

Ultrasonic Testing

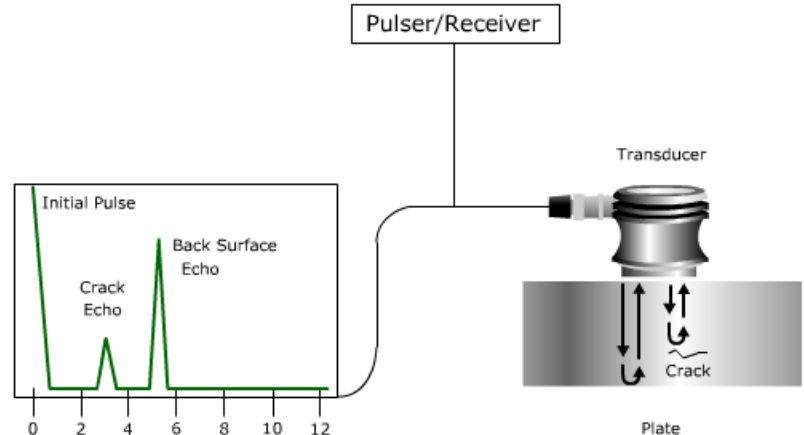
Ultrasonic Testing (UT) uses high frequency sound waves (*typically in the range between 0.5 and 15 MHz*) to conduct examinations and make measurements. Besides its wide use in engineering applications (*such as flaw detection/evaluation, dimensional measurements, material characterization, etc.*), ultrasonics 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. A 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.

Advantages and Disadvantages

The primary advantages and disadvantages when compared to other NDT methods are:

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

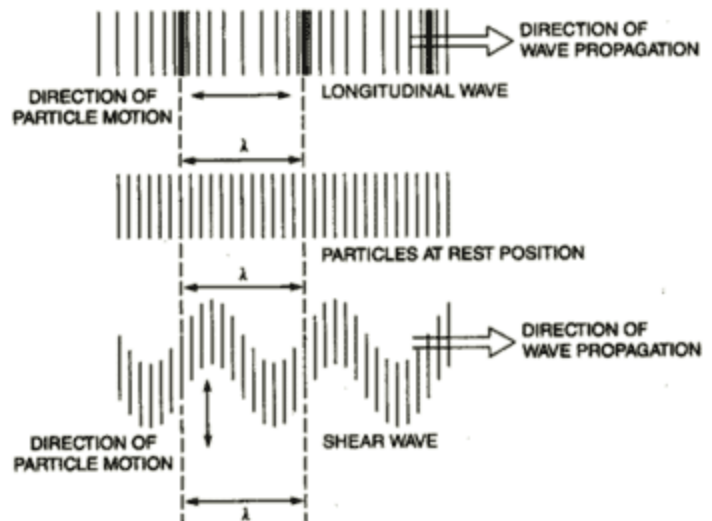
- Surface must be accessible to transmit ultrasound.
- Skill and training is more extensive than with some other methods.
- It normally requires a coupling medium to promote the transfer of sound energy into the test specimen.
- Materials that are rough, irregular in shape, very small, exceptionally 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

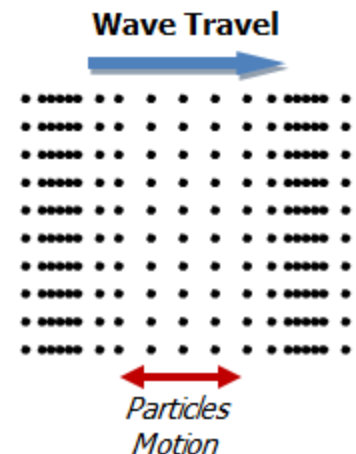
Wave Propagation

Ultrasonic testing is based on the vibration in materials which is generally referred to as acoustics. All material substances are comprised of atoms, which may be forced into vibrational motion about their equilibrium positions. Many different patterns of vibrational motion exist at the atomic level; however, most are irrelevant to acoustics and ultrasonic testing. Acoustics is focused on particles that contain many atoms that move in harmony to produce a mechanical wave. When a material is not stressed in tension or compression beyond its elastic limit, its individual particles perform elastic oscillations. When the particles of a medium are displaced from their equilibrium positions, internal restoration forces arise. These elastic restoring forces between particles, combined with inertia of the particles, lead to the oscillatory motions of the medium.

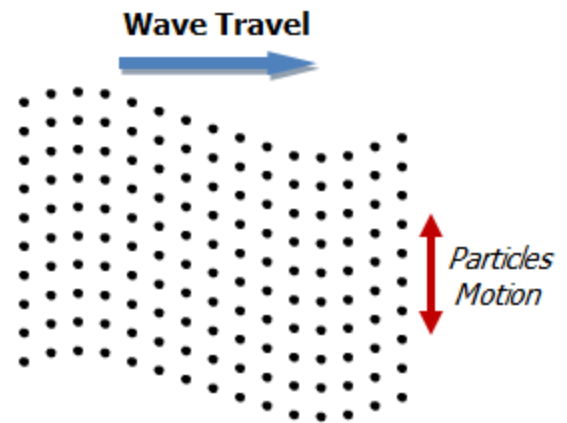
In solids, sound waves can propagate in four principal modes that are based on the way the particles oscillate. Sound can propagate as longitudinal waves, shear waves, surface waves, and in thin materials as plate waves. Longitudinal and shear waves are the two modes of propagation most widely used in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



- 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.



- In the transverse or shear waves, particles oscillate at a right angle or transverse to the direction of propagation. Shear waves 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. In fact, shear waves are usually generated in materials using some of the energy from longitudinal waves.



Modes of Sound Wave Propagation

In air, sound travels by the compression and rarefaction of air molecules in the direction of travel. However, in solids, molecules can support vibrations in other directions. Hence, a number of different types of sound waves are possible. Waves can be characterized by oscillatory patterns that are capable of maintaining their shape and propagating in a stable manner. The propagation of waves is often described in terms of what are called “*wave modes*”.

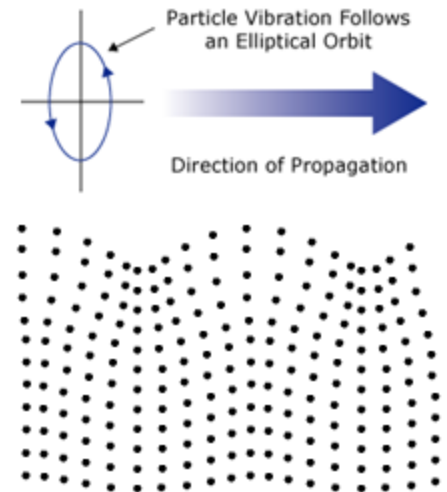
As mentioned previously, longitudinal and transverse (shear) waves are most often used in ultrasonic inspection. However, at surfaces and interfaces, various types of elliptical or complex vibrations of the particles make other waves possible. Some of these wave modes such as Rayleigh and Lamb waves are also useful for ultrasonic inspection.

Though there are many different modes of wave propagation, the table summarizes the four types of waves that are used in NDT.

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

Since longitudinal and transverse waves were discussed previously, surface and plate waves are introduced here.

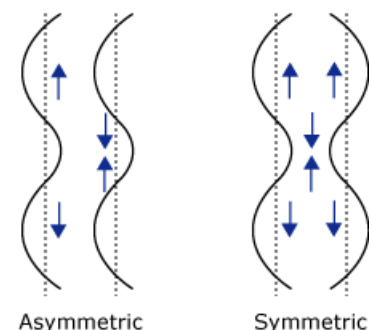
- Surface (or Rayleigh) waves travel at the surface of a relatively thick solid material penetrating to a depth of one wavelength. A surface wave is a combination of both a longitudinal and transverse motion which results in an elliptical motion as shown in the image. The major axis of the ellipse is perpendicular to the surface of the solid. As the depth of an individual atom from the surface increases, the width of its elliptical motion decreases. Surface waves are generated when a longitudinal wave intersects a surface slightly larger than the second critical angle and they travel at a velocity between .87 and .95 of a shear wave. Rayleigh waves are useful because they are very sensitive to surface defects (and other surface features) and they follow the surface around curves. Because of this, Rayleigh waves can be used to inspect areas that other waves might have difficulty reaching.



