What is Ultrasound?

Sound waves, which are all around us, are simply organized mechanical vibrations traveling through a medium, which may be a solid, a liquid, or a gas. This applies to both the everyday sounds that we hear and the ultrasound used for flaw detection. Sound waves will travel through a given medium at a specific speed or velocity, in a predictable direction, and when they encounter a boundary with a different medium they will be reflected or transmitted according to simple rules. This is the principle of physics that underlies ultrasonic flaw detection. In short, ultrasonic waves will reflect from cracks or other discontinuities in a test piece, so by monitoring the pattern of echoes in a part a trained operator can identify and locate hidden internal flaws.

All sound waves oscillate at a specific frequency, or number of vibrations or cycles per second, which we experience as pitch in the familiar range of audible sound. Human hearing extends to a maximum frequency of about 20,000 cycles per second (20 KHz), while the majority of ultrasonic flaw detection applications utilize frequencies between 500,000 and 10,000,000 cycles per second (500 KHz to 10 MHz). At frequencies in the megahertz range, sound energy does not travel efficiently through air or other gasses, but it travels freely through most liquids and common engineering materials like most metals, plastics, ceramics, and composites. Sound waves in the ultrasonic range are much more directional than audible sound, and because of their short wavelengths they are also far more sensitive to small reflectors that lie in their path.

The speed of a sound wave varies depending on the medium through which it is traveling, affected by the medium's density and elastic properties. Different types of sound waves will travel at different velocities.

The ultrasonic waves used for flaw detection are generated and received by small probes called ultrasonic transducers, which convert electrical pulses into sound waves and sound waves into electrical energy. Transducers for flaw detection come in a wide variety of sizes, frequencies, and case styles, but most have a common internal structure.

Typically, the active element of the transducer is a thin disk, square, or rectangle of piezoelectric ceramic or piezocomposite that performs the conversion of electrical energy into mechanical energy (ultrasonic vibrations), and vice versa. When it is excited by an electrical pulse it generates sound waves, and when it is vibrated by returning echoes it generates a voltage. The active element, which is often referred to informally as the crystal, is protected from damage by a wearplate or acoustic lens, and backed by a block of damping material that quiets the transducer after the sound pulse has been generated. This ultrasonic subassembly is mounted in a case with appropriate electrical connections. All common contact, angle beam, delay line, and immersion transducers utilize this basic design. Dual element transducers, commonly used in corrosion survey applications, differ in that they have separate transmitting and receiving elements separated by a sound barrier, n o backing, and an integral delay line to steer and couple the sound energy, rather than a wearplate or lens.

Couplants

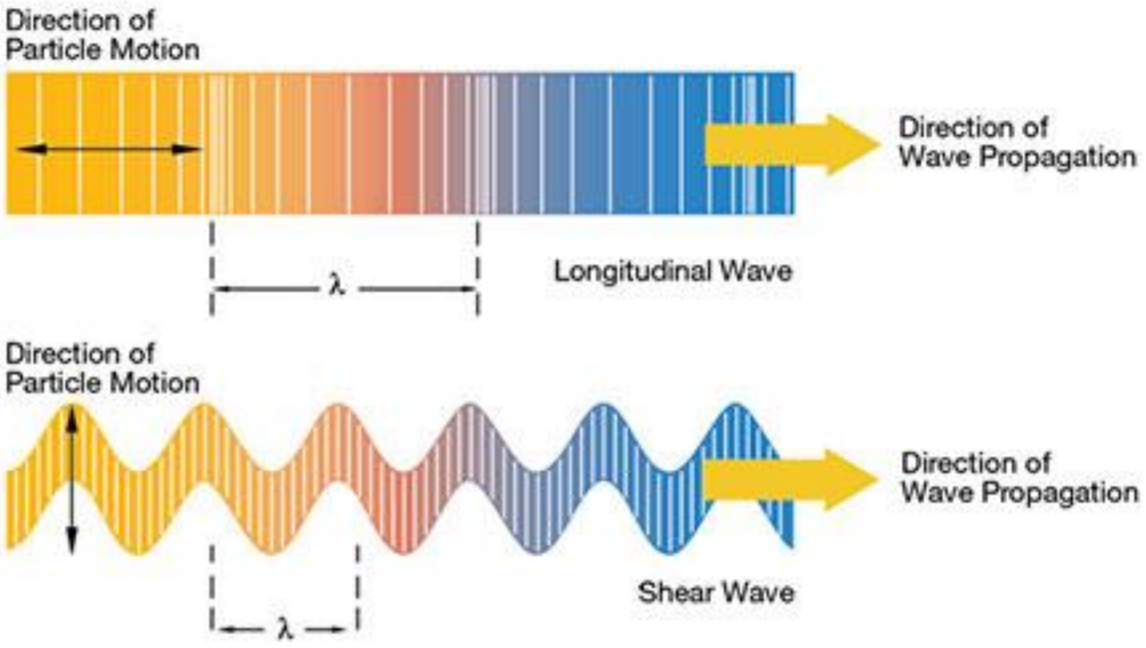
Ultrasonic couplants are used in virtually all contact testing applications to facilitate the transmission of sound energy between the transducer and the test piece. Couplants will typically be moderately viscous, nontoxic liquids, gels, or pastes. Their use is necessary because sound energy at the ultrasonic frequencies typically used for ultrasonic NDT not effectively transmitted through air. Even an extremely thin air gap between the transducer and the test piece will prevent efficient sound energy transmission and make conventional testing impossible.

