ULTRASONIC TESTING

NDT METHOD

COURSE MATERIALS

Department of Mechanical Engineering

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1.0 Introduction to Ultrasonic Testing (UT)

Ultrasonic testing uses sound waves to detect imperfections in material and to measure material properties. The most commonly used ultrasonic testing technique is pulse-echo, wherein sound is introduced into a test object and reflections (echoes) returned to a receiver from internal imperfections or from the parts geometrical surfaces are analyzed.

1.1 History of Ultrasonics

Prior to World War II, sonar, the technique of sending sound waves through water and observing the returning echoes to characterize submerged objects, inspired early ultrasound investigators to explore ways to apply the concept to medical diagnosis. In 1929 and 1935, Sokolov discussed the use of ultrasonic waves in detecting metal objects. Mulhauser, in 1931, obtained a patent for using ultrasonic waves, using two transducers to detect flaws in solids.

Firestone (1940) and Simons (1945) developed pulsed ultrasonic testing using a pulse-echo technique. Shortly after the close of World War II, researchers in Japan began to explore medical diagnostic capabilities of ultrasound. The first ultrasonic instruments used an A-mode presentation with blips on an oscilloscope screen. That was followed by a B-mode presentation with a two dimensional, gray scale imaging.

Japan's work in ultrasound was relatively unknown in the United States and Europe until the 1950s. Then researchers presented their findings on the use of ultrasound to detect gallstones, breast masses, and tumors to the international medical community. Japan was also the first country to apply Doppler ultrasound, an application of ultrasound that detects internal moving objects such as blood coursing through the heart for cardiovascular investigation.

Ultrasound pioneers working in the United States contributed many innovations and important discoveries to the field during the following decades. Researchers learned to use ultrasound to detect potential cancer and to visualize tumors in living subjects and in excised tissue. Real-time imaging, another significant diagnostic tool for physicians, presented ultrasound images directly on the system's CRT screen at the time of scanning. The introduction of spectral Doppler and later color Doppler depicted blood flow in various colors to indicate speed of flow and direction.

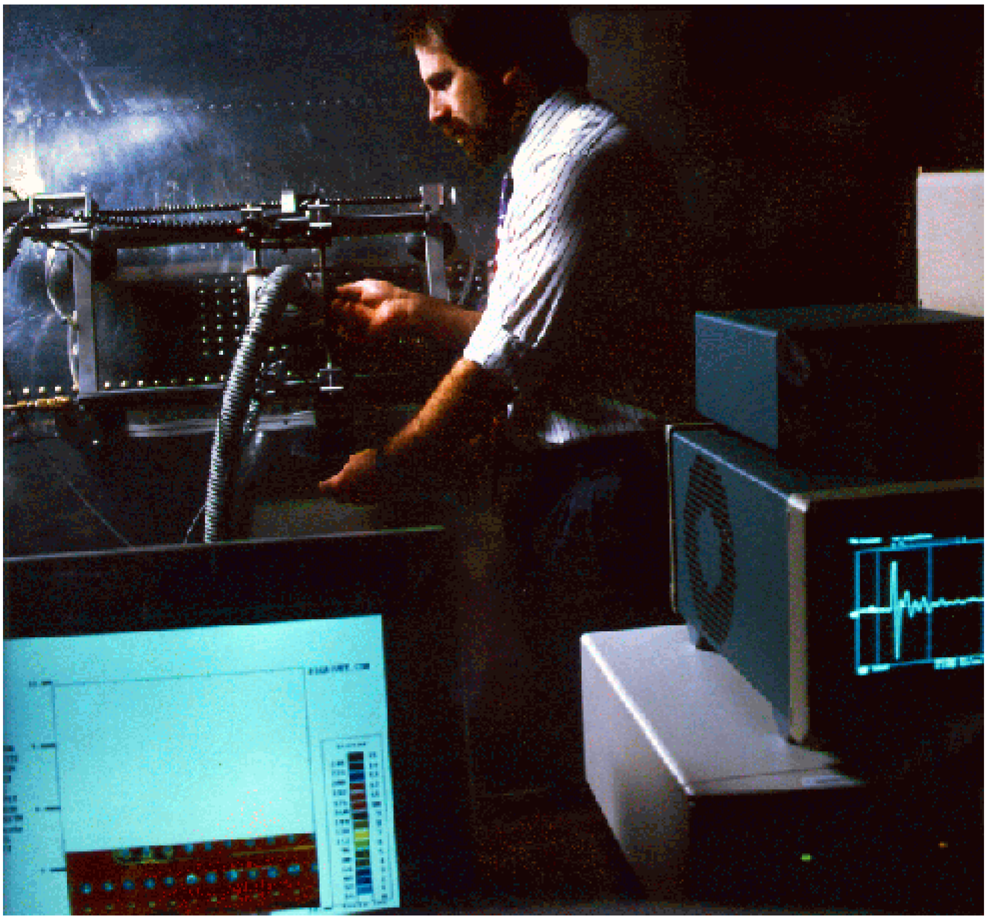
The United States also produced the earliest hand held "contact" scanner for clinical use, the second generation of B-mode equipment, and the prototype for the first articulated-arm hand held scanner, with 2-D images.

1.2 Present State of Ultrasonics

Nondestructive testing has been practiced for many decades, with initial rapid developments in instrumentation spurred by the technological advances that occurred during World War II and the subsequent defense effort. During the earlier days, the primary purpose was the detection of defects. As a part of "safe life" design, it was intended that a structure should not develop macroscopic defects during its life, with the detection of such defects being a cause for removal of the component from service. In response to this need, increasingly sophisticated techniques using ultrasonics, eddy currents, x-rays, dye penetrants, magnetic particles, and other forms of interrogating energy emerged.

In the early 1970's, two events occurred which caused a major change. The continued improvement of the technology, in particular its ability to detect small flaws, led to the unsatisfactory situation that more and more parts had to be rejected, even though the probability of failure had not changed. However, the discipline of fracture mechanics emerged, which enabled one to predict whether a crack of a given size would fail under a particular load if a material property, fracture toughness, were known. Other laws were developed to predict the rate of growth of cracks under cyclic loading (fatigue). With the advent of these tools, it became possible to accept structures containing defects if the sizes of those defects were known. This formed the basis for new philosophy of "fail safe" or "damage tolerant" design. Components having known defects could continue in service as long as it could be established that those defects would not grow to a critical, failure producing size.

A new challenge was thus presented to the nondestructive testing community. Detection was not enough. One needed to also obtain quantitative information about flaw size to serve as an input to fracture mechanics based predictions of remaining life. These concerns, which were felt particularly strongly in the defense and nuclear power industries, led to the creation of a number of research programs around the world and the emergence of quantitative nondestructive evaluation (QNDE) as a new discipline.



In the ensuing years, many important advances have been made. Quantitative theories have been developed to describe the interaction of the interrogating fields with flaws. Models incorporating the results have been integrated with solid model descriptions of real part geometries to simulate practical inspections. These tools allow NDE to be considered, as a part of the design process, on an equal footing with other failure related engineering disciplines. Quantitative descriptions of NDE performance, such as the probability of detection (POD), have become an integral part of statistical risk assessment. Measurement procedures initially developed for metals have been extended to engineered materials, such as composites, in which anisotropy and inhomogeneity become important issues. The rapid advances in digitization and computing capabilities have totally the changed the faces of many instruments and the type of algorithms that can be used in processing the resulting data. High-resolution imaging systems and the use of information from multiple measurement modalities in characterizing a flaw have emerged. An increasing interest is found not only in detecting, characterizing and sizing defects, but in characterizing the materials in which they reside. Goals can range from the determination of fundamental microstructural characteristics such as grain size, porosity and texture (preferred grain orientation) to material properties related to such failure mechanisms as fatigue, creep, and fracture toughness, applications which are sometimes quite challenging due to the existence of competing effects.

1.3 Future Direction of Ultrasonics Education

As one looks to the future, a new set of opportunities present themselves in our rapidly changing society. The industries that played the major role in driving the emergence of QNDE, defense and nuclear power, have been on the wane. Increases in global competition have dramatically changed the product development and business cycles. Finally, the aging of our structural infrastructure, from roads to buildings to aircraft, has presented a new set of measurement and monitoring challenges.

Among the new applications of QNDE spawned by these changes are the increased emphasis on the use of QNDE to improve the productivity of manufacturing processes. Included are the characterization of materials during their development cycles, increasing both the amount of information about failure modes and the speed with which it can be obtained and thus reducing the development cycle time; and the development of in-line measurements for process control. The phrase, "you can not inspect in quality, you must build it in", exemplifies this emphasis on avoiding the formation of flaws. However, the creation and hence need to detect flaws, both during manufacture and in service, will never disappear, and continued development of flaw detection and characterization techniques will be required. Problems associated with aging infrastructure represent an important example. The use of advanced simulation tools to design for inspectability, and the integration of such tools into quantitative strategies for life management will be a key element in increasing the engineering applications of NDE throughout the life cycle.

As the globalization of business continues, companies will increasingly seek to develop uniform practices for use throughout the world. In the area of QNDE, this will drive an increased emphasis on standards, enhanced educational offerings, and simulations which can be easily communicated electronically.

The coming years promise to be an exciting time to be involved in NDE as its emergence as a full-fledged engineering discipline continues.

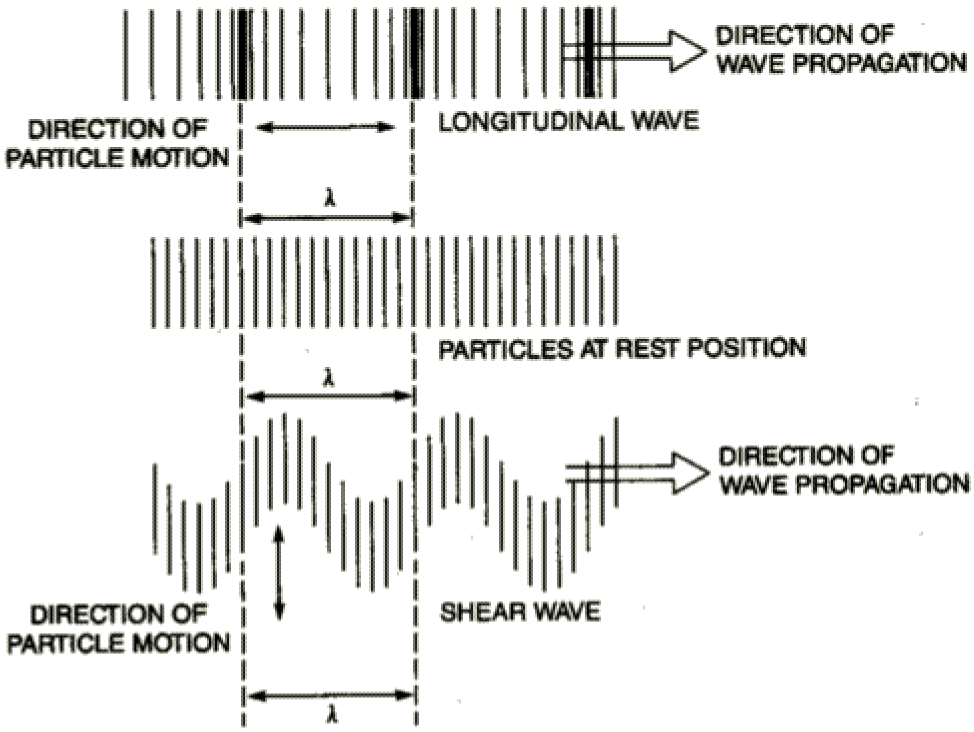
2.0 Basic Physics of Accoustics

2.1 Particle Displacement and Strain

Acoustics is the study of time-varying deformations, or vibrations, in materials. All material substances are composed of atoms, which may be forced into vibrational motion about their equilibrium positions. Many different patterns of vibrational motion exist at the atomic level. Hovever, most of these motional patterns are not relevant to the study of acoustics, which is concerned only with material particles that are small, but yet contain many atoms. Within each particle, the atoms move in unison.

When the particles of a medium are displaced from their equilibrium positions, internal [electro-static] forces arise. It is these elastic restoring forces between particles, combined with inertia of the particles, which lead to oscillatory motions of the medium.

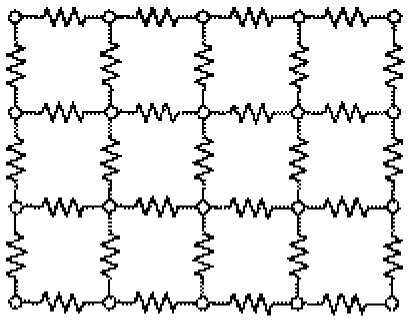
In solids, the particles can oscillate along the direction of sound propagation as ***longitudinal*** waves, or the oscillations can be perpendicular to the direction of sound waves as ***transverse*** waves. At surfaces and interfaces, various types of elliptical or complex vibrations of the particles occur.



Nondestructive testing is mostly done using longitudinal waves or transverse waves. Some advance techniques make use of Rayleigh, Lamb, and other wave modes.

2.2 Elastic Properties of Solids

Within a freely vibrating medium, both inertial and elastic restoring forces act upon each particle. It is the interplay of these forces that produces oscillatory motions in a manner analogous to the free vibration of a macroscopic system of masses and springs. Accordingly, the elastic restoring forces in a medium may be described as microscopic "spring" forces.