- Plate (or Lamb) waves are similar to surface waves except they can only be generated in materials a few wavelengths thick (thin plates). Lamb waves are complex vibrational waves that propagate parallel to the test surface throughout the thickness of the material. They are influenced a great deal by the test wave frequency and material thickness. Lamb waves are generated when a wave hits a surface at an incident angle such that the parallel component of the velocity of the wave (in the source) is equal to the velocity of the wave in the test material. Lamb waves will travel several meters in steel and so are useful to scan plate, wire, and tubes.
 - With Lamb waves, a number of modes of particle vibration are possible, but the two most common are symmetrical and asymmetrical. The complex motion of the particles is similar to the elliptical orbits for surface waves.

Symmetrical Lamb waves move in a symmetrical fashion about the median plane of the plate. This is sometimes called the “*extensional mode*” because the wave is stretching and compressing the plate in the wave motion direction.

The asymmetrical Lamb wave mode is often called the “*flexural mode*” because a large portion of the motion is in a normal direction to the plate, and a little motion occurs in the direction parallel to the plate. In this mode, the body of the plate bends as the two surfaces move in the same direction.



Properties of Acoustic Waves

Among the properties of waves propagating in isotropic solid materials are wavelength, 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 following equation:

$$\lambda = \frac{V}{f}$$

Where;

λ : wavelength (m)

V : velocity (m/s)

f : frequency (Hz)

The velocity of sound waves in a certain medium is fixed where it is a characteristic of that medium. As can be noted from the equation, an increase in frequency will result in a decrease in wavelength. For instance, the velocity of longitudinal waves in steel is *5850 m/s* and that results in a wavelength of *5.85 mm* when the frequency is *1 MHz*.

Wavelength and Defect Detection

In ultrasonic testing, the inspector must make a decision about the frequency of the transducer that will be used in order to control the wavelength. The wavelength of the ultrasound used has a significant effect on the probability of detecting a discontinuity. A general rule of thumb is that a discontinuity must be larger than one-half the wavelength to stand a reasonable chance of being detected.

Sensitivity and **resolution** are two terms that are often used in ultrasonic inspection to describe a technique's ability to locate flaws. Sensitivity is the ability to locate small discontinuities. Sensitivity generally increases with higher frequency (shorter wavelengths). Resolution is the ability of the system to locate discontinuities that are close together within the material or located near the part surface. Resolution also generally increases as the frequency increases.

The wave frequency can also affect the capability of an inspection in adverse ways. Therefore, selecting the optimal inspection frequency often involves maintaining a balance between the favorable and unfavorable results of the selection. Before selecting an inspection frequency, the material's grain structure and thickness, and the discontinuity's type, size, and probable location should be considered. As frequency

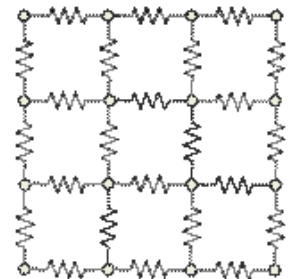
increases, sound tends to scatter from large or coarse grain structure and from small imperfections within a material. Cast materials often have coarse grains and thus require lower frequencies to be used for evaluations of these products. Wrought and forged products with directional and refined grain structure can usually be inspected with higher frequency transducers.

Since more things in a material are likely to scatter a portion of the sound energy at higher frequencies, the ***penetration depth*** (*the maximum depth in a material that flaws can be located*) is also reduced. Frequency also has an effect on the shape of the ultrasonic beam. Beam spread, or the divergence of the beam from the center axis of the transducer, and how it is affected by frequency will be discussed later.

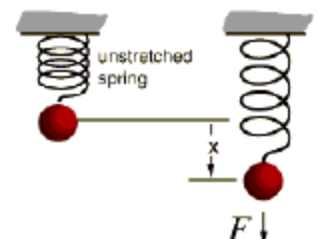
It should be mentioned, so as not to be misleading, that a number of other variables will also affect the ability of ultrasound to locate defects. These include the pulse length, type and voltage applied to the crystal, properties of the crystal, backing material, transducer diameter, and the receiver circuitry of the instrument. These are discussed in more detail in a later section.

Sound Propagation in Elastic Materials

It was mentioned previously that sound waves propagate due to the vibrations or oscillatory motions of particles within a material. An ultrasonic wave may be visualized as an infinite number of oscillating masses or particles connected by means of elastic springs. Each individual particle is influenced by the motion of its nearest neighbor and both inertial and elastic restoring forces act upon each particle.



A mass on a spring has a single resonant frequency (*natural frequency*) determined by its spring constant ***k*** and its mass ***m***. Within the elastic limit of any material, there is a linear relationship between the displacement of a particle and the force attempting to restore the particle to its equilibrium position. This linear dependency is described by Hooke's Law. In terms of the spring model, the relation between force and displacement is written as **$F = kx$** .



The Speed of Sound

Hooke's Law, when used along with Newton's Second Law, can explain a few things about the speed of sound. The speed of sound within a material is a function of the

properties of the material and is independent of the amplitude of the sound wave. Newton's Second Law says that the force applied to a particle will be balanced by the particle's mass and the acceleration of the particle. Mathematically, Newton's Second Law is written as $F = m a$. Hooke's Law then says that this force will be balanced by a force in the opposite direction that is dependent on the amount of displacement and the spring constant. Therefore, since the applied force and the restoring force are equal, $m a = k x$ can be written.

Since the mass m and the spring constant k are constants for any given material, it can be seen that the acceleration a and the displacement x are the only variables. It can also be seen that they are directly proportional. For instance, if the displacement of the particle increases, so does its acceleration. It turns out that the time that it takes a particle to move and return to its equilibrium position is independent of the force applied. So, within a given material, sound always travels at the same speed no matter how much force is applied when other variables, such as temperature, are held constant.

Material Properties Affecting the Speed of Sound

Of course, sound does travel at different speeds in different materials. This is because the mass of the atomic particles and the spring constants are different for different materials. The mass of the particles is related to the density of the material, and the spring constant is related to the elastic constants of a material. The general relationship between the speed of sound in a solid and its density and elastic constants is given by the following equation:

$$V = \sqrt{\frac{C_{ij}}{\rho}}$$

Where;

V : speed of sound (m/s)

C_{ij} : elastic constant "in a given direction" (N/m^2)

ρ : density (kg/m^3)

This equation may take a number of different forms depending on the type of wave (*longitudinal or shear*) and which of the elastic constants that are used. It must also be mentioned that the subscript "*ij*" attached to "*C*" in the above equation is used to indicate the directionality of the elastic constants with respect to the wave type and

direction of wave travel. In isotropic materials, the elastic constants are the same for all directions within the material. However, most materials are anisotropic and the elastic constants differ with each direction. For example, in a piece of rolled aluminum plate, the grains are elongated in one direction and compressed in the others and the elastic constants for the longitudinal direction differs slightly from those for the transverse or short transverse directions.

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

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

Where;

V_L : speed of sound for longitudinal waves (m/s)

E : Young's modulus (N/m^2)

ν : Poisson's ratio

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

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

Where;

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

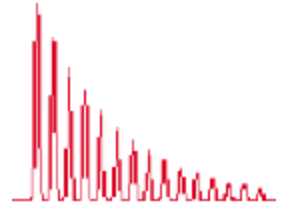
G : Shear modulus of elasticity (N/m^2); $G = E/2(1 + \nu)$

From the above equations, it can be found that longitudinal waves travel faster than shear waves (*longitudinal waves are approximately twice as fast as shear waves*). The table below gives examples of the compressional and shear sound velocities in some metals.

Material	Compressional velocity V_L (m/s)	Shear velocity V_T (m/s)
Aluminum	6320	3130
Steel (1020)	5890	3240
Cast iron	4800	2400
Copper	4660	2330
Titanium	6070	3310

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. Attenuation is generally proportional to the square of sound frequency.