A number of common substances such as water, motor oil, grease, and even some commercial products like hair gel can be used as ultrasonic couplants in many applications. Specialized couplants are used for high temperature testing and cases where special chemistry such as low halogen content is required.

Wave Propagation

Sound energy used in flaw detection travels in different wave modes based on the direction of the wave and the corresponding motion of molecules in the test piece. The most commonly used modes are longitudinal waves, shear waves, and surface waves.

Longitudinal waves: In a longitudinal wave, particle motion in the medium is parallel to the direction of the wave front. Audible sound waves are longitudinal waves. Longitudinal waves travel the fastest of the wave modes commonly used in ultrasonic NDT, approximately 5900 meters per second (0.23 inches per microsecond) in steel. Longitudinal waves may convert to shear waves through refraction or reflection, as discussed in section 2.5 below.



Shear waves: In a shear wave, particle motion is perpendicular to wave direction. Shear waves have a slower velocity and shorter wavelength than longitudinal waves of the same frequency and are used for most angle beam testing in ultrasonic flaw detection. Typical shear wave velocity in steel is approximately 3250 meters per second (0.128 inch per microsecond). Shear waves can exist in solids only, not in liquids or gasses. They can convert to longitudinal waves through reflection or refraction at a boundary.

Surface waves: Surface waves, also known as Rayleigh waves, represent an oscillating motion that travels along the surface of a test piece to a depth of one wavelength. Velocity and wavelength are similar to shear waves. Ocean waves are an example of surface waves. Surface waves can be used to detect surface-breaking cracks in a test piece.

Several additional wave modes exist but are much less commonly used in ultrasonic flaw detection. These include Lamb waves and various other forms of plate waves and guided waves that are outside the scope of this tutorial.

Beam Characteristics

Conventional single element longitudinal wave ultrasonic transducers work as a piston source of high frequency mechanical vibrations, or sound waves. As voltage is applied, the piezoelectric transducer element (often called a crystal) deforms by compressing in the direction perpendicular to its face. When the voltage is removed, typically less than a microsecond later, the element springs back, generating the pulse of mechanical energy that comprises an ultrasonic wave. The graphic below shows a conceptualized example of how a piezoelectric element responds to a brief electrical pulse.

Transducers of the kind most commonly used for ultrasonic NDT will have these fundamental functional properties:

Type -- The transducer will be identified according to function as a contact, delay line, angle beam, or immersion type. Inspected material characteristics such as surface roughness, temperature, and accessibility as well as the position of a defect within the material and the inspection speed will all influence the selection of transducer type.

Diameter -- The diameter of the active transducer element, which is normally housed in a somewhat larger case.

Frequency -- The number of wave cycles completed in one second, normally expressed in Kilohertz (KHz) or Megahertz (MHz). Most industrial ultrasonic testing is done in the frequency range from 500 KHz to 20 MHz, so most transducers fall within that range, although commercial transducers are available from below 50 KHz to greater than 200 MHz. Penetration increases with lower frequency, while resolution and focal sharpness increase with higher frequency.

