provides a reflector for checking beam angle and for setting the instrument gain.

Time-of-flight diffraction (TOFD) method

- **TOFD** method of ultrasonic testing is a sensitive and accurate method for the nondestructive testing of welds for defects.
- Measuring the amplitude of reflected signal is a relatively unreliable method of sizing defects because the amplitude strongly depends on the orientation of the crack.
- Instead of amplitude, TOFD uses the time of flight of an ultrasonic pulse to determine the position of a reflector.

- In a TOFD system, a pair of ultrasonic probes sits on opposite sides of a weld.
- One of the probes, the transmitter, emits an ultrasonic pulse that is picked up by the probe on the other side, the receiver.
- In undamaged pipes, the signals picked up by the receiver probe are from two waves: one that travels along the surface and one that reflects off the far wall.
- When a crack is present, there is a diffraction of the ultrasonic wave from the tip(s) of the crack.
- Using the measured time of flight of the pulse, the depth of a crack tip can be calculated automatically by simple trigonometry.
- This method is even more reliable than traditional radiographic, pulse echo manual and automated weld testing methods


Transmitter
Receiver
Lateral Wave
a
b
Diffracted Waves
Crack
c
Back wall echo
d


Lateral Wave
Tip diffraction
Backwall Reflection
Backwall
Lower Tip
Upper Tip
Lateral Wave

Applications of Ultrasonic Testing

- To test welds in pressure vessels, structures, bridges, aircrafts, marines etc.
- Ferrous and non ferrous pipes, rods, bars are also tested.
- Inspection of large castings and forgings.
- Inspection of rails, rolled steel sections.
- Fatigue detection in welds and boilers.
- Detection of corrosion in various petroleum and gas supply lines.
- Determining thickness of pipings, tubings, fins etc.
- Detection of slags, blow holes, inclusions, porosity and grain size.

Thank you