The amplitude change of a decaying plane wave can be expressed as:

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

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.*

The **Decibel (dB)** is a logarithmic unit that describes a ratio of two measurements. The difference between two measurements X_1 and X_2 is described in decibels as:

$$\Delta X \text{ (dB)} = 10 \log \frac{X_2}{X_1}$$

The intensity of sound waves (I) is quantified by measuring the variation in sound pressure using a transducer, and then the pressure is transferred to a voltage signal. Since the intensity of sound waves is proportional to the square of the pressure amplitude, the ratio of sound intensity in decibels can be expressed as:

$$\Delta I \text{ (dB)} = 10 \log \frac{I_2}{I_1} = 10 \log \frac{P_2^2}{P_1^2} = 20 \log \frac{P_2}{P_1} = 20 \log \frac{V_2}{V_1}$$

where;

ΔI : the change in sound intensity between two measurements

V_1 & V_2 : are the two different transducer output voltages (or readings)

Use of dB units allows ratios of various sizes to be described using easy to work with numbers.

Ratio between Measurement 1 and 2	Equation	dB
1/2	$\text{dB} = 20 \log (1/2)$	- 6 dB
1	$\text{dB} = 20 \log (1)$	0 dB
2	$\text{dB} = 20 \log (2)$	6 dB
10	$\text{dB} = 20 \log (10)$	20 dB
100	$\text{dB} = 20 \log (100)$	40 dB

Attenuation can be determined by evaluating the multiple back-wall reflections seen in a typical A-scan display (*like the one shown in the image in the previous page*). The number of decibels between two adjacent signals is measured and this value is divided by the time interval between them. This calculation produces an attenuation coefficient in decibels per unit time. Then knowing the velocity of sound it can be converted to decibels per unit length.

Acoustic Impedance

Sound travels through materials under the influence of sound pressure. Because molecules or atoms of a solid are bound elastically to one another, the excess pressure results in a wave propagating through the solid.

The acoustic impedance (Z) of a material is defined as the product of its density (ρ) and the velocity of sound in that material (V).

$$Z = \rho V$$

Where;

Z : acoustic impedance (kg/m^2s) or ($N s/m^3$)

ρ : density (kg/m^3)

V : sound velocity (m/s)

The table gives examples of the acoustic impedances for some materials:

	Aluminum	Copper	Steel	Titanium	Water (20°C)	Air (20°C)
Acou. Imp. (kg/m^2s)	17.1×10^6	41.6×10^6	46.1×10^6	28×10^6	1.48×10^6	413

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.

Reflection and Transmission Coefficients

Ultrasonic waves are reflected at boundaries where there is a difference in acoustic impedances (Z) of the materials on each side of the boundary. This difference in Z is

commonly referred to as the impedance mismatch. The greater the impedance mismatch, the greater the percentage of energy that will be reflected at the interface or boundary between one medium and another.

The fraction of the incident wave intensity that is reflected can be derived based on the fact that particle velocity and local particle pressures must be continuous across the boundary. When the acoustic impedances of the materials on both sides of the boundary are known, the fraction of the incident wave intensity that is reflected (*the reflection coefficient*) can be calculated as:

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

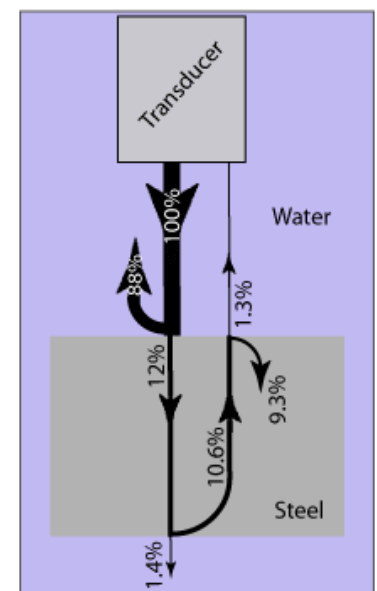
Multiplying the reflection coefficient by 100 yields the amount of energy reflected as a percentage of the original energy.

Where Z_2 & Z_1 are the acoustic impedances of the two materials at the interface.

Since the amount of reflected energy plus the transmitted energy must equal the total amount of incident energy, the "transmission coefficient" is calculated by simply subtracting the reflection coefficient from one ($T = 1 - R$).

Taking for example a water steel interface and calculating the reflection and transmission coefficients (*using the acoustic impedance information given in the previous table*), we get $R = 0.88$ and $T = 0.12$. This means that the amount of energy transmitted into the second material is only 12% while 88% is reflected back at the interface. If we convert the amounts of reflection and transmission to decibels, we find that to be -1.1 dB and -18.4 dB respectively. The negative sign indicates that individually, the amount of reflected and transmitted energy is smaller than the incident energy.

If reflection and transmission at interfaces is followed through the component, only a small percentage of the original energy makes it back to the transducer, even when loss by attenuation is ignored. For example, consider an immersion inspection of a steel block. The sound energy leaves the transducer, travels through the water, encounters the front surface of the steel, encounters the back surface of the steel and reflects back through the front surface on its way back to the transducer. At the water steel interface (front surface), 12% of the energy is transmitted. At the back surface, 88% of the 12% that made it through the front surface is reflected. This is 10.6% of the intensity of the initial incident wave. As the wave exits the part back through the front surface, only 12% of



10.6 or 1.3% of the original energy is transmitted back to the transducer.

Note that in such calculation the attenuation of the signal as it travels through the material is not considered. Should it be considered, the amount of signal received back by the transducer would be even smaller.

Q: What portion of the signal will be reflected at an Air-Steel interface?

A: 99.996%

Refraction and Snell's Law

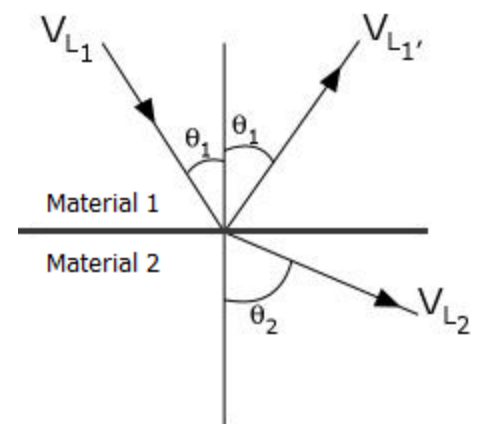
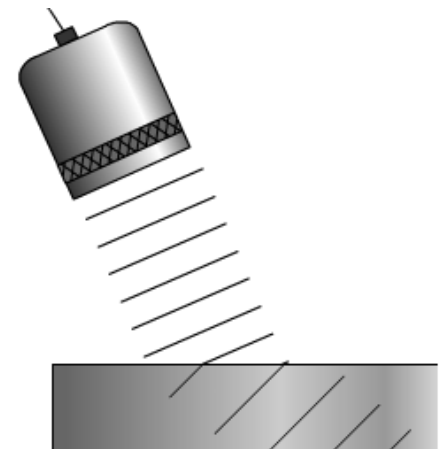
When an ultrasonic wave passes through an interface between two materials at an oblique angle, and the materials have different indices of refraction, both reflected and refracted waves are produced. This also occurs with light, which is why objects seen across an interface appear to be shifted relative to where they really are. For example, if you look straight down at an object at the bottom of a glass of water, it looks closer than it really is.

Refraction takes place at an interface of two materials due to the difference in acoustic velocities between the two materials. The figure shows the case where plane sound waves traveling in one material enters a second material that has a higher acoustic velocity. When 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"*).

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:

$$\frac{\sin \theta_1}{V_{L1}} = \frac{\sin \theta_2}{V_{L2}}$$

Where;



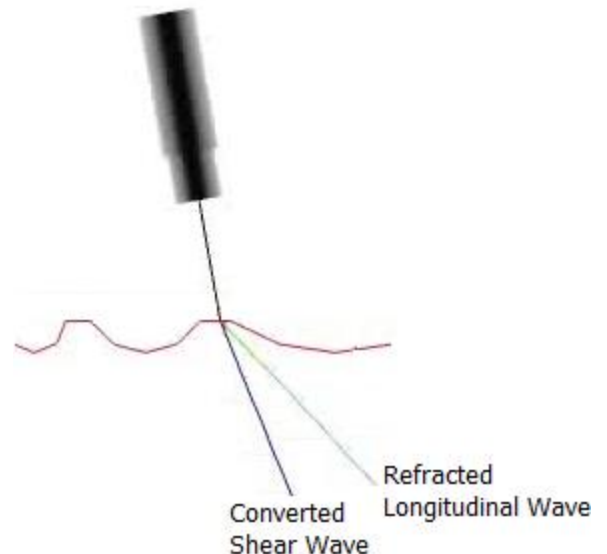
V_{L_1} & V_{L_2} : the longitudinal wave velocities in the first and second materials respectively

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

Note that in the diagram, there is a reflected longitudinal wave (V_{L_1}) shown. This wave is reflected at the same angle as the incident wave because the two waves are traveling in the same material, and hence have the same velocities. This reflected wave is unimportant in our explanation of Snell's Law, but it should be remembered that some of the wave energy is reflected at the interface.