This concept is valid and obeys Hook's Law, which states, "Within the elastic limit of any body the ratio of the stress to the strain produced is constant". The model "springs" in the diagram below obeys Newton's second law, **F =** m**a**. Rewritten as **F =** k**x** which obeys Hook's Law, the spring model makes accurate predictions for the propagation of sound.

Sound wave propagation velocity is determined by material properties: elastic constants, C**ij**, and material density, ***p***. The velocity of a longitudinal wave is described by the following equation:

$$(c_{11}/\rho)^{1/2}$$

where C**11** is the elastic constant governing the oscillatory motion in the direction of wave propagation. Shear (transverse) wave velocity is:

$$= (c_{44}/\rho)^{1/2}$$

where C**44** is the elastic constant governing the oscillatory motion in the transverse direction.

2.3 Modes of Sound Waves

In air, sound travels by compression and rarifications of the air molocules in the direction of sound travel. However, in solids, the molocules can support vibrations in other directions, hence, a number of different types (modes) of sound waves are possible. The table below shows some of the wave modes possible in solids.

Wave Type In Solids	**Particle Vibrations**
Longitudinal	Parallel to wave direction
Transverse (Shear)	Perpendicular to wave direction
Surface (Rayleigh)	Elliptical orbit - symmetrical mode
Surface	Bleustein-Gulyaev
Plate Wave - Lamb	Component perpendicular to surface (extensional wave)
Plate Wave - Love	Parallel to plane layer, perpendicular to wave direction
Stoneley (Leaky Rayleigh Waves)	Wave guided along interface
Sezawa	Antisymmetric mode

Piezoelectric transducers are designed to generate *longitudinal* and *transverse* (*shear*) waves, the workhorses of the NDT community. These two wave modes are visualized in the next section. Longitudinal piezoelectric transducers can also generate *Rayleigh* (surface) waves, plate wave modes, such as *Lamb* and *Love* waves, as well as other wave modes. EMATs, like piezoelectric transducers, can generate a wide variety of wave modes. Both piezoelectric transducers and EMATs are discussed in later sections.

2.4 Acoustic Plane Wave in Isotropic Solids

Any mechanical wave is composed of oscillations of discrete particles of material. Provided a material is not stressed by compression or tension beyond its elastic limit, its individual particles perform elastic oscillationsThe top wave is call a ***longitudinal*** wave because the oscillations occur in the longitudinal direction, that is the direction of propagation. Since compressional and dilational forces are active in it, it is also called a ***pressure*** or ***compressional*** wave. Because its particle density fluctuates, it has also been given the name ***density wave***.

This is a sound wave because it transmits the oscillations of a source of acoustic energy through the air to our ears. Experience shows that the same wave also transmits sound through liquid or solid bodies.

In solid bodies another kind of wave can also occur, the ***transverse*** wave (also refered to as ***shear*** wave) shown at the bottom. It can be seen that in this case the particles no longer oscillate in the direction of propagation but at right angles to it, that is transverse.

Among the properties of propagating waves are the quantities, ***wavelength***, ***frequency***, and ***velocity.***

$$V=f/\lambda$$

V=Velocity, F=Frequency, λ=Wavelength

2.5 Attenuation of Sound Waves

It is well known that sound energy decreases with distance traveled. Attenuation is the decrease of sound intensity with distance. In idealized materials, sound pressure (signal amplitude) is only reduced by the spreading of the wave. Natural materials, however, all produce an effect which further weakens the sound. This further weakening results from two basic causes, scattering and absorption. The combined affect of scattering and absorption is called "attenuation". Attenuation of sound is generally proportional to the square of sound frequency.

Attenuation itself is often not of intrinsic interest, however, natural properties and loading conditions can be related to attenuation. Attenuation is often the result of some physical or chemical phenomenon which is of interest, so attenuation provides a measurement for the inductive study of the theories purporting to explain the phenomenon.

Ultrasonic attenuation is the decay rate of mechanical radiation at ultrasonic frequency as it propagates through material. A decaying plane wave is expressed as:

$$A = Ao \exp(-az) \exp[i(wt - kz)]$$

with ***a*** being the attenuation of the wave traveling in the z-direction with propagation constant ***k = 2pi/lambda*** and wavelength ***lambda***. The wave's angular frequency is ***w*** is defined as 2pi times the frequency ***f*** in Hertz (cycles per second).

2.6 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 density, ***p***, and acoustic velocity, ***V***, of that material.

$$Z = pV$$

Acoustic impedance is important in; 1) the determination of acoustic transmission and reflection at the boundary of two materials having different acoustic impedance, 2) the design of ultrasonic transducers, and 3) assessing absorption of sound in a medium.

Furthermore, you may compare two materials and "see" the relative reflection and transmission of sound energy between the two materials. The reflected energy is square of the difference divided by the sum of the acoustic impedances of the two materials.

$$R = \left[\frac{Z_2 - Z_1}{Z_2 + Z_1}\right]^2$$

Note that Transmitted Sound Energy + Reflected Sound Energy = 1

2.7 Reflection and Transmission Coefficients (Pressure)

Ultrasonic waves are reflected at boundaries where there are discontinuities in acoustic impedance, Z. This is commonly referred to as impedance mismatch. The fraction of the incident-wave intensity in the reflected waves can be derived because the particle velocity and local particle pressures are required to be continuous across the boundary between materials.

Note that reflection and transmission coefficients are often expressed in decibels (dB), where decibels are defined as 20 time the log of the reflection or transmission coefficient.

2.8 Snell's Law and Critical Angles

Light and sound are both refracted when passing from one medium to another with different indices of refraction. Because light is refracted at interfaces, objects you see across an interface appear to be shifted relative to where they really are. If you look straight down at an object at the bottom of a glass of water, for example, it looks closer to you than it really is. A good way to visualize how sound refracts is to shine a flashlight into a bowl of slightly cloudy water noting the refraction angle with respect to the incidence angle.

The velocity of sound in each material is determined by the material properties (in the case of sound, elastic modulus and density) for that material. When sound waves pass between materials having different acoustic velocities refraction takes place at an interface.

Snell's law equates the ratio of material velocities **v1** and **v2** to the ratio of the **sines** of incident and refraction angles.

The ***critical angle*** can be found from Snell's law, putting in an angle of 90° for the angle of the refracted ray. For any angle of incidence larger than the critical angle, **Snell's law** will not be able to be solved for the angle of refraction. At the critical angle of incidence, much of the acoustic energy is mode converted to a Rayleigh (surface) wave.

2.9 Refraction and Mode Conversion

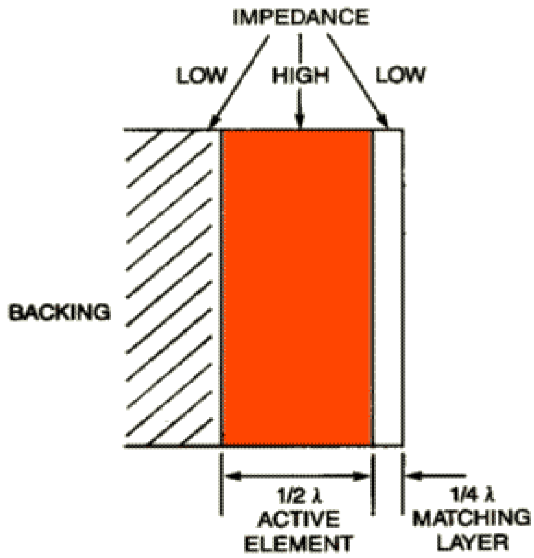
In contrast to optics, with sound, a new phenomenon can occur in which one kind of wave can be transformed into another, for example longitudinal waves into transverse waves an vice versa. Mode conversion, i.e., the conversion of the mode of sound wave propagation, occurs at interfaces between materials of different acoustic impedances.

In the previous section it was pointed out that the velocity of sound in each material is determined by the material properties (elastic modulus and density) for that material. When sound waves pass between materials having different acoustic velocities, refraction takes place at an interface.

3.0 Equipment and Transducers

3.1 Piezoelectric Transducers

The active element of most acoustic transducers is **piezoelectric ceramic**. This ceramic is the heart of the transducer which converts electrical to acoustic energy, and vice versa. Piezoelectric ceramics were introduced in the early 1950s. Preceding the advent of piezoelectric ceramic, piezoelectric crystals made from quartz and magnetostrictive materials were used in the design of underwater transducers. Due to the high costs to manufacture and limitations in the piezoelectric properties of both these materials they are rarely used in transducers today.

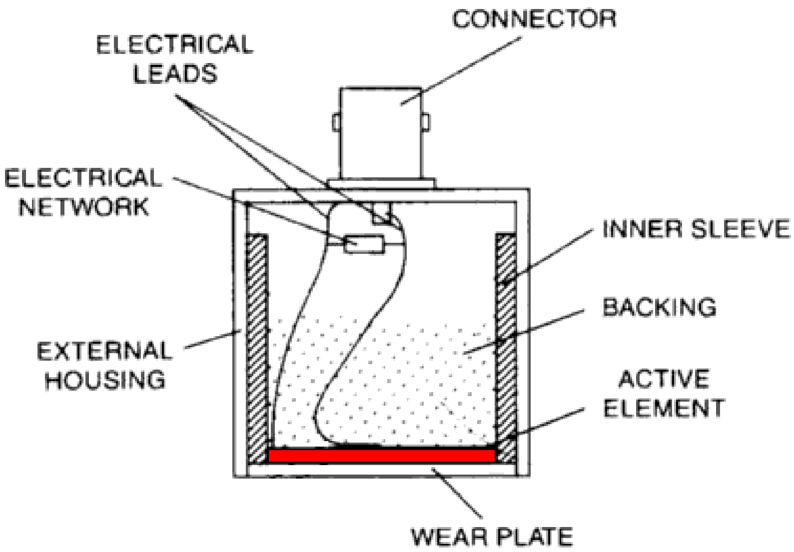


A thin waffer vibrates with a wavelength that is twice its thickness, therefore, piezoelectric crystals are cut to a thickness that is 1/2 the desired radiated wavelength. Optimal impedance matching is achieved by a matching layer with thickness 1/4 wavelength.

When piezoelectric ceramics were introduced they soon became the dominant materials for transducers due to their good piezoelectric properties and their ease of manufacture into a variety of shapes and sizes. The first piezoceramic in general use was barium titanate, and that was followed during the 1960s by lead zirconate titanate compositions, which are now the most commonly employed ceramic for making transducers.

3.1.1 Characteristics of Piezoelectric Transducers

An important feature of any ultrasonic instrumentation system is the transducer. This typically incorporates a **piezoelectric element**, which converts electrical signals into mechanical vibrations (transmit mode) and into mechanical vibrations electrical signals (receive mode). The ultrasonic field from such a transducer is often the feature that limits the performance of a given system.



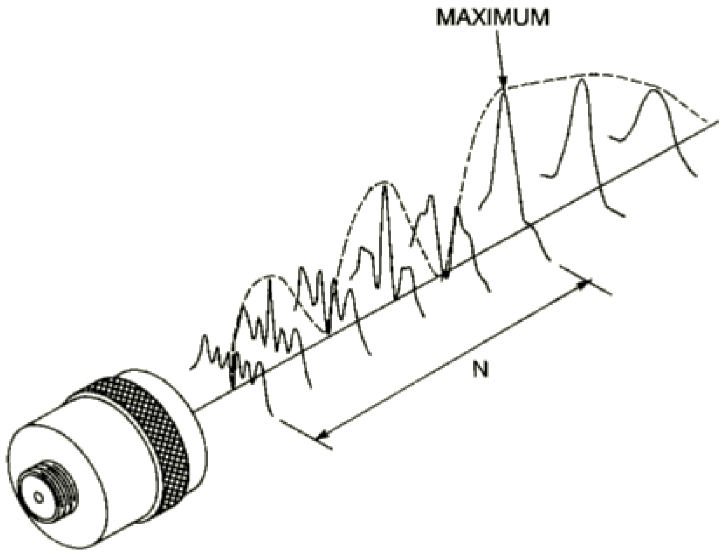
There are many factors, which influence the behavior, a transducer, including the choice of material, mechanical and electrical construction and the external mechanical and electrical load conditions. Mechanical construction is the greatest factor influencing performance, with parameters such as radiation surface area, mechanical damping, housing, and other variables of physical construction being important. As of this writing, transducer manufactures have a devil of a time constructing two transducers that have identical performance characteristics. Transducer manufacture still has a "black art" component.

3.1.2 Radiated Fields of Ultrasonic Transducers (Fresnel and Fraunhofer Effects)

Ultrasound intensity along the beam is not uniform, but varies due to the limited size of the source that gives rise to diffraction effects. There are extensive fluctuations near the source, known as the near field (near zone) or Fresnel zone. Because of the variations within the near field, it can be extremely difficult to accurately evaluate flaws in materials.

The ultrasonic beam is more uniform in the far field, or Fraunhofer zone, where the beam spreads out as if originating from the center of the transducer.

The transition between these zones occurs at a distance, ***N*** and is sometimes referred to as the "natural focus" of a flat (of unfocused) transducer. The near/far distance, ***N*** is significant because amplitude variations that characterize the near field (and can make flaw evaluation difficult) change to a smoothly declining amplitude as the distance from the transducerincreases.