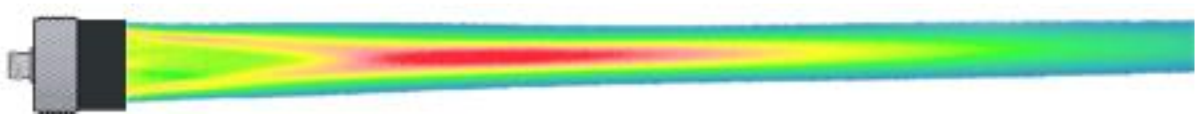
Bandwidth -- The portion of the frequency response that falls within specified amplitude limits. In this context, it should be noted that typical NDT transducers do not generate sound waves at a single pure frequency, but rather over a range of frequencies centered at the nominal frequency designation. The industry standard is to specify this bandwidth at the -6dB (or half amplitude) point.

Waveform duration -- The number of wave cycles generated by the transducer each time it is pulsed. A narrow bandwidth transducer has more cycles than a broader bandwidth transducer. Element diameter, backing material, electrical tuning and transducer excitation method all impact waveform duration.

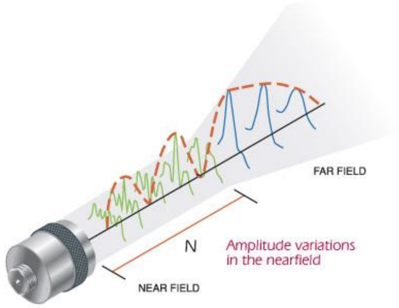
Sensitivity -- The relationship between the amplitude of the excitation pulse and that of the echo received from a designated target.

As a working approximation, the beam from a typical unfocused disk transducer is often thought of as a column of energy originating from the active element area that expands in diameter and eventually dissipates.

In fact, the actual beam profile is complex, with pressure gradients in both the transverse and axial directions. In the beam profile illustration below, red represents areas of highest energy, while green and blue represent lower energy.

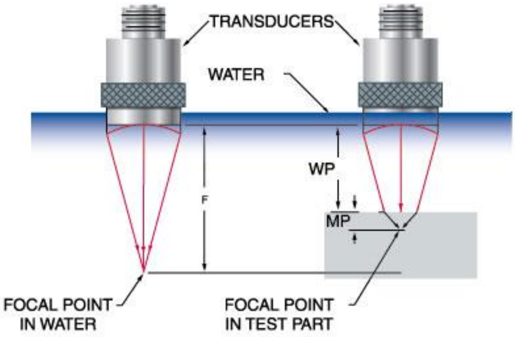


The sound field of a transducer is divided into two zones, the near field and the far field. The near field is the region close to the transducer where the sound pressure goes through a series of maximums and minimums, and it ends at the last on-axis maximum at distance N from the face. Near field distance N represents the natural focus of the transducer.



The far field is the region beyond N where the sound pressure gradually drops to zero as the beam diameter ex
dissipates. The near field distance is a function of the transducer's frequency and diameter, and the sound velo
and it may be calculated as follows for the circular elements most commonly used in ultrasonic flaw detection:

Because of the sound pressure variations within the near field, it can be difficult to accurately evaluate flaws using amplitude based techniques (although thickness gaging within the near field is not a problem). Additionally, N represents the greatest distance at which a transducer's beam can be focused by means of either an acoustic lens or phasing techniques. Immersion transducers can be focused with acoustic lenses to create an hourglass-shaped beam that narrows to a small focal zone and then expands. Certain types of delay line transducers can be focused as well. Beam focusing is very useful when testing small diameter tubing or other test pieces with sharp radiuses, since it concentrates sound energy in a small area and improves echo response.