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.



In the previous section, it was pointed out that 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:

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

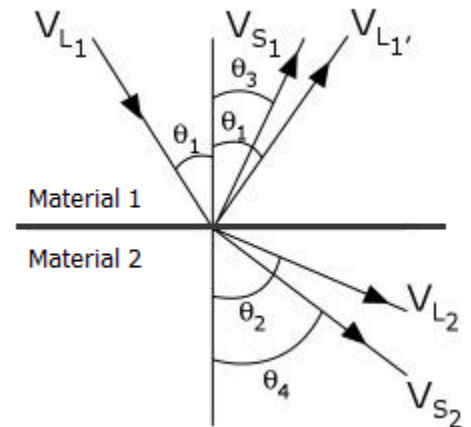
Where;

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

When a longitudinal wave moves from a slower to a faster material (*and thus the wave is refracted*), there is an incident angle that makes the angle of refraction for the "longitudinal wave" to become 90°. This angle is known as **"the first critical angle"**. The first critical angle can be found from Snell's law by putting in an angle of 90° for the angle of the refracted ray. At the critical angle of incidence, much of the acoustic energy is in the form of an inhomogeneous compression wave, which travels along the interface and decays exponentially with depth from the interface. This wave is sometimes referred to as a "*creep wave*". Because of their inhomogeneous nature and the fact that they decay rapidly, creep waves are not used as extensively as Rayleigh surface waves in NDT.

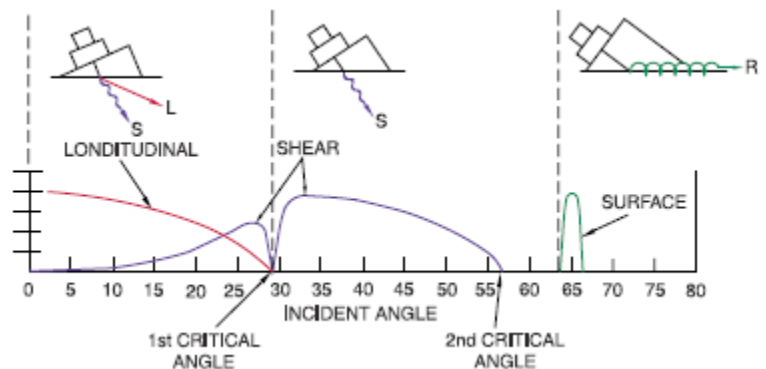
When the incident angle is equal to or greater than the first critical angle, only the mode converted shear wave propagates into the material. For this reason, most angle beam transducers use a shear wave so that the signal is not complicated by having two waves present.

In many cases there is also an incident angle that makes the angle of refraction for the "shear wave" to become 90°. This is known as the **"second critical angle"** and at this

point, all of the wave energy is reflected or refracted into a surface following shear wave or shear creep wave. Slightly beyond the second critical angle, surface (Rayleigh) waves will be generated.

The incident angle for angle-beam transducers is somewhere between the first and second critical angles such that a shear wave, at a desired angle, is introduced into the material being inspected.

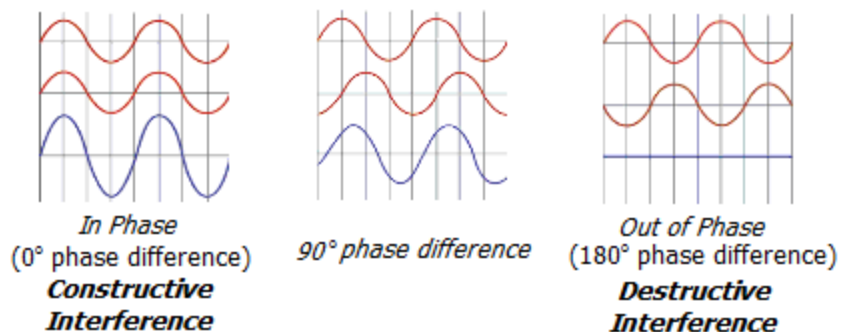
The figure shows the mode of waves introduced into a steel surface as a function of the incident angle of the wave generated by the transducer. It can be seen from the figure that the incident angle for angle beam (*shear*) transducers ranges between 30° to 55° . But it is important to remember that, due to refraction, the angle of the shear wave inside the material is completely different than the incident angle.



Wave Interaction or Interference

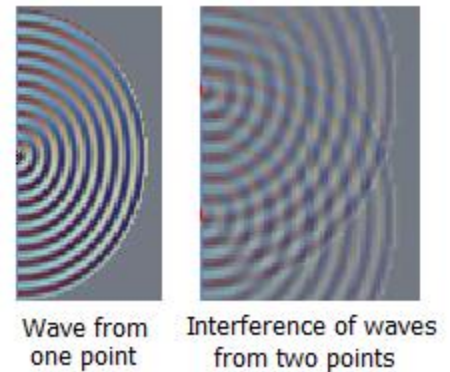
The understanding of the interaction or interference of waves is important for understanding the performance of an ultrasonic transducer. When sound emanates from an ultrasonic transducer, it does not originate from a single point, but instead originates from many points along the surface of the piezoelectric element. This results in a sound field with many waves interacting or interfering with each other.

When waves interact, they superimpose on each other, and the amplitude of the sound pressure at any point of interaction is the sum of the amplitudes of the two individual waves. First, let's consider two identical waves that originate from the same point. When they are in phase (so that the peaks and valleys of one are exactly aligned with those of the other), they combine to double the pressure of either wave acting alone. When they are completely out of phase (so that the peaks of one wave are exactly aligned with the valleys of the other wave), they combine to cancel each other out. When the two waves are not completely in phase or out of phase, the resulting wave



is the sum of the wave amplitudes for all points along the wave.

When the origins of the two interacting waves are not the same, it is a little harder to picture the wave interaction, but the principles are the same. Up until now, we have primarily looked at waves in the form of a 2D plot of wave amplitude versus wave position. However, anyone that has dropped something in a pool of water can picture the waves radiating out from the source with a circular wave front. If two objects are dropped a short distance apart into the pool of water, their waves will radiate out from their sources and interact with each other. At every point where the waves interact, the amplitude of the particle displacement is the combined sum of the amplitudes of the particle displacement of the individual waves.

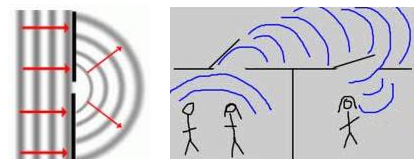


As stated previously, sound waves originate from multiple points along the face of the transducer. The image shows what the sound field would look like if the waves originated from just three points (*of course there are more than three points of origin along the face of a transducer*). It can be seen that where the waves interact near the face of the transducer and as a result there are extensive fluctuations and the sound field is very uneven. In ultrasonic testing, this is known as the “near field” or Fresnel zone. The sound field is more uniform away from the transducer in the “far field” or Fraunhofer zone. At some distance from the face of the transducer and central to the face of the transducer, a uniform and intense wave field develops.

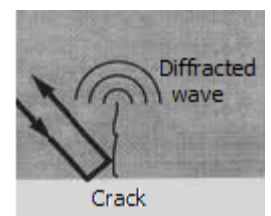


Wave Diffraction

Diffraction involves a change in direction of waves as they pass through an opening or around a barrier in their path. Diffraction of sound waves is commonly observed; we notice sound diffracting around corners or through door openings, allowing us to hear others who are speaking to us from adjacent rooms.