The sound that eminates from a piezoelectric transducer does not originate from a point, but instead originates from most of the surface of the piezoelecric element. Round transducers are often referred to as piston source transducers because the sound field resembles a cylindrical mass in front of the transducer.

Spherical or cylindrical focusing changes the structure of the transducer field by "pulling" the *N* point nearer the transducer, to the focal point of the transducer. It is important to note that the driving excitation normally used in NDT applications is either spike or rectangular pulsars, not single frequency. They can significantly alter the performance of a transducer. Nonetheless, the supporting analysis is widely used because it represents a reasonable approximation and a good starting point.

3.1.3 Transducer Beam Spread

The sound that emanating from a piezoelectric transducer does not originate from a point, but instead, originates from most of the surface of the piezoelecric element. Round transducers are often referred to as piston-source transducers because the sound field resembles a cylindrical mass in front of the transducer. In the far field, or Fraunhofer zone, the maximum sound pressure is always found along the acoustic axis of the transducer.

Beam angle is an important consideration in transducer selection. It defines how much the beam will spread with distance. Beam angle is largely determined by the frequency of the sound waves. A high frequency transducer produces a narrow beam. A low frequency produces a wider beam. Beam angle can be shaped to some extent in the physical design of a transducer.

Characterisation of soundfields generated by ultrasonic transducers is a pre-requisite to understanding observed signals in traditional ultrasonic testing and to provide the operator a method of determining if a probe has been constructed to the required specifications for a particular application. Numerous codes exist around the world that can be used to standardize the method used for this characterization. In North America the most commonly used standards are those established by the American Society for Testing and Materials (ASTM).

ASTM E-1065 has addressed methods for ascertaining beam shapes in Section A6 "Measurement of Sound Field Parameters"; however, these measurements are limited to immersion probes (see Note 2 after Paragraph 4.1.5.3 page 455 of the 1995 edition). In fact, the methods described in E-1065 are primarily concerned with the measurement of beam characteristics in water and as such are limited to measurements of the compression mode only. Techniques described in E-1065 include pulse-echo using a ball target and hydrophone receivers. Such setups allow the soundfield of the probe to be assessed for the entire volume infront of the probe.

For a flat piston source transducer the beam shape, often referred to as beam spread, an approximation may be calculated as a function of radius (***a***), frequency (***f***), and velocity (***V***) of a liquid or solid medium.

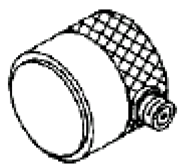
The applet below allows the user to calculate the beam spread angle which represents a falling of sound pressure (intensity) to the side of the acoustic axis of one half (-6 dB) as a function of transducer parameters radius and frequency and as a function of acoustic velocity in a medium.

3.1.4 Transducer Types

Transducer manufactures make ultrasonic transducers for applications as diverse as flaw detection, thickness gaging, materials research, and medical diagnostics. As a result a good deal of attention should be paid to selecting the proper transducer for the application. Of equal importance is the performance of the system as a whole. Variations in instrument characteristics and settings as well as material properties and coupling conditions play a major role in system performance.

Most often the transducer is chosen to enhance either the sensitivity or the resolution of the system.

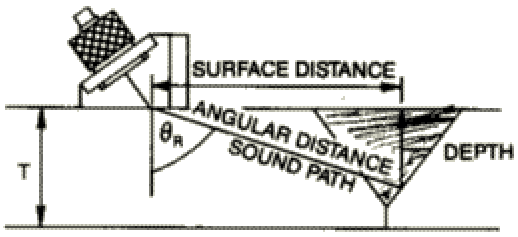
Contact Transducers - are rugged enough to withstand direct contact testing of metals and versatile enough to be used on materials such as composites and plastics. Features such as wear plates and ergonomic sleeves make contact transducers highly durable and easy to grip while different case styles provide enough variety to cover a wide range of applications.



Dual Element Transducers - contain two elements in a single housing allowing transmitter and receiver to operate independently. With single element transducers, operating in pulse echo mode, the receiving electronics can be saturated (be overwhelmed) during the transmission pulse. Receivers require a finite amount of time to recover from saturation. The two elements are angled towards each other to create a crossed-beam sound path in the test material.

Immersion Transducers - are specifically designed to transmit ultrasound in situations where the test part is partially or wholly immersed in fresh water. Typically, immersion transducers are used inside a water tank in scanning applications or as part of a squirter or bubbler system. A focused immersion transducer can improve sensitivity and axial resolution by concentrating the sound energy in a small area.

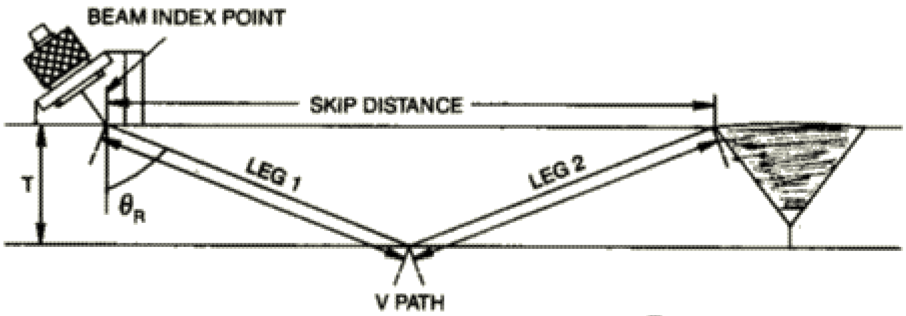
Angle Beam Transducers - and wedges are typically used to introduce a refracted shear wave into the test material. The angled sound path allows the sound beam to be reflected from the back wall to improve delectability of flaws in and around welded areas.



Surface Distance = Sin θ_R × Sound Path

Depth (1st Leg) = Cos θ_R × Sound Path

Depth (2nd Leg) = 2T − [Cos θ_R × Sound Path]



θ_R = Refracted Angle

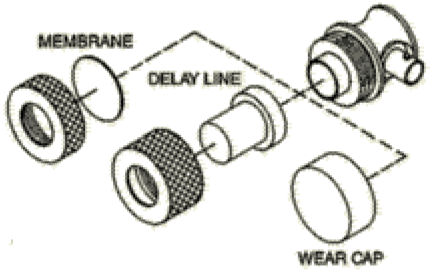
T = Material Thickness

$$\text{Leg} = \frac{T}{\cos \theta_R}$$

$$\text{V-Path} = \frac{2T}{\cos \theta_R}$$

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

Delay Line Transducers - provide versatility with a variety of replaceable options. Removable delay line, protective membrane, and protective wear cap options can make a single transducer effective for a wide range of applications. The Standard Protected Face Transducer Series is recommended for general purpose contact scanning and for use on high temperature materials. Replaceable Delay Line Transducers are recommended for applications that require a contact transducer with good near surface resolution while providing the economy and versatility of a removable delay line configuration. They are designed for use in applications such as high precision thickness gaging of thin materials and delamination checks in composite materials.



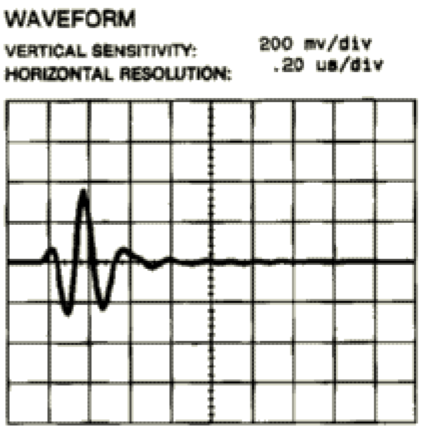
Normal Incidence Shear Wave Transducers - are unique because they allow introduction of shear waves directly into the test piece without the use of an angle beam wedge. Careful design has enabled manufacturing of transducers with minimal longitudinal wave contamination. The ratio of the longitudinal to shear wave components is generally below -30dB.

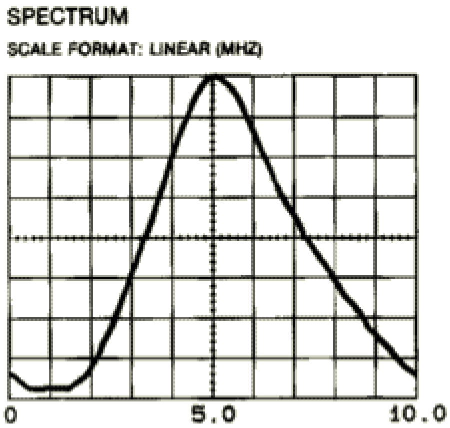
High Frequency Transducers - In many specialized applications the use of high frequency ultrasonic transducers and instrumentation can dramatically improve flaw resolution and minimum thickness measurement capabilities. High frequency broadband transducers are commercially available between 20MHz and 150MHz.

In addition to the transducers listed above, many manufactures offer special design and application specific transducers for medical, industrial and OEM applications.

3.1.5 Transducer Testing

Some transducer manufactures have lead in the development of transducer characterization techniques and has participated in the development of the AIUM Standard Methods for Testing Single-Element Pulse-Echo Ultrasonic Transducers as well as ASTM-E 1065 Standard Guide for Evaluating Characteristics of Ultrasonic Search Units.





Additionally some manufactures perform characterizations according to AWS, ESI, and many other industrial and military standards. Often equipment in test labs is maintained in compliance with MIL-C-45662A Calibration System Requirements. As part of the documentation process an extensive database containing records of the waveform and spectrum of each transducer is maintained and can be accessed for comparative or statistical studies of transducer characteristics.

Manufactures often provide time and frequency domain plots for each transducer. The signals below were generated by a spiked pulser. The waveform image on the left shows the test response signal in the time domain (amplitude versus time). The spectrum image on the right shows the same signal in the frequency domain (amplitude versus frequency). The signal path is usually a reflection from the back wall (fused silica) with the reflection in the far field of the transducer.

Other tests may include:

Electrical Impedance Plots provide important information about the design and construction of a transducer and can allow users to obtain electrically similar transducers from multiple sources.

Beam Alignment Measurements provide data on the degree of alignment between the sound beam axis and the transducer housing. This information is particularly useful in applications that require a high degree of certainty regarding beam positioning with respect to a mechanical reference surface.

Beam Profiles provide valuable information about transducer sound field characteristics. Transverse beam profiles are created by scanning the transducer across a target (usually either a steel ball or rod) at a given distance from the transducer face and are used to determine focal spot size and beam symmetry. Axial beam profiles are created by recording the pulse-echo amplitude of the sound field as a function of distance from the transducer face and provide data on depth of field and focal length.

3.1.6 Transducer Characterization

As noted in the ASTM E1065 Standard Guide for Evaluating Characteristics of Ultrasonic Transducers, the acoustic and electrical characteristics which can described from the data, are obtained by procedures outlined as follows:

Frequency Response--The frequency response may be obtained from one of two procedures: (a) shock excitation and (b) sinusoidal burst.

Relative Pulse-Echo Sensitivity--The relative pulse-echo sensitivity may be obtained from the frequency response data obtained using a sinusoidal burst procedure. The value is obtained from the relationship of the amplitude of the voltage applied to the transducer and the amplitude of the pulse-echo signal received from a specified target.

Time Response--The time response provides a means for describing the radio frequency (rf) response of the waveform. A shock excitation, pulse-echo procedure is used obtain the response. The time or waveform responses are recorded from specific targets that are chosen for the type of transducer under evaluation (for example, immersion, contact straight beam, or contact angle beam).

Typical time and frequency domain plots provided by transducer manufacturers

Frequency Response--The frequency response of the above transducer has a peak at 5 MHz, and operates over a broad range of frequencies. Its bandwidth (4.1 to 6.15 MHz) is measured at the -6 dB points, or 70 percent of the peak frequency. The useable bandwidth of broadband transducers, especially in frequency analysis measurements, is often quoted at the -20 dB points. Transducer sensitivity and bandwidth (more of one means less of the other) are chosen based on inspection needs.

Complex Electrical Impedance--The complex electrical impedance may be obtained with commercial impedance measuring instrumentation, and these measurements may be used to provide the magnitude and phase of impedance of the search unit over the operating frequency range of the unit. These measurements are generally made under laboratory conditions with minimum cable lengths or external accessories and in accordance with the specifications of the instrument manufacturer. The value of magnitude of the complex electrical impedance may also obtained using values recorded from the sinusoidal burst.

Sound Field Measurements--The objective of these measurements is to establish parameters such as the on-axis and transverse sound beam profiles for immersion flat and curved transducers. These measurements are often achieved by scanning the sound field with a hydrophone transducer mapping the sound fields in three-dimensional space. An alternative approach to sound field measurements is a measure of the transducer's radiating surface motion using laser interferometry.

3.2 Electromagnetic Acoustic Transducers (EMATs)

One of the essential features of ultrasonic measurements is the mechanical coupling between the transducer, generally a piezoelectric disk, and the solid, whose properties or structure are to be studied. This coupling is generally achieved in one of two ways. In immersion measurements, energy is coupled between the transducer and the sample by placing them in a tank filled with a fluid, generally water. In contact measurements, the transducer is pressed directly against the sample, and coupling is achieved by the presence of a thin fluid layer inserted between the two. When shear waves are to be transmitted, the fluid is generally selected to have a significant viscosity.