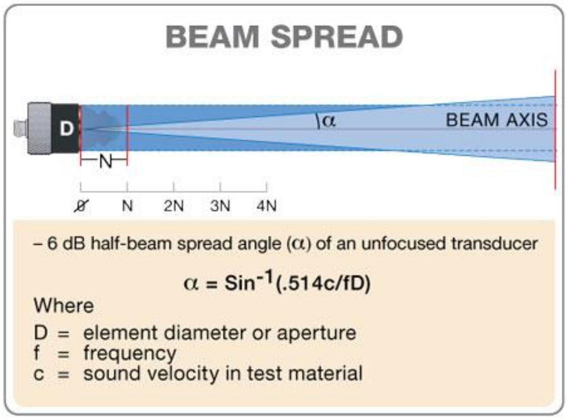
Wave Front Dynamics

Wave front formation

While a single element transducer may be thought of as a piston source, a single disk or plate pushing forward on the test medium, the wave it generates may be mathematically modeled as the sum of the waves from a very large number of point sources. This derives from Huygens' Principle, first proposed by seventeenth-century Dutch physicist Christiaan Huygens, which states that each point on an advancing wavefront may be thought of as a point source that launches a new spherical wave, and that the resulting unified wave front is the sum of all of these individual spherical waves.

Beam spreading

In principle, the sound wave generated by a transducer will travel in a straight line until it encounters a material boundary. What happens then is discussed below. But if the sound path length is longer than the near field distance, the beam will also increase in diameter, diverging like the beam of a spotlight. The beam spread angle of an unfocused transducer can be calculated as follows:



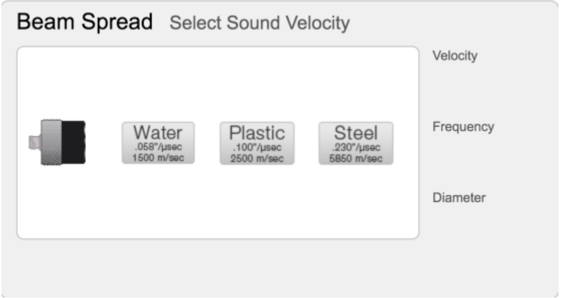
– 6 dB half-beam spread angle (α) of an unfocused transducer

$$\alpha = \sin^{-1}(.514c/fD)$$

Where

D = element diameter or aperture
f = frequency
c = sound velocity in test material

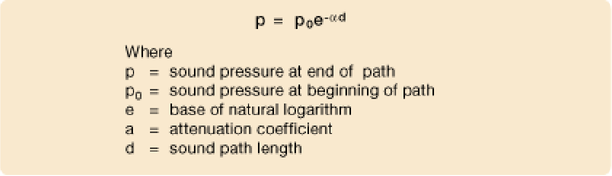
From this equation it can be seen that beam spreading increases with lower frequencies and smaller diameters. Since a large beam spread angle can cause sound energy per unit area to quickly drop with distance, effectively decreasing sensitivity to small reflectors, echo response in some applications involving long sound paths can be improved by using higher frequency and/or larger diameter transducers.



Attenuation

As it travels through a medium, the organized wave front generated by an ultrasonic transducer will begin to break down due to imperfect transmission of energy through the microstructure of any material. Organized mechanical vibrations (sound waves) turn into random mechanical vibrations (heat) until the wave front is no longer detectable. This process is known as sound attenuation.

The mathematical theory of attenuation and scattering is complex. The loss of amplitude due to attenuation across a given sound path will be the sum of absorption effects, which increase linearly with frequency, and scattering effects, which vary through three zones depending on the ratio of the size of grain boundaries or other scatterers to wavelength. In all cases, scattering effects increase with frequency. For a given material at a given temperature, tested at a given frequency, there will be a specific attenuation coefficient, commonly expressed in Nepers per centimeter (Np/cm). Once this attenuation coefficient is known, losses across a given sound path may be calculated according to the equation



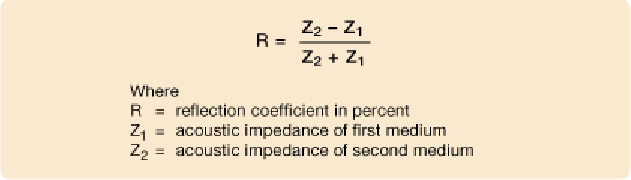
$$p = p_0 e^{-\alpha d}$$

Where
p = sound pressure at end of path
p_0 = sound pressure at beginning of path
e = base of natural logarithm
a = attenuation coefficient
d = sound path length

As a practical matter, in ultrasonic NDT applications attenuation coefficients are normally measured rather than calculated. Higher frequencies will be attenuated more rapidly than lower frequencies in any medium, so low test frequencies are usually employed in materials with high attenuation coefficients like low density plastics and rubber.