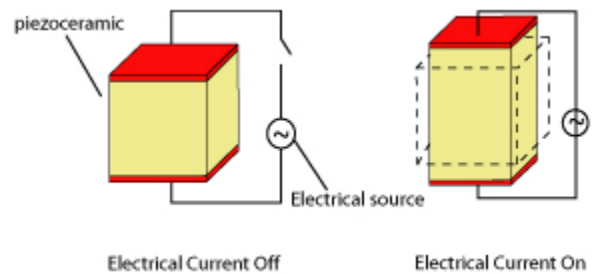
In ultrasonic testing of solids, diffraction patterns are usually generated at the edges of sharp reflectors (or discontinuities) such as cracks. Usually the tip of a crack behaves as point source spreading waves in all directions due to the diffraction of the incident wave.



EQUIPMENT & TRANSDUCERS

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 (SiO_2) or barium titanate (BaTiO_3) 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.



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. A large piezoelectric ceramic element can be seen in the image of a sectioned low frequency transducer. 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.

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.



A cut away of a typical contact transducer is shown in the figure. 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. This keeps waves that are reflected within the matching layer in phase when they exit the layer. 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.

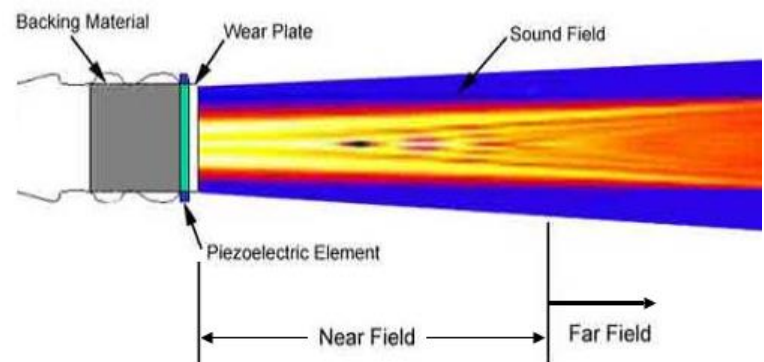
The backing material supporting the crystal has a great influence on the damping characteristics of a transducer. Using a backing material with an impedance similar to that of the active element will produce the most effective damping. Such a transducer will have a wider bandwidth resulting in higher 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. The sound field from a typical piezoelectric transducer is shown in the figure where lighter colors indicating higher intensity. 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 as discussed previously. 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, N , and is sometimes referred to as the “*natural focus*” of a flat (or unfocused) transducer. Spherical or cylindrical focusing changes the structure of a transducer field by “pulling” the N point nearer the transducer. The area just beyond the near field is where the sound wave is well behaved and at its maximum strength. Therefore, optimal detection results will be obtained when flaws occur in this area.

For a round transducer (often referred to as piston source transducer), the near field distance can be found as:

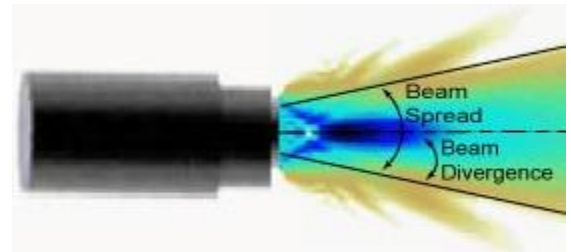
$$N = \frac{D^2 f}{4V}$$

Where;

D : transducer diameter, f : transducer frequency, and V : sound longitudinal velocity in the medium through which waves are transmitted.

Transducer Beam Spread

As the sound waves exits the near field and propagate through the material, the sound beam continuously 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.



Although beam spread must be considered when performing an ultrasonic inspection, it is important to note that in the far field, or Fraunhofer zone, the maximum sound pressure is always found along the acoustic axis (*centerline*) of the transducer. Therefore, the strongest reflections are likely to come from the area directly in front of the transducer.

Beam spread occurs because the vibrating particle of the material (*through which the wave is traveling*) 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.

The beam spread is largely influenced by the frequency and diameter of the transducer. For a flat piston source transducer, an approximation of the beam divergence angle at which the sound pressure has decreased by one half (-6 dB) as compared to its value at the centerline axis can be calculated as:

$$\sin \theta = 1.2 \frac{V}{D f}$$

Where;

θ : the beam divergence angle from centerline to point where signal is at half strength

V : sound velocity in the material

D : diameter of the transducer

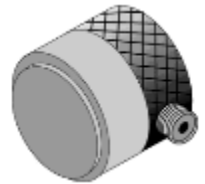
f : frequency of the transducer

Transducer Types

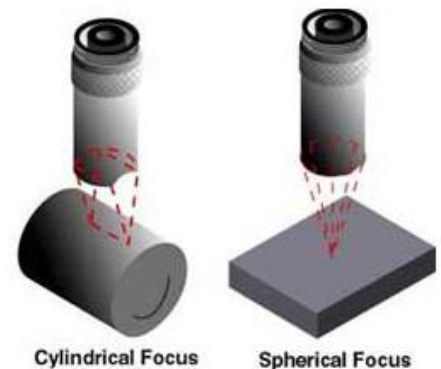
Ultrasonic transducers are manufactured for a variety of applications and can be custom fabricated when necessary. Careful attention must be paid to selecting the proper transducer for the application. It is important to choose transducers that have the desired frequency, bandwidth, and focusing to optimize inspection capability. Most often the transducer is chosen either to enhance the sensitivity or resolution of the system.

Transducers are classified into two major groups according to the application.

Contact transducers are used for direct contact inspections, and are generally hand manipulated. They have elements protected in a rugged 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.



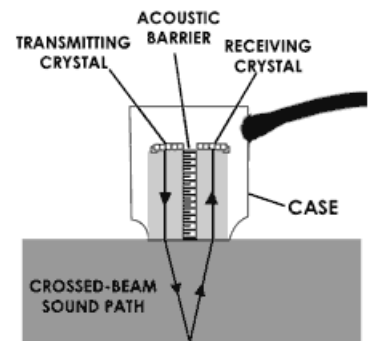
Immersion transducers do not contact the component. These transducers are designed to operate in a liquid environment and all connections are watertight. Immersion transducers usually have an impedance matching layer that helps to get more sound energy into the water and, in turn, into the component being inspected. Immersion transducers can be purchased with a planer, 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.



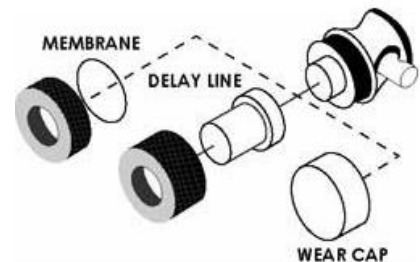
Other Types of Contact Transducers

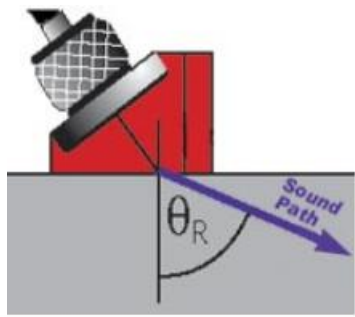

Contact transducers are available in a variety of configurations to improve their usefulness for a variety of applications. The flat contact transducer shown above is used in normal beam inspections of relatively flat surfaces, and where near surface resolution is not critical. If the surface is curved, a shoe that matches the curvature of the part may need to be added to the face of the transducer. If near surface resolution is important or if an angle beam inspection is needed, one of the special contact transducers described below might be used.

- Dual element transducers contain two independently operated elements in a single housing. 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*). 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.



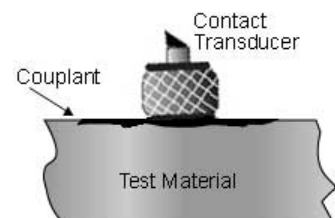
- Delay line transducers provide versatility with a variety of replaceable options. Removable delay line, surface conforming membrane, and protective wear cap options can make a single transducer effective for a wide range of applications. As the name implies, the primary function of a delay line transducer 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. 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.



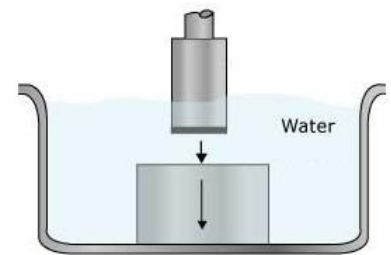
- Angle beam transducers and wedges are typically used to introduce a refracted shear wave into the test material. Transducers can be purchased in a variety of fixed angles or in adjustable versions where the user determines the angles of incidence and refraction. In the fixed angle versions, the angle 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.
- 
- 
- 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.