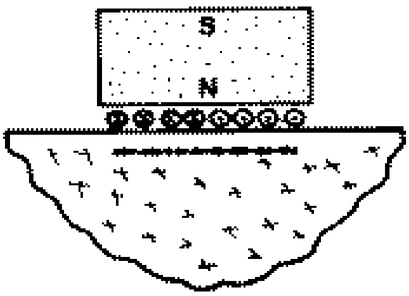
Electromagnetic-acoustic transducers (EMAT) acts through totally different physical principles. When a wire is placed near the surface of an electrically conducting object and is driven by a current at the desired ultrasonic frequency, eddy currents will be induced in a near surface region of the object. If a static magnetic field is also present, these eddy currents will experience Lorentz forces of the form

$$\boldsymbol{F} = \boldsymbol{J} \times \boldsymbol{B}$$

where $\boldsymbol{F}$ is a body force per unit volume, $\boldsymbol{J}$ is the induced dynamic current density, and $\boldsymbol{B}$ is the static magnetic induction.

The most important application of EMATs has been in nondestructive evaluation (NDE) applications such as flaw detection or material property characterization. Couplant free transduction allows operation without contact at elevated temperatures and in remote locations. The coil and magnet structure can also be designed to excite complex wave patterns and polarizations that would be difficult to realize with fluid coupled piezoelectric probes. In the inference of material properties from precise velocity or attenuation measurements, use of EMATs can eliminate errors associated with couplant variation, particularly in contact measurements.

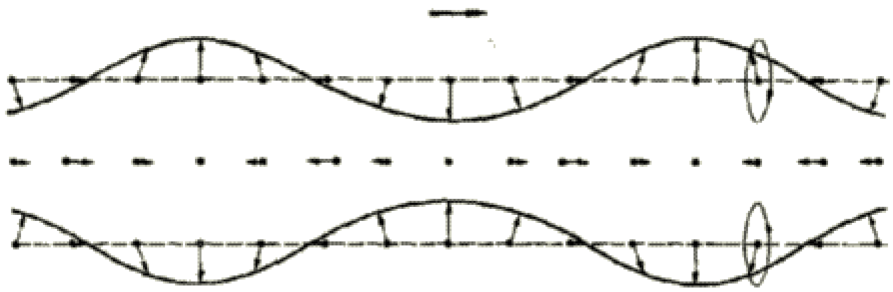
A number of practical EMAT configurations are shown below. In each, the biasing magnet structure, the coil, and the forces on the surface of the solid are shown in an exploded view. The first three configurations will excite beams propagating normal to the surface of the half-space and produce, respectively, beams with radial, longitudinal, and transverse polarizations. The final two use spatially varying stresses to excite beams propagating at oblique angles or along the surface of a component. A great number of variations on these configurations have been conceived and utilized in practice. However, consideration of these geometries suffices to introduce the fundamentals.



Cross-sectional view of a spiral coil EMAT exciting radially polarized shear waves propagating normal to the surface.

3.2.1 Lamb Wave Generation

Lamb waves are similar to longitudinal waves, with compression and rarefaction, but bounded by the sheet or plate surface causing a wave-guide effect.



Electromagnetic-acoustic transducers (EMAT) designed to generate Lamb waves actually vibrate the atoms within the material being investigated. When a wire is placed near to 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. If a static magnetic field is also present, these currents will experience Lorentz forces of the form

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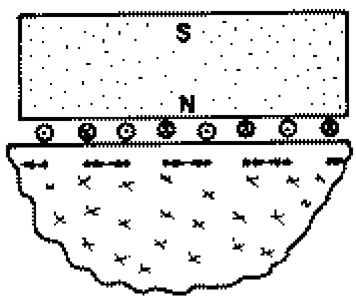


Cross-sectional view of a meander coil EMAT for exciting Lamb waves in plates.

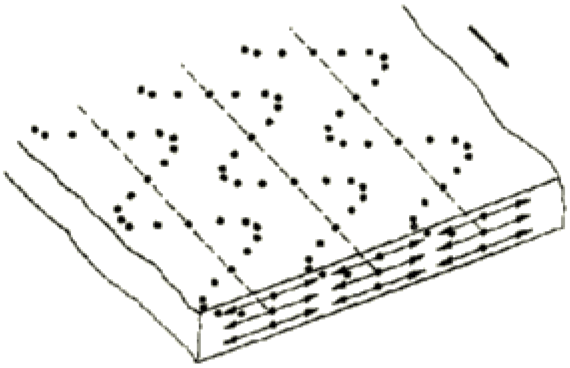
Practical EMAT designs are relatively narrow-band and require strong magnetic fields and large currents to produce ultrasound that is often weaker than that produced by piezoelectric transducers. Rare-Earth materials such as Samarium-Cobalt and Neodymium-Iron-Boron are often used to produce sufficiently strong magnetic fields. Magnetic fields may also be generated by pulsed electromagnets.

The EMAT offers many advantages based on its couplant-free operation. Included are the abilities to operate in remote environments at elevated speeds and temperatures, to excite polarizations not easily excited by fluid coupled piezoelectrics and to produce measurement results, which are highly reproducible.

These advantages are tempered by low efficiencies, and careful electronic design is essential to applications.

3.2.2 Shear Wave Generation

Shear waves have an inherent polarization direction depending on how they are generated. Pictured below are horizontally polarized shear waves propagating along the length of a plate.



Electromagnetic-acoustic transducers (EMAT) designed to generate shear waves actually vibrate the atoms within the material being investigated. When a wire is placed near to 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. If a static magnetic field is also present, these currents will experience Lorentz forces of the form

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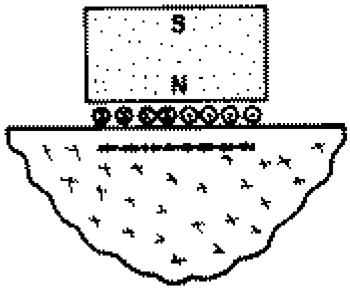
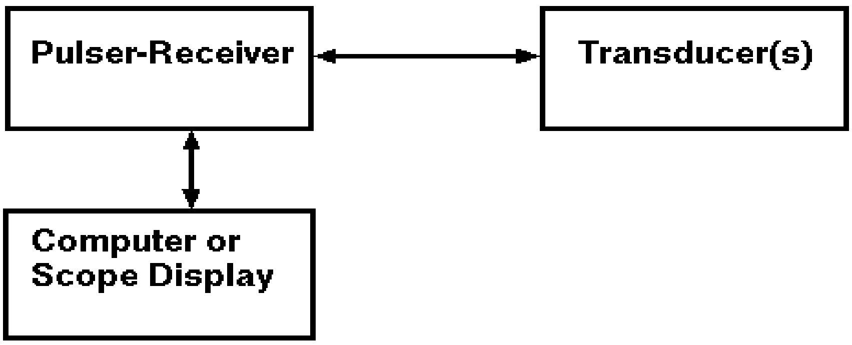


Cross-sectional view of a spiral coil EMAT exciting redially polarized shear waves propagating normal to the surface.

3.3 Equipment

3.3.1 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 gaging in a wide variety of metals, plastics, ceramics, and composites. Ultrasonic pulser-receivers provide a unique, low-cost ultrasonic measurement capability.



The pulser section of the instrument generates short, large amplitude electric pulses of controlled energy which, when applied to an ultrasonic transducer, are converted into short ultrasonic pulses. Most pulser sections have very ***low impedance*** outputs to better drive transducers. The ultrasonic pulses are received either by the transmitting transducer after partial or total reflection (pulse-echo method), or by a separate receiving transducer (pitch-catch or trough transmission methods).

In the receiver section the voltage signals produced by the transducer, which represents the received ultrasonic pulses, are amplified by a ***high impedance, low noise*** receiver section. The amplified radio frequency (rf) signal is available as output for display or capture for signal processing. Some pulser-receivers include filtering, time gating, and other useful control features. Many new models are completely computer interfaced for control and data acquisition.

The pulser-receiver can be used in material characterization work measuring sound velocity or attenuation, which in turn can be correlated to such material properties as elastic modulus or grain orientation. In conjunction with a step less gate and a spectrum analyzer the pulser-receiver can also be used to study frequency dependent material properties or to characterize the performance of ultrasonic transducers.

3.3.2 Tone Burst Generators

Tone burst generators are often employed in high power ultrasonic applications. Modern computer controlled ultrasonic instrumentation, such as Ritec's RAM 10000, is a complete advanced measurement system designed to satisfy the needs of the acoustic researcher in materials science or advanced NDE. Its purpose is to transmit bursts of acoustic energy into a test piece, receive signals from the piece following this burst, and manipulate and analyze these received signals in various ways. Extreme versatility is achieved through a modular approach allowing an instrument to be configured for unique applications not previously encountered. Unwanted modules need not be purchased and in many cases special modules can be designed and constructed.

The high power radio frequency (RF) burst capability allows the researcher to work with difficult, highly attenuative materials or inefficient transducers such as EMATs.

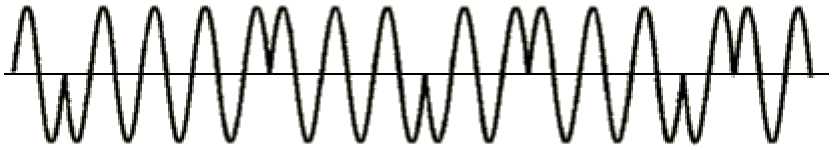
A computer interface makes it possible for the system to make high speed complex measurements, such as those involving multiple frequencies. Many of these measurements are very limited or impossible with manually controlled instruments. A Windows or DOS based personal computer controls and acquires data from the system. Software is supplied with each RAM-10000 suitable for a wide variety of applications including those involving EMATs, acoustic resonance, velocity, relative velocity, and attenuation measurements. In addition, the source code for this software is made available so that it may be modified to include new applications or changes in technique.

The unique automatic tracking super heterodyne receiver, quadrature phase sensitive detection circuits and gated integrators offer superb analog signal processing capability. Both the real and imaginary parts of the value of the Fourier transform at the driving frequency are obtained. This increases the dynamic range of the instrumentation and allows phase and amplitude information at the driving frequency to be extracted from noise and out-of-band spurious signals more efficiently than using Fast Fourier Transform (FFT) techniques.

3.3.3 Arbitrary Function Generators

Arbitrary waveform generators permit the user to design and generate virtually any waveform in addition to the standard function generator signals (e.g. sine wave, square wave, etc.). Waveforms are generated digitally from memory. Most instruments allow the downloading of digital waveform files from computers.

Ultrasonic generation pulses must be varied to accommodate different types of ultrasonic transducers. General-purpose highly damped contact transducers are usually excited by a wideband, spike-like pulse that is provided by many common pulser/receiver units. Lightly damped transducers, used for example in high power generation, require a narrowband tone-burst excitation from a separate generator unit. Sometimes, even the same transducer will be excited differently, for instance, to study the dispersion of a material's ultrasonic attenuation or to characterize ultrasonic transducers.



Section of biphase modulated spread spectrum ultrasonic waveform

In spread spectrum ultrasonics, encoded sound is generated by an arbitrary waveform generator which is continuously transmitted coded sound into the part or structure being tested. Instead of receiving echoes, spread spectrum ultrasonics generates an acoustic correlation signature having a one-to-one correspondence with the acoustic state of the part or structure (in its environment) at the instant of the measurement. In its simplest embodiment, the acoustic correlation signature is generated by cross correlating an encoding sequence (with suitable cross and auto correlation properties) transmitted into a part (structure) with received signals returning from the part (structure).

3.3.4 Electrical Impedance Matching and Termination

When computer systems were first introduced decades ago, they were all relatively large, slow speed devices that were incompatible with each other. Today, national and international networking standards have established electronic control protocols that enable different systems to "talk" to each other. The Electronics Industries Associations (EIA) and the Institute of Electrical and Electronics Engineers (IEEE) developed standards that established common terminology and interface requirements, such as EIA RS-232 and IEEE 802.3. If a system designer builds equipment to comply with these standards, the equipment will interface with other systems. But what about analog signals as used in ultrasonics?

Data Signals: Input versus Output

Consider this signal going to and from ultrasonic transducers. When you transmit data through cable, the requirement usually simplifies into comparing what goes in one end with what comes out the other. High frequency pulses degrade or deteriorate when they are passed through any cable. Both the height of the pulse (magnitude) and the shape of the pulse (wave form) change dramatically, and the amount of change depends on the data rate, transmission distance and cable electrical characteristics. Sometimes a marginal electrical cable may perform adequately if used in only short lengths, but the same cable with the same data in long lengths will fail. This is why system designers and industry standards specify precise cable criteria.

Cable Electrical Characteristics

The most important characteristics in an electronic cable are impedance, attenuation, shielding and capacitance. In this article, we can only review these characteristics very generally, however, we will discuss capacitance in more detail.

Impedance (Ohms) represents the total resistance that the cable presents to the electrical current passing through it. At low frequencies the impedance is largely a function of the conductor size, but at high frequencies, conductor size, insulation material and insulation thickness all affect the cable's impedance. Matching impedance is very important. If the system is designed to be 100 Ohms, then the cable should match that impedance, otherwise error-producing reflections are created.

Attenuation is measured in decibels per unit length (dB/m), and provides an indication of the signal loss as it travels through the cable. Attenuation is very dependent on signal frequency. A cable that works very well with low frequency data may do very poorly at higher data rates. Cables with lower attenuation are better.