Reflection and transmission at a perpendicular plane boundary

When a sound wave traveling through a medium encounters a boundary with a dissimilar medium that lies perpendicular to the direction of the wave, a portion of the wave energy will be reflected straight back and a portion will continue straight ahead. The percentage of reflection versus transmission is related to the relative acoustic impedances of the two materials, with acoustic impedance in turn being defined as material density multiplied by speed of sound. The reflection coefficient at a planar boundary, the percentage of sound energy that is reflected back to the source, may be calculated as follows:



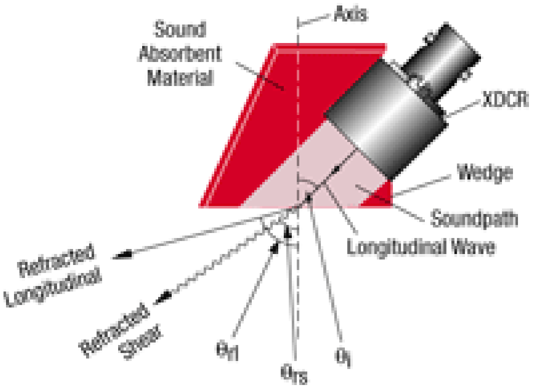
$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

Where
R = reflection coefficient in percent
Z_1 = acoustic impedance of first medium
Z_2 = acoustic impedance of second medium

From this equation it can be seen that as the acoustic impedances of the two materials become more similar, the reflection coefficient decreases, and as the acoustic impedances become less similar, the reflection coefficient increases. In theory the reflection from the boundary between two materials of the same acoustic impedance is zero, while in the case of materials with very dissimilar acoustic impedances, *as in a boundary between steel and air, the reflection coefficient approaches 100%.*

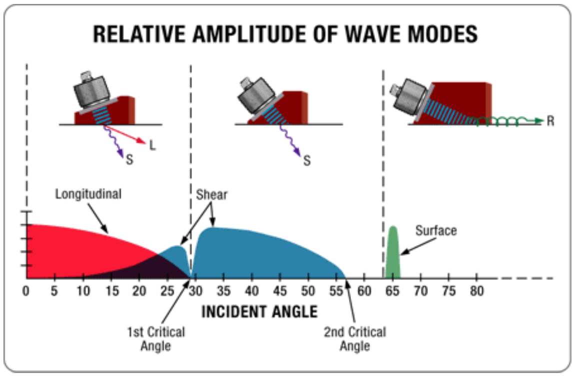
Refraction and mode conversion at non-perpendicular boundaries

When a sound wave traveling through a material encounters a boundary with a different material at an angle other than zero degrees, a portion of the wave energy will be reflected forward at an angle equal to the angle of incidence. At the same time, the portion of the wave energy that is transmitted into the second material will be refracted in accordance with Snell's Law, which was independently derived by at least two seventeenth-century mathematicians. Snell's law related the sines of the incident and refracted angle to the wave velocity in each material as diagramed below.



$$\sin\theta_i/c_i = \sin\theta_{rl}/c_{rl} = \sin\theta_{rs}/c_{rs}$$

θ_i = Incident Angle of the Wedge
θ_{rl} = Angle of the Refracted Longitudinal Wave
θ_{rs} = Angle of the Refracted Shear Wave
c_i = Velocity of the Incident Material (Longitudinal)
c_{rl} = Material Sound Velocity (Longitudinal)
c_{rs} = Velocity of the Test Material (Shear)



If sound velocity in the second medium is higher than that in the first, then above certain angles this bending will be accompanied by mode conversion, most commonly from a longitudinal wave mode to a shear wave mode. This is the basis of widely used angle beam inspection techniques. As the incident angle in the first (slower) medium such as a wedge or water increases, the angle of the refracted longitudinal wave in the second (faster) material such as metal will increase. As the refracted longitudinal wave angle approaches 90 degrees, a progressively greater portion of the wave energy will be converted to a lower velocity shear wave that will be refracted at the angle predicted by Snell's Law. At incident angles higher than that which would create a 90 degree refracted longitudinal wave, the refracted wave exists entirely in shear mode. A still higher incident angle will result in a situation where the shear wave is theoretically refracted at 90 degrees, at which point a surface wave is generated in the second material. The diagram below shows this effect for a typical angle beam assembly coupled into steel.