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 oil, glycerin or water 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.

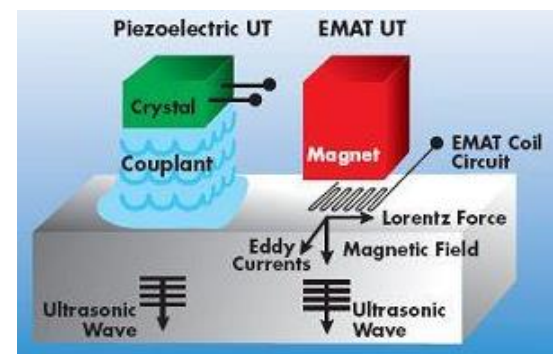


When scanning over the part, an immersion technique is often used. In immersion ultrasonic testing both the transducer and the part are immersed in the couplant, which is typically water. This method of coupling makes it easier to maintain consistent coupling while moving and manipulating the transducer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

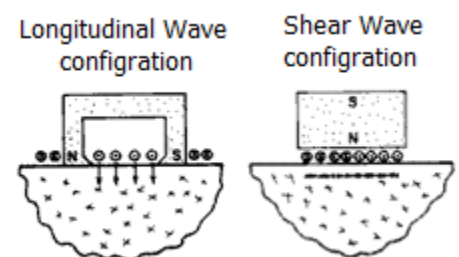


Electromagnetic Acoustic Transducers (EMATs)

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.



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.



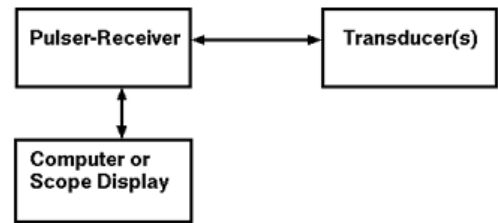
EMATs can be used for thickness measurement, flaw detection, and material property characterization. The EMATs offer many advantages based on its non-contact couplant-free operation. These advantages include the ability to operate in remote environments at elevated speeds and temperatures.

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.

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. Control functions associated with the pulser circuit include:



- *Pulse length or damping*: The amount of time the pulse is applied to the transducer.
- *Pulse energy*: The voltage applied to the transducer. Typical pulser circuits will apply from 100 volts to 800 volts to a 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. Control functions associated with the receiver circuit include:

- *Signal rectification*: The signal can be viewed as positive half wave, negative half wave or full wave.
- *Filtering to shape and smoothing*
- *Gain, or signal amplification*
- *Reject control*

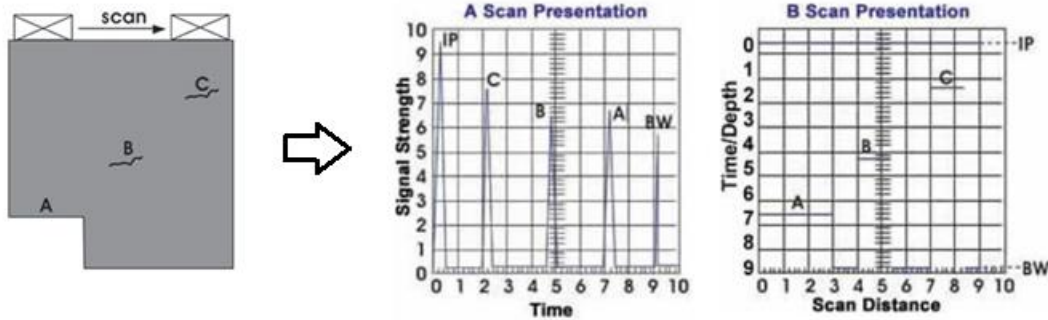
Data Presentation

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*), as a fully rectified RF signal, or as either the positive or negative half of the RF signal. 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.



In the illustration of the A-scan presentation shown in the figure, the initial pulse generated by the transducer is represented by the signal **IP**, which is near time zero. As the transducer is scanned along the surface of the part, four other signals are likely to appear at different times on the screen. When the transducer is in its far left position, only the **IP** signal and signal **A**, the sound energy reflecting from surface **A**, will be seen on the trace. As the transducer is scanned to the right, a signal from the backwall **BW** will appear later in time, showing that the sound has traveled farther to reach this surface. When the transducer is over flaw **B**, signal **B** will appear at a point on the time scale that is approximately halfway between the **IP** signal and the **BW** signal. Since the **IP** signal corresponds to the front surface of the material, this indicates that flaw **B** is about halfway between the front and back surfaces of the sample. When the transducer is moved over flaw **C**, signal **C** will appear earlier in time since the sound travel path is shorter and signal **B** will disappear since sound will no longer be reflecting from it.

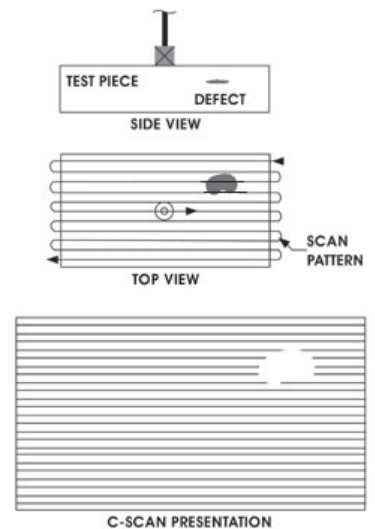
B-Scan Presentation

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. In the B-scan image shown previously, line **A** is produced as the transducer is scanned over the reduced thickness portion of the specimen. When the transducer moves to the right of this section, the backwall line **BW** is produced. When the transducer is over flaws **B** and **C**, lines that are similar to the length of the flaws and at similar depths within the material are drawn on the B-scan. It should be noted that a limitation to this display technique is that reflectors may be masked by larger reflectors near the surface.

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. Typically, a data collection gate is established on the A-scan and the amplitude or the time-of-flight of the signal is recorded at regular intervals as the transducer is scanned over the test piece. The relative signal amplitude or the time-of-flight is displayed as a shade of gray or a color for each of the positions where data was recorded. 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.



High resolution scans can produce very detailed images. The figure shows two ultrasonic C-scan images of a US quarter. Both images were produced using a pulse-echo technique with the transducer scanned over the head side in an immersion scanning system. For the C-scan image on the top, the gate was set to capture the amplitude of the sound reflecting from the front surface of the quarter. Light areas in the image indicate areas that reflected a greater amount of energy back to the transducer. In the C-scan image on the bottom, the gate was moved to record the intensity of the sound reflecting from the back surface of the coin. The details on the back surface are clearly visible but front surface features are also still visible since the sound energy is affected by these features as it travels through the front surface of the coin.



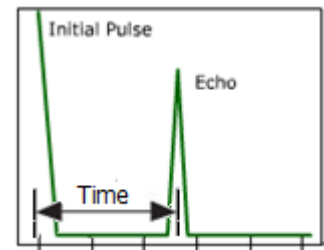
MEASUREMENT AND CALIBRATION TECHNIQUES

Normal Beam Inspection

Pulse-echo ultrasonic measurements can determine the location of a discontinuity in a part or structure by accurately measuring the time required for a short ultrasonic pulse generated by a transducer to travel through a thickness of material, reflect from the back or the surface of a discontinuity, and be returned to the transducer. In most applications, this time interval is a few microseconds or less. 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 in the well-known relationship:

$$d = \frac{V t}{2}$$

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.



Precision ultrasonic thickness gages usually operate at frequencies between 500 kHz and 100 MHz, by means of piezoelectric transducers that generate bursts of sound waves when excited by electrical pulses. Typically, lower frequencies are used to optimize penetration when measuring thick, highly attenuating or highly scattering materials, while higher frequencies will be recommended to optimize resolution in thinner, non-attenuating, non-scattering materials. It is possible to measure most engineering materials ultrasonically, including metals, plastic, ceramics, composites, epoxies, and glass as well as liquid levels and the thickness of certain biological specimens. On-line or in-process measurement of extruded plastics or rolled metal often is possible, as is measurements of single layers or coatings in multilayer materials.

Angle Beam Inspection

Angle beam transducers and wedges are typically used to introduce a refracted shear wave into the test material. An angled sound path allows the sound beam to come in from the side, thereby improving detectability of flaws in and around welded areas.