Shielding is normally specified as a cable construction detail. For example, the cable may be unshielded, contain shielded pairs, have an overall aluminum/mylar tape and drain wire or even a double shield. Cable shields usually have two functions: the first to act as a barrier to keep external signal from getting in and internal signals from getting out and the second to be a part of the electrical circuit. Shielding effectiveness is very complex to measure and depends on the data frequency within the cable and the precise shield design. A shield may be very effective in one frequency range, but a different frequency may require a completely different design. System designers often test complete cable assemblies or connected systems for shielding effectiveness.

Capacitance in cable is usually measured as picofarads per foot (pf/m). It indicates how much charge the cable can store within itself. If a voltage signal is being transmitted by a twisted pair, the insulation of the individual wires becomes charged by the voltage within the circuit. Since it takes a certain amount of time for the cable to reach its charged level, this slows down and interferes with the signal being transmitted. Digital data pulses are a string of voltage variations that are represented by square waves. A cable with a high capacitance slows down these signals so that they come out of the cable looking more like "saw-teeth", rather than square waves. The lower the capacitance of the cable, the better it performs with high speed data.

3.3.5 Error Analysis

All measurement, including ultrasonic measurements, however careful and scientific, are subject to some uncertainties. Error analysis is the study and evaluations of these uncertainties, its two main functions being to allow the practitioner to estimate how large the uncertainties are, and to help him or her to reduce them when necessary. Since the whole ultrasonics depends on measurements, it is therefore crucially important to be able to evaluate these uncertainties and to keep them to a minimum.

In science the word "error" does not carry the usual connotations of "mistake" or "blunder." "Error" in an ultrasonic measurement means the inevitable uncertainty that attends all measurements. As such, errors are not mistakes; you cannot avoid them by being very careful. The best you can hope to do is to ensure that errors are as small as reasonably possible, and to have some reliable estimate of how large they are.

To illustrate the inevitable occurrence of uncertainties, we have only to examine carefully any everyday measurement. Consider, for example, a carpenter who must measure the height of a doorway to an x-ray vault in order to install a door. As a first rough measurement, he might simply look at the doorway and estimate that it is 210 cm high. This crude "measurement" is certainly subject to uncertainty. If pressed, the carpenter might express this uncertainty by admitting that the height could be as little as 205 or as much as 215 cm.

If he wanted a more accurate measurement, he would use a tape measure, and he might find that the height is 211.3 cm. This measurement is certainly more precise than his original estimate, but it is obviously still subject to some uncertainty, since it is inconceivable that he could know the height to be exactly 211.3000 rather than 211.3001 cm, for example.

There are many reasons for this remaining uncertainty. Some of these causes of uncertainty could be removed if he took enough trouble. For example, one source of uncertainty might be that poor lighting is making it difficult to read the tape; this could be corrected by improving the lighting.

On the other hand, some sources of uncertainty are intrinsic to the process of measurement and can never be entirely removed. For example, let us suppose the carpenter's tape is graduated in half-centimeters. The top of the door will probably not coincide precisely with one of the half-centimeter marks, and if it does not, then the carpenter must estimate just where the top lies between two marks. Even if the top happens to coincide with one of the marks, the mark itself is perhaps a millimeter wide; so he must estimate just where the top lies within the mark. In either case, the carpenter ultimately must estimate where the top of the door lies relative to the markings on his tape, and this necessity causes some uncertainty in his answer.

By buying a better tape with closer and finer markings, the carpenter can reduce his uncertainty, but he cannot eliminate it entirely. If he becomes obsessively determined to find the height of the door with the greatest precision that is technically possible, he could buy an expensive laser interferometer. But even the precision of an interferometer is limited to distances of the order of the wavelength of light (about 0.000005 meters). Although he would now be able to measure the height with fantastic precision, he still would not know the height of the doorway exactly.

Furthermore, as the carpenter strives for greater precision, he will encounter an important problem of principle. He will certainly find that the height is different in different places. Even in one place, he will find that the height varies if the temperature and humidity vary, or even if he accidentally rubs off a thin layer of dirt. In other words, he will find that there is no such thing as one exact height of the doorway. This kind of problem is called a problem of definition (the height of the door is not well-defined and plays an important role in many scientific measurements).

Our carpenter's experiences illustrate what is found to be generally true. No physical quantity (a thickness, time between pulse-echoes, a transducer position, etc.) can be measured with complete certainty. With care we may be able to reduce the uncertainties until they are extremely small, but to eliminate them entirely is impossible.

In everyday measurements we do not usually bother to discuss uncertainties. Sometimes the uncertainties simply are not interesting. If we say that the distance between home and school is 3 miles, it does not matter (for most purposes) whether this means "somewhere between 2.5 and 3.5 miles" or "somewhere between 2.99 and 3.01 miles." Often the uncertainties are important, but can be allowed for instinctively and without explicit consideration. When our carpenter comes to fit his door, he must know its height with an uncertainty that is less than 1 mm or so. However, as long as the uncertainty is this small, the door will (for all practical purposes) be a perfect fit, x-rays won't leak out, and his concern with error analysis is at an end.

4.0 Measurement Techniques

4.1 Normal Beam Inspection

A pulse-echo ultrasonic measurements can determine the location of a discontinuity with 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 the material, reflect from the back or surface of a discontinuity, and be returned to the transducer. In most applications this time interval is only a few microseconds or less. The measured two-way transit time is divided by two to account for the down-and-back travel path, and then multiplied by the velocity of sound in the test material. The result is expressed in the well-known relationship:

$$d = vt/2 \quad \text{or} \quad v = 2d/t$$

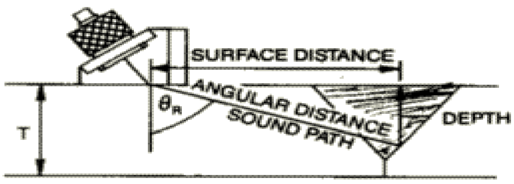
where ***d*** is the distance from the surface to the discontinuity in the test piece, ***v*** is the velocity of sound waves in the material and ***t*** is the measured round-trip transit time.

Precision ultrasonic thickness gages usually operate at frequencies between 500 KHz and 100 MHZ, using piezoelectric transducers to generate bursts of sound waves when excited by electrical pulses. A wide variety of transducers with various acoustic characteristics have been developed to meet the needs of industrial applications. Typically, lower frequencies will be 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.

In thickness gauging, ultrasonic techniques permit quick and reliable measurement of thickness without requiring access to both sides of a part. Accuracies as high as ±1 micron or ±0.0001 inch are achievable in some applications. Most engineering materials can be measured 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 is often possible, as is measurement of single layers or coatings in multi layer materials. Modern hand held gages are simple to use and highly reliable.

4.2 Angle Beams

Angle Beam Transducers and wedges are typically used to introduce a refracted shear wave into the test material. The angled sound path allows the sound beam to come in from the side to improve detectability of flaws in and around welded areas.



Surface Distance = Sin θ_R × Sound Path

Depth (1st Leg) = Cos θ_R × Sound Path

Depth (2nd Leg) = 2T − [Cos θ_R × Sound Path]

Angle Beam Transducers and wedges are typically used to introduce a refracted shear wave into the test material. In this geometry the angled sound path allows the sound beam to be reflected from the back wall to improve detectability of flaws in and around welded areas.

4.3 Crack Tip Diffraction

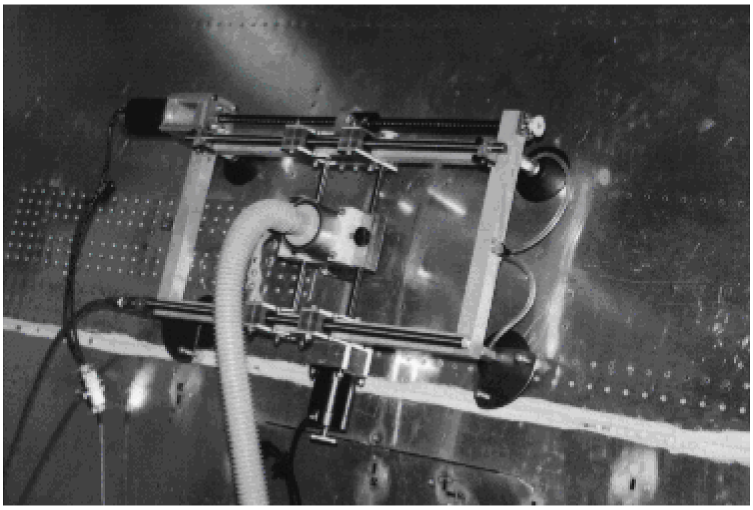
The height ***a*** of the cracks can be determined by the tip diffraction method. The principle echo comes from the base of the crack, and it can easily be found and used to locate the position of the flaw. A second much weaker echo comes from the tip of the crack, and this echo is displaced forward in time from the main echo by ***delta-t***.

Crack height ***a*** is a function of the ultrasound velocity ***v*** in the material, the incident angle and ***delta-t***. The equation for estimating crack height from these variables is shown in the following applet. The waveform display is calibrated to 2 microseconds per division.

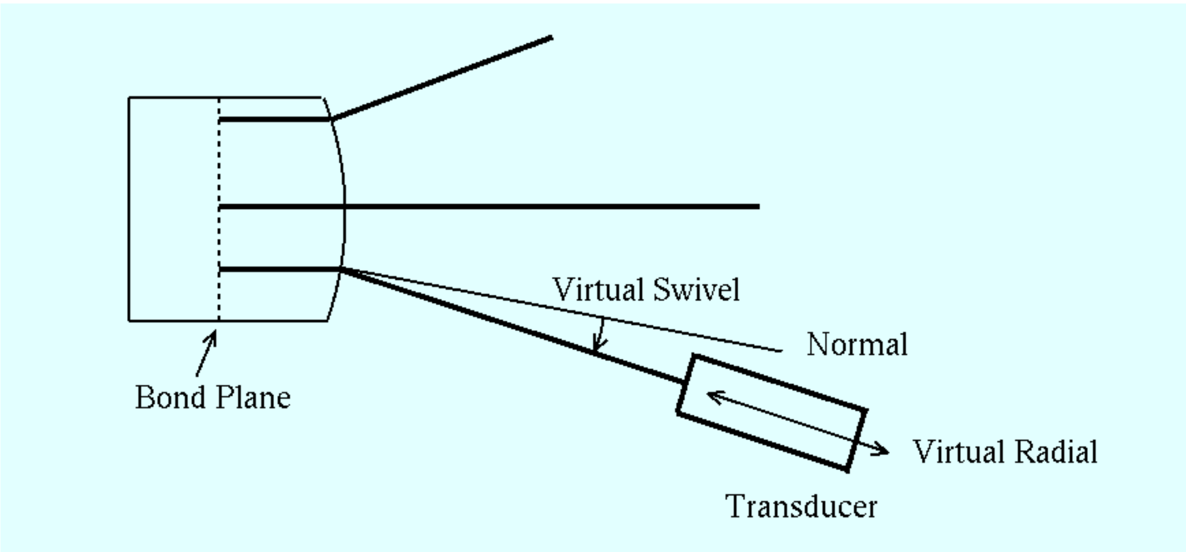
4.4 Automated Scanning

With any ultrasonic scanning system there are two factors to consider:

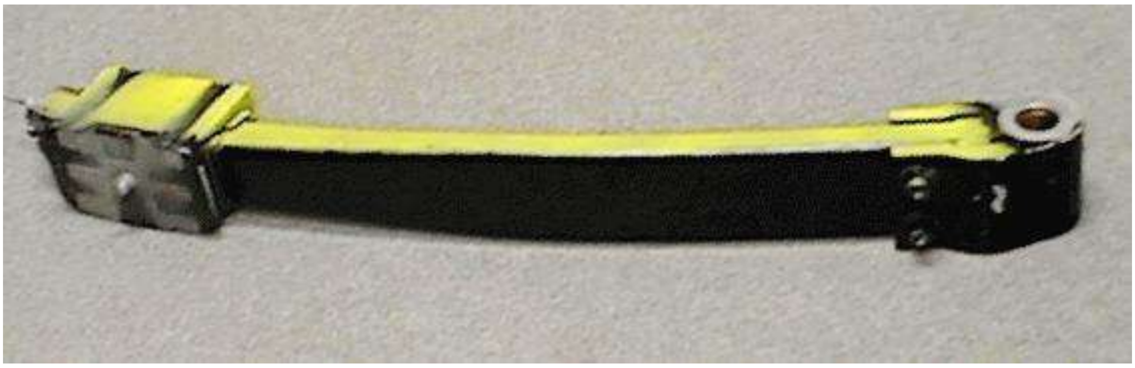
1. how to generate and receive the ultrasound, and
2. how to scan the transducer(s) with respect to the part being inspected.



Rectangular Field Scanning Example - Dripless Bubbler - A laboratory prototype for the "dripless bubbler" was developed such that water-coupled ultrasonic C-scans using focused beams could be used to inspect aircraft. The object was to conduct field trials of the laboratory prototype on actual airplanes and to improve device-based on-trial results.



Arbitrary Scan Example - Diffusion Bond Through Cylindrical Surface - An example of complex scanning whereby the diffusion bond of interest is inaccessible through a planer surface, resulting in a complex scan plan. To achieve desired results, the scanning transducer must follow a complex "pseudosurface."