Angle beam inspection is somehow different than normal beam inspection. In normal beam inspection, the backwall echo is always present on the scope display and when the transducer passes over a discontinuity a new echo will appear between the initial pulse and the backwall echo. However, when scanning a surface using an angle beam transducer there will be no reflected echo on the scope display unless a properly oriented discontinuity or reflector comes into the beam path.

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:

$$\text{Sound Path} = \frac{V_T t}{2}$$

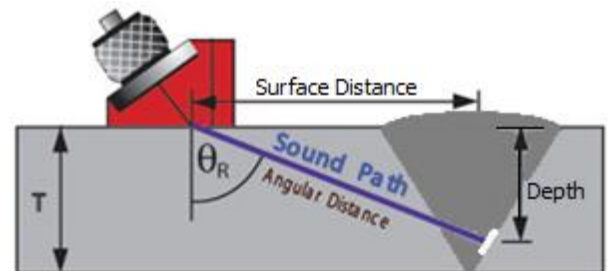
where V_T is the shear sound velocity in the material.

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

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

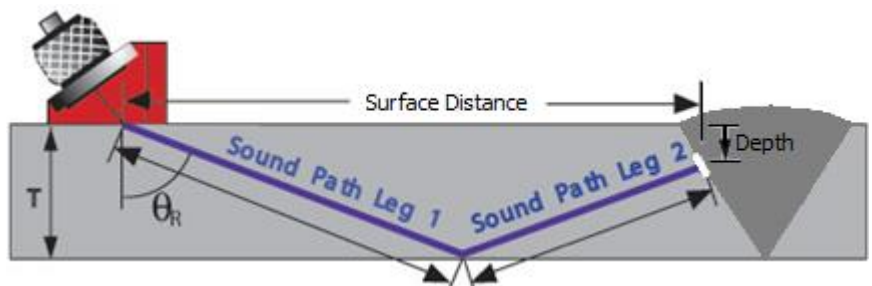
$$\text{Depth}_{1^{st} \text{ leg}} = \text{Sound Path} \times \cos \theta_R$$

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:

$$\text{Depth}_{2^{nd} \text{ leg}} = 2T - (\text{Sound Path} \times \cos \theta_R)$$



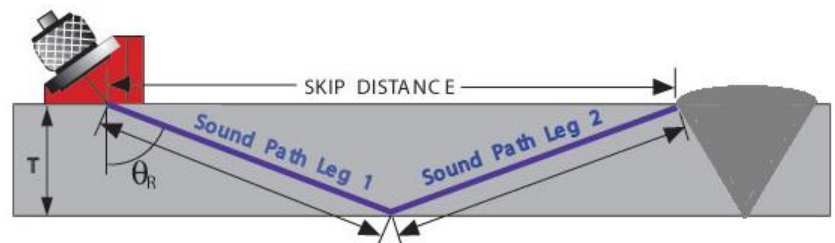
Inspection of Welded Joints

The most commonly occurring defects in welded joints are porosity, slag inclusions, lack of side-wall fusion, lack of intermediate-pass fusion, lack of root penetration, undercutting, and longitudinal or transverse cracks. With the exception of single gas pores all the listed defects are usually well detectable using ultrasonics.

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:



$$\boxed{\text{Skip Distance} = 2 T \times \tan \theta_R}$$

where T is the material thickness.

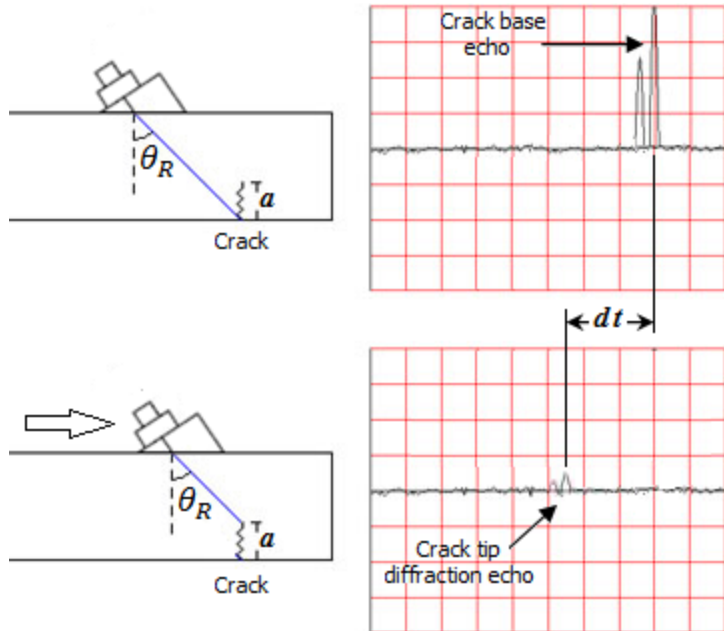
Based on such calculations, the inspector can identify the transducer locations on the surface of the material corresponding to the face, sidewall, and root of the weld.

The angle of refraction for the angle beam transducer used for inspection is usually chosen such that ($\theta_R = 90 - \text{weldment bevel angle}$). 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*). However, for improving the detectability of the different types of weld discontinuities, it is recommended to repeat the scanning using several transducers having different angles of refraction.

Crack Tip Diffraction

When the geometry of the part is relatively uncomplicated and the orientation of a flaw is well known, the length of a crack can be determined by a technique known as “crack tip diffraction”.

One common application of the tip diffraction technique is to determine the length of a crack originating from on the backside of a flat plate as shown below. In this case, when an angle beam transducer is scanned over the area of the flaw, an echo appears on the scope display because of the reflection of the sound beam from the base of the crack (*top image*). As the transducer moves, a second, but much weaker, echo appears due to the diffraction of the sound waves at the tip of the crack (*bottom image*). However, since the distance traveled by the diffracted sound wave is less, the second signal appears earlier in time on the scope.

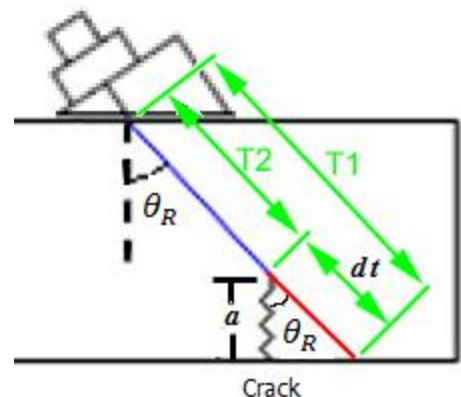


Crack height (a) is a function of the ultrasound shear velocity in the material (V_T), the incident angle (θ_R) and the difference in arrival times between the two signal (dt). Since the beam angle and the thickness of the material is the same in both measurements, two similar right triangles are formed such that one can be overlaid on the other. A third similar right triangle is made, which is comprised on the crack, the length dt and the angle θ_R . The variable dt is really the difference in time but can easily be converted to a distance by dividing the time in half (*to get the one-way travel time*) and multiplying this value by the velocity of the sound in the material. Using trigonometry, we can write:

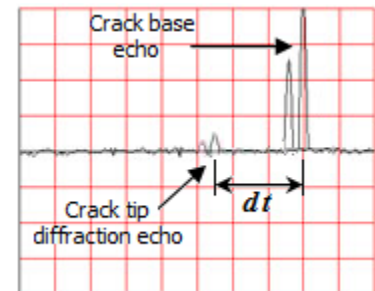
$$a = (\text{Distance } dt) \times \cos \theta_R$$

Therefore, the crack height is found to be:

$$a = \left(\frac{V_T dt}{2} \right) \times \cos \theta_R$$



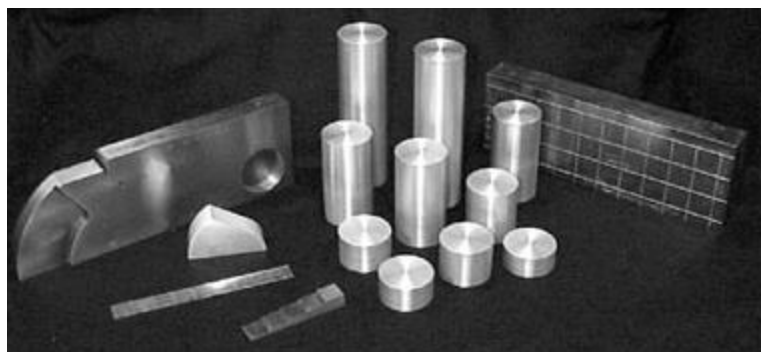
If the material is relatively thick or the crack is relatively short, the crack base echo and the crack tip diffraction echo could appear on the scope display simultaneously (as seen in the figure). This can be attributed to the divergence of the sound beam where it becomes wide enough to cover the entire crack length. In such case, though the angle of the beam striking the base of the crack is slightly different than the angle of the beam striking the tip of the crack, the previous equation still holds reasonably accurate and it can be used for estimating the crack length.