Arbitrary Scan Example - Composite Leafspring - An example of complex contour scanning of a part with varying radii of curvature. "Teach" utilities are used to generate part and scanner coordinates. "Part coordinates" define location, orientation, size, and shape of the object or part to be inspected or scanned. "Scanner coordinates" define the location and orientation of the ultrasonic transducer or scanning assembly. Curved parts are defined by a set of points in space that are located on the surface of the part and used to generate scanner coordinates. These surface points, or "teach points," are obtained during teaching or imported from external CAD/CAM software and processed in various ways to obtain a scan plan, which consists of scanner coordinates organized in a raster pattern. When followed, the scan plan moves the transducer so that the desired area is inspected.

4.5 Precision Velocity Measurements

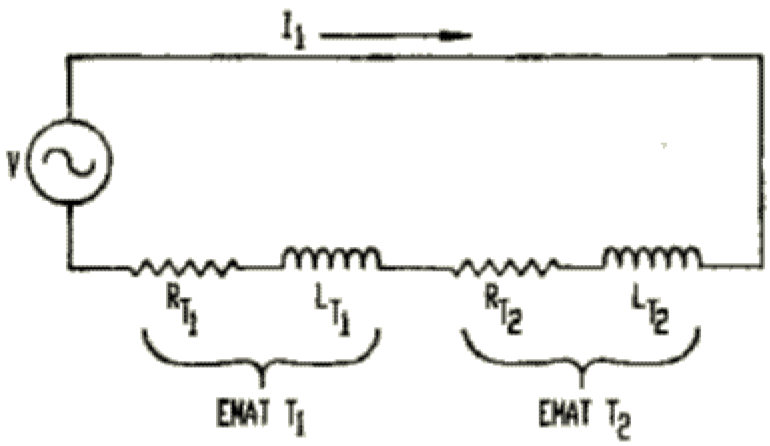
Of interest in velocity measurements are longitudinal wave, which propagate in gases, liquids and solid. In solids, of interest also are transverse (shear) waves. The longitudinal velocity is independent of sample geometry when the dimensions at right angles to the beam are large compared to the beam area and wave length. The transverse velocity is little affected bt physical dimensions of the sample.

	Texture	Stress	
Ferrous	0, 45, 90	0, 90	Pulsed Magnets
Non-Ferrous	0, 45, 90	0, 90	Permanent Magnets
	S_0	SH_0	

Pulse-Echo and Pulse-Echo-Overlap Methods

Rough ultrasonic velocity measurement are as simple as measuring the time it takes for a pulse of ultrasound to travel from one transducer to another (pitch-catch) or return to the same transducer (pulse-echo). These methods are suitable for estimating acoustic velocity to about 1 part in 100. Standard practice for measuring velocity in materials is detailed in ASTM E494.

Precision Velocity Measurements (using EMATs)



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$$\boldsymbol{F} = \boldsymbol{J} \times \boldsymbol{B}$$

where ***F*** is a body force per unit volume, ***J*** is the induced dynamic current density, and ***B*** is the static magnetic induction.

The most important application of EMATs has been in nondestructive evaluation (NDE) applications such as flaw detection or material property characterization. Couplant free transduction allows operation without contact at elevated temperatures and in remote locations. The coil and magnet structure can also be designed to excite complex wave patterns and polarizations that would be difficult to realize with fluid coupled piezoelectric probes. In the inference of material properties from precise velocity or attenuation measurements, use of EMATs can eliminate errors associated with couplant variation, particularly in contact measurements.

Differential velocity is measured using a T**1**-T**2**---R fixed array of EMAT transducers at 0, 45°, 90° or 0°, 90° relative rotational directions depending on device configuration:

EMAT Driver Frequency: 450-600 KHz (nominal)
Sampling Period: 100 ns
Time Measurement Accuracy:
Resolution 0.1 ns
Accuracy required for less than 2 KSI Stress Measurements: Variance 2.47 ns
Accuracy required for texture: Variance 10.0 ns
W440 < 3.72E-5
W420 < 1.47E-4
W400 < 2.38E-4

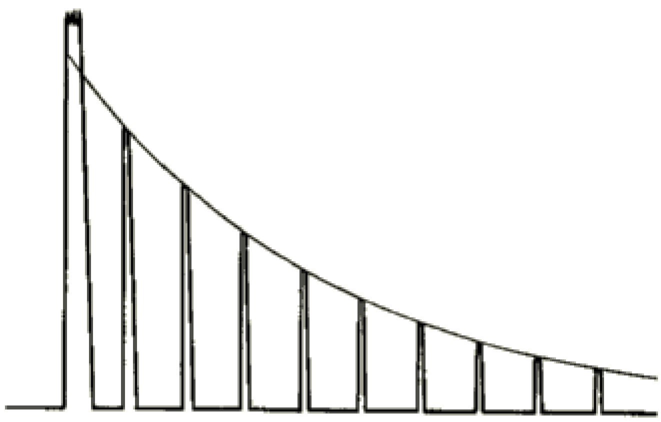
Time Measurement Technique:

Fourier Transform-Phase-Slope determination of delta time between received RF bursts (T**2**-R) - (T**1**-R), where T**2** and T**1** EMATs are driven in series to eliminate differential phase shift due to probe liftoff.

Slope of the phase is determined by linear regression of weighted data points within the signal bandwidth and a weighted y-intercept. The accuracy obtained with this method can exceed one part in one hundred thousand (1:100,000).

4.6 Attenuation Measurements

Absolute measurements of attenuation are very difficult because the echo amplitude depends not only on the attenuation but also on a number of other influencing factors. Relative measurements are easier to make, such as the change of attenuation during a given test, and also simple qualitative tests.



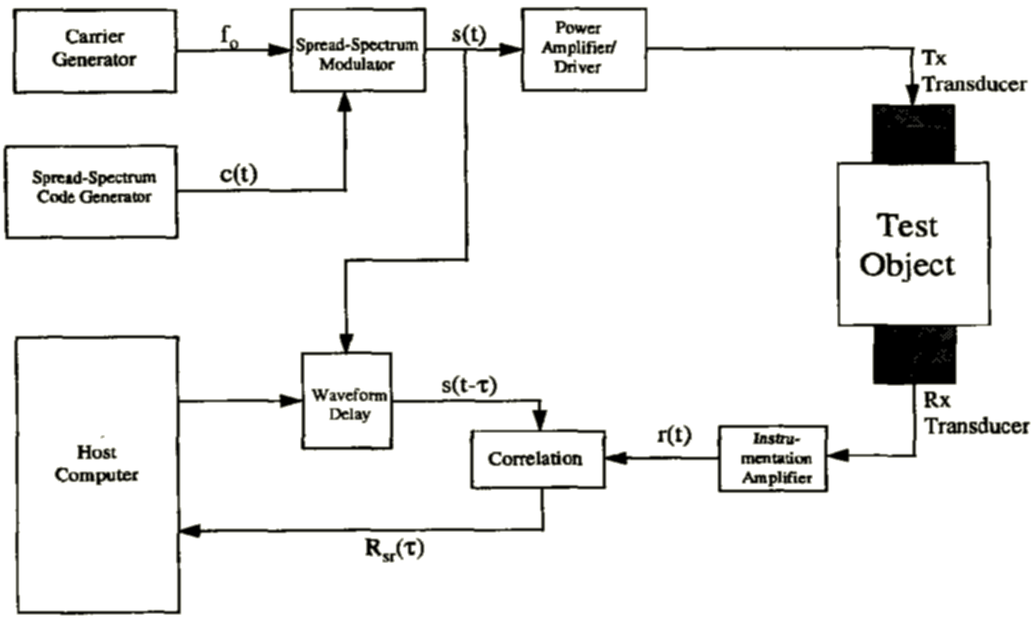
Exponential decay of multiple back surface reflections

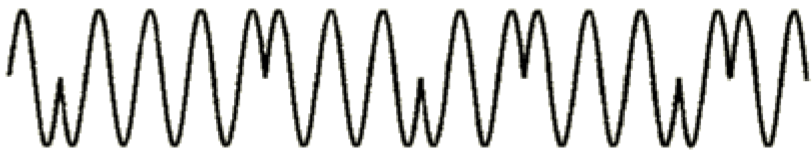
4.7 Spread Spectrum Ultrasonics

Instead of a pulse-echo or pitch-catch technique, spread spectrum ultrasonics makes use of correlation of continuous signals.

Spread spectrum ultrasonics is a patented new broad-band spread-spectrum ultrasonic nondestructive evaluation method. In conventional ultrasonics a pulse or tone burst is transmitted and received echoes or through transmission signals are received and analyzed.

In spread spectrum ultrasonics, encoded sound is continuously transmitted into the part or structure being tested. Instead of receiving echoes, spread spectrum ultrasonics generates an ***acoustic correlation signature*** having a one-to-one correspondence with the acoustic state of the part or structure (in its environment) at the instant of the measurement. In its simplest embodiment, the acoustic correlation signature is ***generated by cross correlating*** an ***encoding sequence*** (with suitable cross and auto correlation properties) transmitted into a part (structure) ***with received signals*** returning from the part (structure).



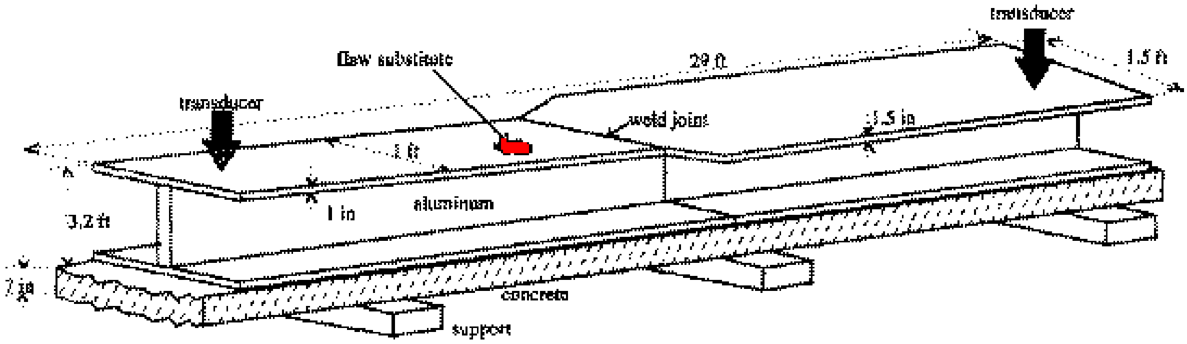


Section of biphase modulated spread spectrum ultrasonic waveform

Multiple probes may be used to ensure that acoustic energy is propagated through all critical volumes of the structure. Triangulation may be incorporated with multiple probes to locate regions of detected distress. Spread spectrum ultrasonics can achieve very high sensitivity to acoustic propagation changes with a low level acoustic on energy.

Two significant applications are:

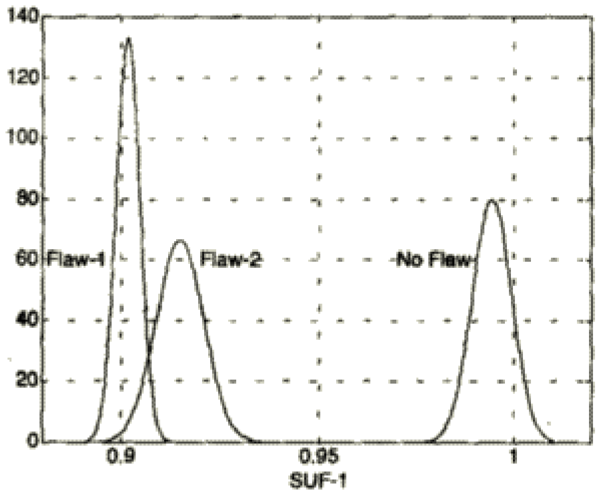
1. **Large Structures** that allow ultrasonic transducers to be "permanently" affixed to the structures eliminating variations in transducer registration and couplant. Comparisons with subsequent acoustic correlation signatures can be used to monitor critical structures such as fracture critical bridge girders. In environments where structures experience a great many variables (temperature, load, vibration, environmental coupling), in addition to those sources of acoustic change of detection interest, discrimination algorithms become a necessary and integral part of Spread spectrum ultrasonics.



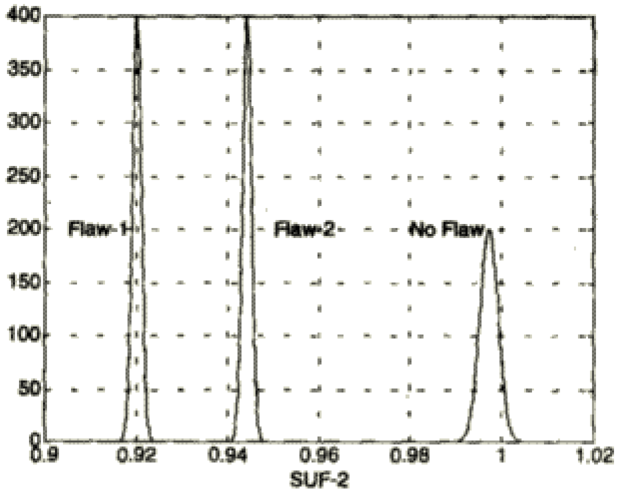
In the example below simulated defects were created by setting a couple of steel blocks on the top of the bridge girder.