Calibration Methods

Calibration refers to the act of evaluating and adjusting the precision and accuracy of measurement equipment. In ultrasonic testing, several forms of calibrations must occur. 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 and will not be discussed further in this material. It is also usually necessary for the operator to perform a "user calibration" of the equipment. This user calibration is necessary because most ultrasonic equipment can be reconfigured for use in a large variety of applications. 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. The figure shows some of the most commonly used reference standards for the calibration of ultrasonic equipment. 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. Producing more "realistic" defects is cost prohibitive in most cases and, therefore, the inspector can only make an estimate of the flaw size.

Reference standards are mainly used to calibrate instruments prior to performing the inspection and, in general, they are also useful for:

- Checking the performance of both angle-beam and normal-beam transducers (*sensitivity, resolution, beam spread, etc.*)
- Determining the sound beam exit point of angle-beam transducers
- Determining the refracted angle produced
- Calibrating sound path distance
- Evaluating instrument performance (*time base, linearity, etc.*)

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). Only two of the most commonly used standard calibration blocks are introduced here.

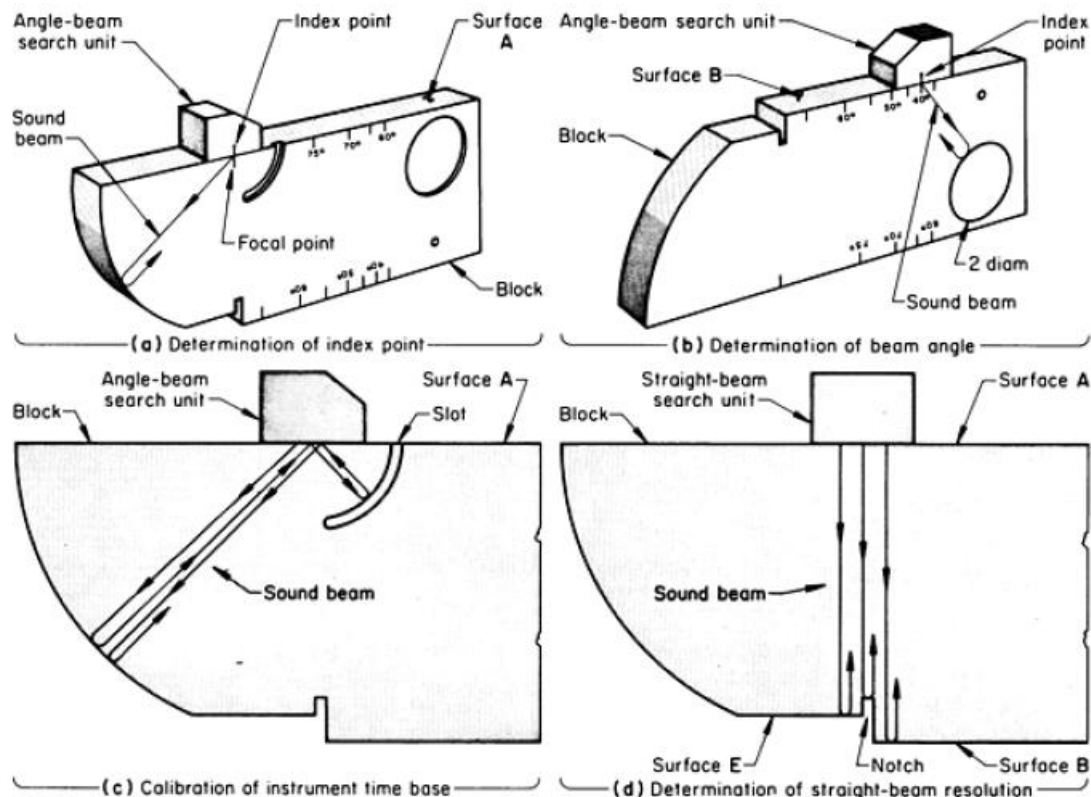
IIW Type US-1 Calibration Block

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 and with a grain size of McQuaid-Ehn No. 8 (*fine grain*). 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 spread, time base, linearity, resolution, dead zone, sensitivity and range setting.



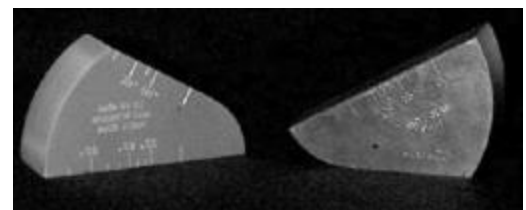
The figure below shows some of the uses of the block.



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.

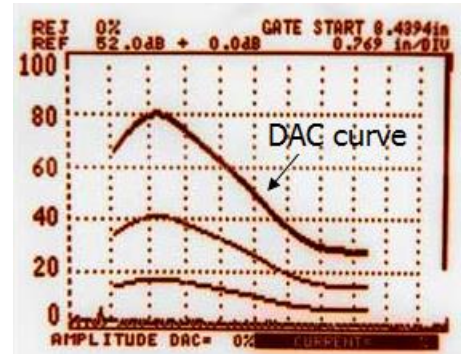
With the miniature block, beam angle and exit point can be checked for an angle-beam transducer. Both the 25 and 50 mm radius surfaces provide ways for checking the location of the exit point of the transducer and for calibrating the time base of the



instrument in terms of metal distance. The small hole provides a reflector for checking beam angle and for setting the instrument gain.

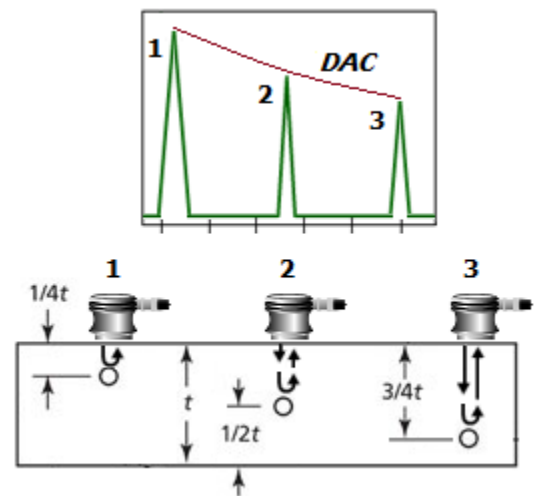
Distance Amplitude Correction (DAC)

Acoustic signals from the same reflecting surface will have different amplitudes at different distances from the transducer. A distance amplitude correction (DAC) curve provides a means of establishing a graphic “reference level sensitivity” as a function of the distance to the reflector (*i.e., time on the A-scan display*). The use of DAC allows signals reflected from similar discontinuities to be evaluated where signal attenuation as a function of depth has been correlated.



DAC will allow for loss in amplitude over material depth (time) to be represented graphically on the A-scan display. Because near field length and beam spread vary according to transducer size and frequency, and materials vary in attenuation and velocity, a DAC curve must be established for each different situation. DAC may be employed in both longitudinal and shear modes of operation as well as either contact or immersion inspection techniques.

A DAC curve is constructed from the peak amplitude responses from reflectors of equal area at different distances in the same material. Reference standards which incorporate side drilled holes (SDH), flat bottom holes (FBH), or notches whereby the reflectors are located at varying depths are commonly used. A-scan echoes are displayed at their non-electronically compensated height and the peak amplitude of each signal is marked to construct the DAC curve as shown in the figure. It is important to recognize that regardless of the type of reflector used, the size and shape of the reflector must be constant.



The same method is used for constructing DAC curves for angle beam transducers, however in that case both the first and second leg reflections can be used for constructing the DAC curve.