Trial	Setup	Contact area
Baseline	No Flaw	------
Flaw 1	One block laying flat on girder	12.5 sq in
Flaw 2	One block standing on its long side	1.25 sq in
Flaw 3	Both blocks standing on their long sides	2.50 sq in
Flaw 4	Both blocks laying flat on girder	25.0 sq in

2. **Piece-part assembly-line environments** where transducers and couplant may be precisely controlled eliminating significant variations in transducer registration and couplant. Acoustic correlation signatures may be statistically compared to an ensemble of known "good" parts for sorting or accept/reject criteria in a piece-part assembly-line environment.



Impurities in the in-coming steel used in forging piece parts may result in sulfite stringer inclusions. In this next example simulated defects were created by placing a magnetized steel wire on the surface of a small steel cylindrical piston used in hydraulic transmissions.



Two discrimination techniques are tested here, SUF-1 and SUF-2, with the latter giving the best discrimination between defect conditions. The important point being that spread spectrum ultrasonics can be extremely sensitive to the acoustic state of a part or structure being tested, and therefore, is a good ultrasonic candidate for testing and monitoring, especially where scanning is not an economic alternative.

4.8 Signal Processing Techniques

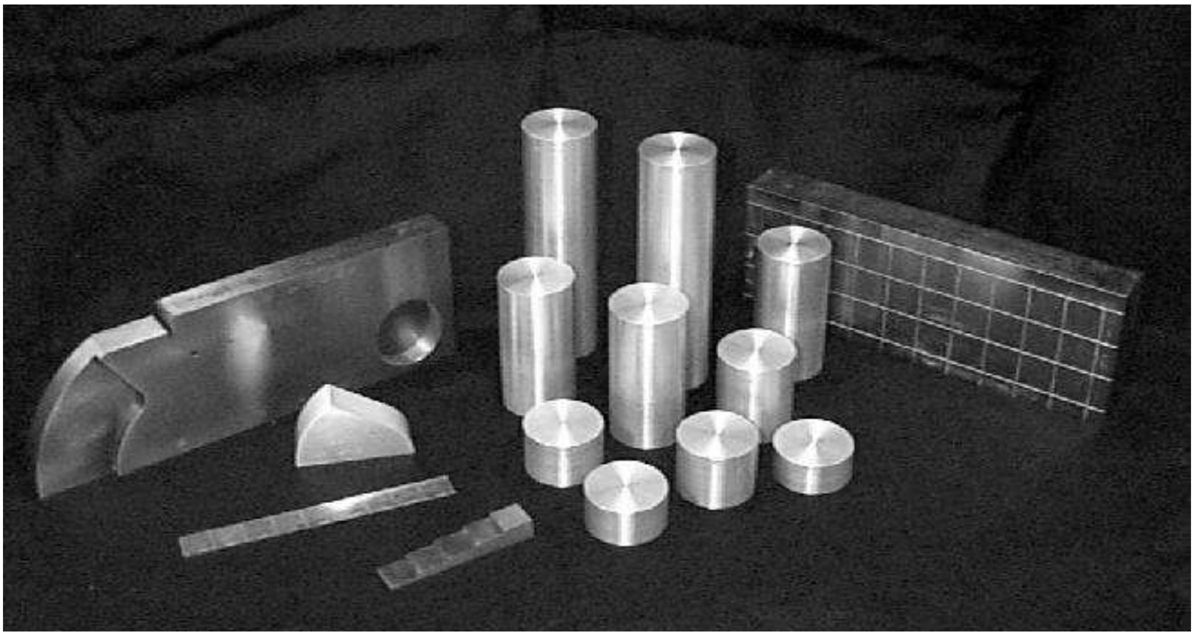
Signal processing involves techniques that improve our understanding of of information contained in received ultrasonic data. Normally, when a signal is measured with an oscilloscope, it is viewed in the time domain. That is, the vertical axis is amplitude or voltage and the horizontal axis is time. For many signals, this is the most logical and intuitive way to view them. But when the frequency content of the signal is of interest, it makes sense to view the signal in the frequency domain. In the frequency domain, the vertical axis is still voltage but the horizontal axis is frequency.

Linear transforms, especially the Fourier transform, are widely used in solving problems in science and engineering. The Fourier transform, in a convenient signal processing algorithm call the fast Fourier transform (FFT) allows computers to transform signals back and forth between time and frequency domains. The Fourier transform, in essence, decomposes or separates a waveform or function into sinusoids of different frequency which sum to the original waveform. It identifies or distinguishes the different frequency sinusoids and their respective amplitudes.

5.0 Calibration Methods and Modeling

5.1 Calibration Methods

Calibration refers to the act of checking the precision and accuracy of measurement equipment. In ultrasonic testing, several forms of calibration need to occur. First, the electronics of the equipment must be calibrated to assure that they are performing as designed. This operation is usually performed by the equipment manufacture 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 users must "calibrate" the system, which includes the equipment settings, the transducer, and the test set-up, to validate that the desired level of precision and accuracy are being achieved. The term calibration standard is usually only used when an absolute value is measured and in many cases, the standards are traceable back to standards at the National Institute for Standards and Technology.



In ultrasonic testing, there is also a need for reference standards. Reference standards are used to establish a general level of consistency in measurements and to help interpret and quantify the information contained in the received signal. Reference standards are used to validate that the equipment and the set-up are providing similar results from one day to the next and that similar results are being produced by different systems. Reference standards also help the inspector to estimate the size of flaws. In a pulse-echo type set-up, the signal strength varies with 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.

This section will discuss some of the more common calibration and reference specimen that are used in ultrasonic inspection. Some of these specimens are shown in the figure above. Please be aware that are other standards available and that specially designed standards may be required for many applications. The information provided here is intended to serve a general introduction to the standards and not to be instruction on the proper use of the standards.

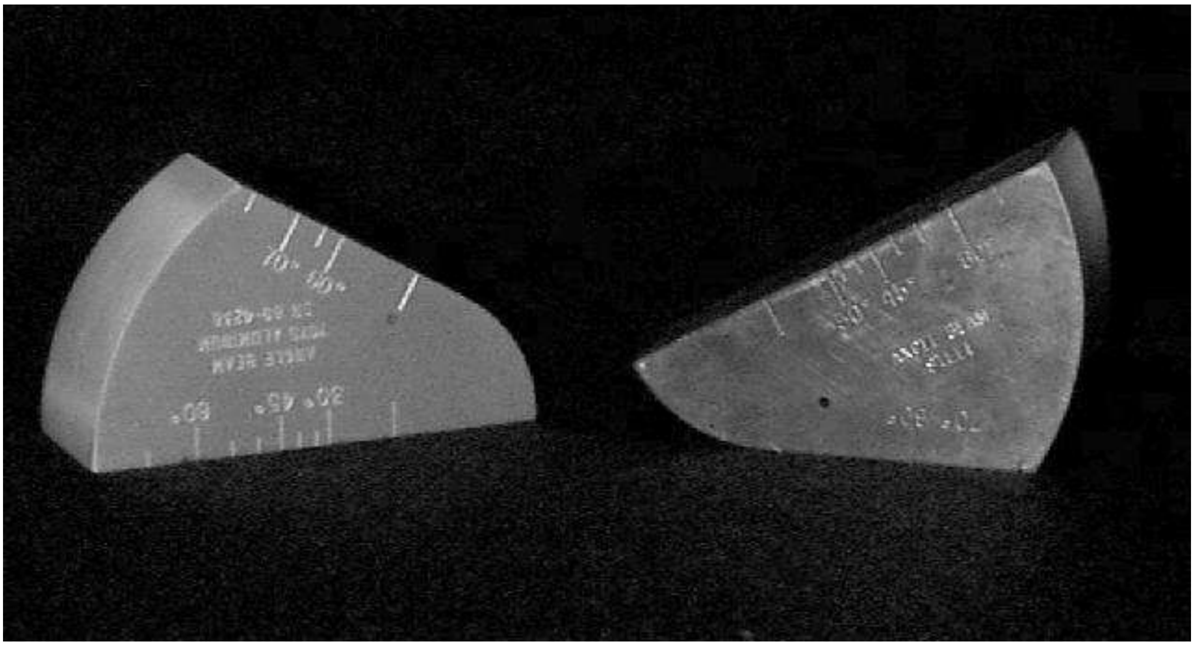
Introduction to the Common Standards

Calibration and reference standards for ultrasonic testing come in many shapes and sizes. The type of standard used is dependent on the NDE application and the form and shape of the object being evaluated. 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. The use of computer programs that allow the inspector to create computer models of the part and flaw and then simulate the inspection, may one day lessen this limitation.

The IIW Type Calibration Block

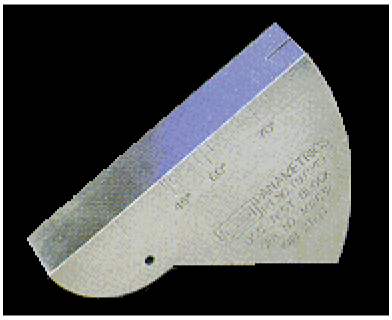
The standard shown in the above figure is commonly known in the US as an IIW type reference block. IIW is an acronym for the International Institute of Welding. It is referred to as an IIW "type" reference block because it was patterned after the "true" IIW block but does not conform to IIW requirements in IIS/IIW-23-59. "True" IIW blocks are only made out of steel (killed, open hearth or electric furnace, low-carbon steel in the normalized condition with a grain size of McQuaid-Ehn #8, to be exact) where IIW "type" blocks can be commercially obtained in a selection of materials. The dimensions of "true" IIW blocks are in metric units while IIW "type" blocks usually have English units. IIW "type" blocks may also include additional calibration and references features such as notches, circular groves and scales that are not specified by IIW. There are two full-sized and a mini versions of the IIW type blocks. The Mini version is about one-half the size of the full-sized block and weighs only about one-fourth as much. The IIW type US-1 block was derived the basic "true" IIW block and is shown in the figure on the left, below. The IIW type US-2 block was developed for US Air Force application. The Mini version is shown below.

IIW Type Mini



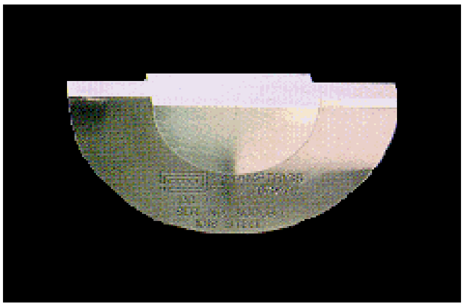
IIW type blocks are used to calibrate instruments for both angle beam and normal incident inspections. Some of their uses include setting metal-distance and sensitivity settings, determining the sound exit point and refracted angle of angle beam transducers, and evaluating depth resolution of normal beam inspection set-ups. Instructions on using the IIW type blocks can be found in the annex of American Society for Testing and Materials Standard E164, Standard Practice for Ultrasonic Contact Examination of Weldments.

The Miniature Angle-Beam or ROMPAS Calibration Block



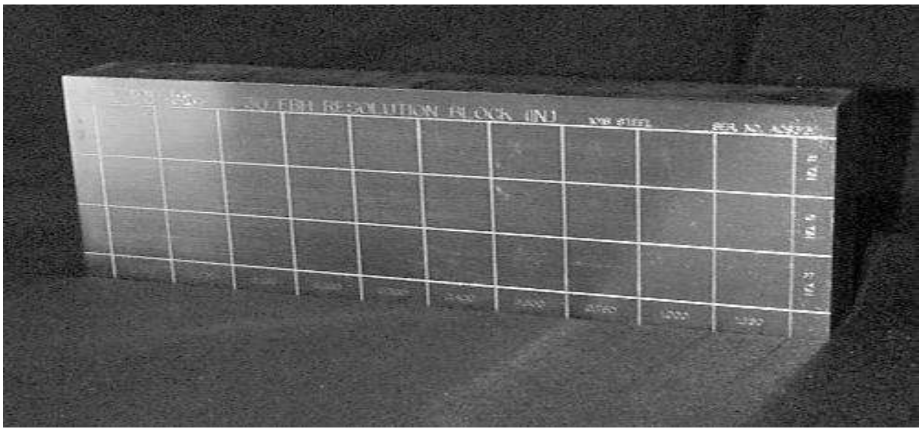
The miniature angle-beam is a calibration block that was designed for the US Air Force for use in the field for instrument calibration. The block is much smaller and lighter than the IIW block but performs many of the same functions. The miniature angle-beam block can be used to check the beam angle and exit point of the transducer. The block can also be used to make metal-distance and sensitivity calibrations for both angle and normal-beam inspection set-ups.

AWS Shear wave Distance/Sensitivity Calibration (DSC) Block



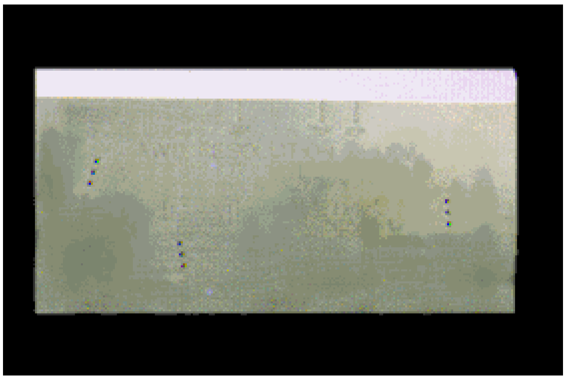
A block that closely resembles and is used similarly as the miniature angle-beam block is the DSC AWS Block. This block is used to determine the beam exit point and refracted angle of angle-beam transducers and; to calibrate distance and set the sensitivity for both normal and angle beam inspection set-ups. Instructions on using the DSC block can be found in the annex of American Society for Testing and Materials Standard E164, Standard Practice for Ultrasonic Contact Examination of Weldments.

AWS Shear wave Distance Calibration (DC) Block



The DC AWS Block is a metal path distance and beam exit point calibration standard that conforms to the requirements of the American Welding Society (AWS) and the American Association of State Highway and Transportation Officials (AASHTO). Instructions on using the DC block can be found in the annex of American Society for Testing and Materials Standard E164, Standard Practice for Ultrasonic Contact Examination of Weldments.

AWS Resolution Calibration (RC) Block

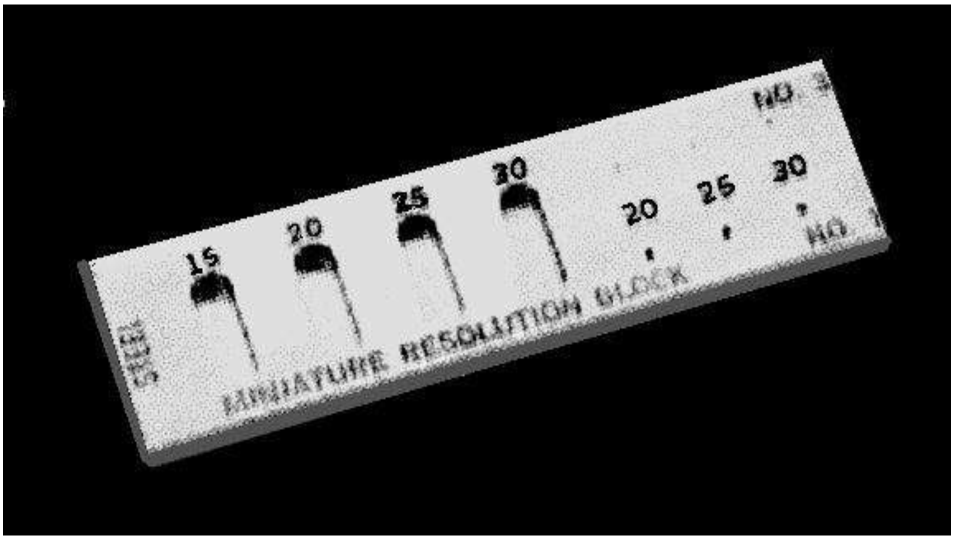


The RC Block is used to determine the resolution of angle beam transducers per the requirements of AWS and AASHTO**.** Engraved Index markers are provided for 45, 60, and 70 degree refracted angle beams.

30 FBH Resolution Reference Block

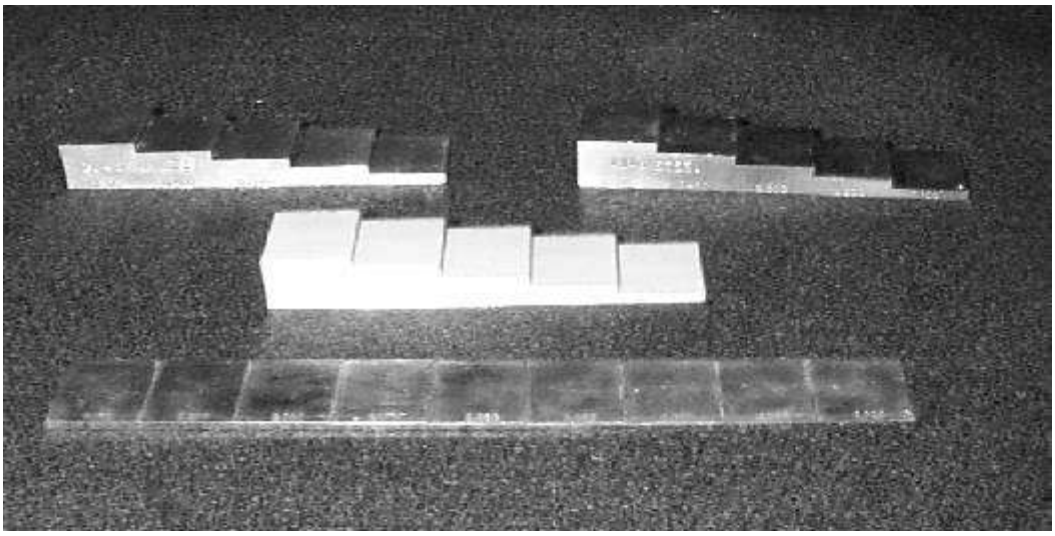
The 30 FBH resolution reference block is used to evaluate the near-surface resolution and flaw size/depth sensitivity of a normal-beam set-up. The block contains number 3 (3/64"), 5 (5/64"), and 8 (8/64") ASTM flat bottom holes at ten metal-distances ranging from 0.050 inch (1.27 mm) to 1.250 inch (31.75 mm).

Miniature Resolution Block



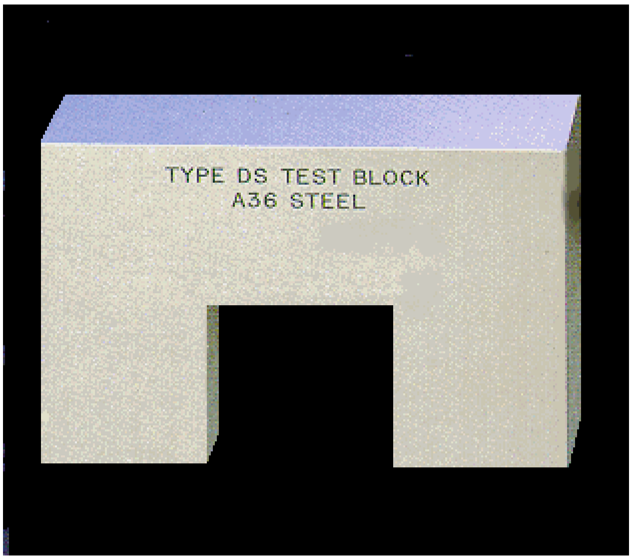
The miniature resolution block is used to evaluate the near-surface resolution and sensitivity of a normal-beam set-up. It can be used to calibrate high-resolution thickness gages over the range of 0.015 inches (0.381 mm) to 0.125 inches (3.175 mm).

Step and Tapered Calibration Wedges



Step and tapered calibration wedges come in a large variety of sizes and configurations. Step wedges are typically manufactured with four or five steps but custom wedge can be obtained with any number of steps. Tapered wedges have a constant taper over the desired thickness range.

Distance/Sensitivity (DS) Block



The DS test block is a calibration standard is to check the horizontal linearity and the db accuracy per requirements of AWS and AASHTO.

Distance/Area-Amplitude Blocks

Distance/area amplitude correction blocks are typically purchased as a ten-block set as shown above. Aluminum sets are manufacture per the requirements of ASTM E127 and steel sets per ASTM E428. They can also be purchased in titanium. The blocks are used to each block contains a single flat-bottomed, plugged hole. The hole sizes and metal path distances are as follows:

3/64" at 3",

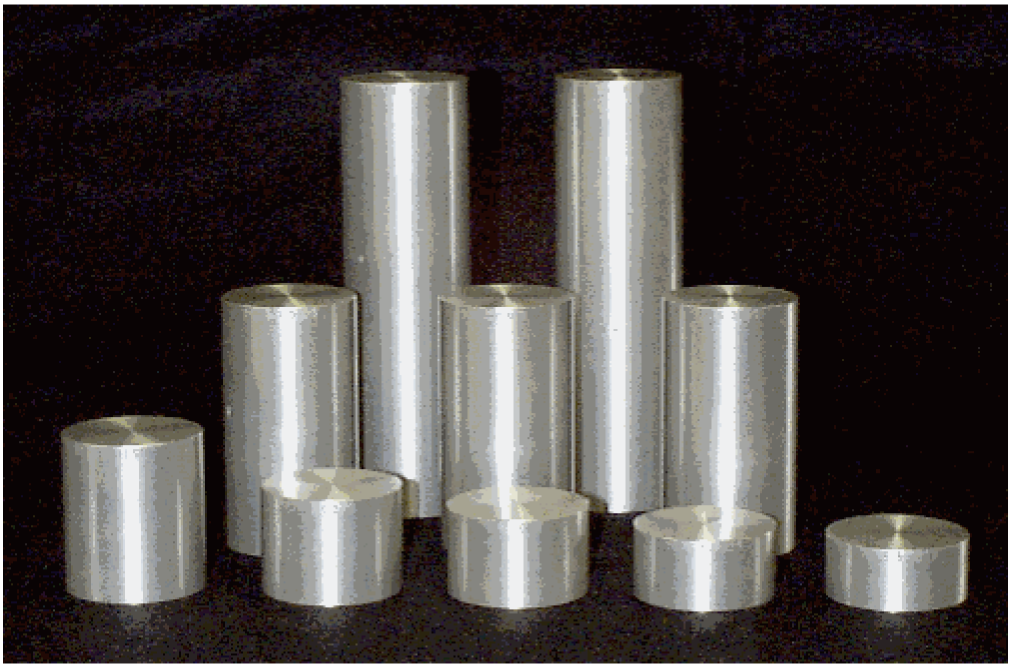
5/64" at 1/8", 1/4", 1/2", 3/4", 11/2", 3" and 6"

8/64" at 3" and 6"

Sets are commonly sold in 4340 Vacuum melt Steel, 7075-T6 Aluminum, and Type 304 Corrosion Resistant Steel. Aluminum blocks are fabricated per the requirements of ASTM E127, Standard Practice for Fabricating and Checking Aluminum Alloy Ultrasonic Standard Reference Blocks. Steel blocks are fabricated per the requirements of ASTM E428, Standard Practice for Fabrication and Control of Steel Reference Blocks Used in Ultrasonic Inspection.

Area-Amplitude Blocks

Area-amplitude blocks are also usually purchased in an eight-block set and look very similar to Distance/Area-Amplitude Blocks. However, area area-amplitude blocks have a constant 3-inch metal path distance and the hole sizes is varied from 1/64" to 8/64" in 1/64" steps. The blocks are used to determine the relationship between flaw size and signal amplitude by comparing signal responses for the different sized holes. Sets are commonly sold in 4340 Vacuum melt Steel, 7075-T6 Aluminum, and Type 304 Corrosion Resistant Steel. Aluminum blocks are fabricated per the requirements of ASTM E127, Standard Practice for Fabricating and Checking Aluminum Alloy Ultrasonic Standard Reference Blocks. Steel blocks are fabricated per the requirements of ASTM E428, Standard Practice for Fabrication and Control of Steel Reference Blocks Used in Ultrasonic Inspection.



Distance-Amplitude #3, #5, #8 FBH Blocks

Distance-amplitude blocks also like very similar to the distance/area-amplitude blocks pictured above. 19 block sets with flat-bottom holes of a single size and varying metal path distances are also commercially available. Sets have either a #3 (3/64") FBH, a #5 (5/64") FBH, or a #8 (8/64") FBH. The metal path distances are 1/16", 1/8", 1/4", 3/8", 1/2", 5/8", 3/4", 7/8", 1", 1-1/4", 1-3/4", 2-1/4", 2-3/4", 3-14", 3-3/4", 4-1/4", 4-3/4", 5-1/4", and 5-3/4". The relationship between the metal path distance and the signal amplitude is determined by comparing signals from same size flaws at different depth. Sets are commonly sold in 4340 Vacuum melt Steel, 7075-T6 Aluminum, and Type 304 Corrosion Resistant Steel. Aluminum blocks are fabricated per the requirements of ASTM E127, Standard Practice for Fabricating and Checking Aluminum Alloy Ultrasonic Standard Reference Blocks. Steel blocks are fabricated per the requirements of ASTM E428, Standard Practice for Fabrication and Control of Steel Reference Blocks Used in Ultrasonic Inspection.

5.2 Distance Amplitude Correction (DAC) and Curvature Corrections

Distance Amplitude Correction (DAC)

Acoustic signals from the same reflecting surface will have different amplitudes at different distances in the same material. A distance amplitude correction (DAC) curve can be constructed from the peak amplitude responses from reflectors of equal area at different distances in the same material.

Such curves are plotted specifically for a flat-bottom hole target and engraved on a transparent plastic sheet for attachment to the CRT screen. Disk-shaped reflectors, side drilled holes and hemispherical bottom holes are used as equivalent reflectors when using contact probes. With immersion probes usually a small-sized steel ball is used to measure a distance-amplitude curve. This techniques are important because of the amplitude of ultrasonic pulses varies width with distance from the probe, and this causes the echo from a constant reflector to vary with distance. Therefore, to evaluate echoes of reflectors, for all kind of probes, distance-amplitude curves are needed.

Curvature Corrections

Planar contact ultrasonic transducers are commonly used to inspect components with curved surfaces. Examples include inspections of large diameter forgings, such as are used in the electrical power generation equipment, and of railroad rail. Previous work by Ying and Baudry (ASME 62-WA175, 1962) and by Birchak and Serabian (Mat. Eval. 36(1), 1978) derived methods for determining "correction factors" to account for degradation of signal amplitude as a function of the radius of curvature of convex, cylindrical components. Those methods were for narrowband (single frequency) inspections.

Now exists an alternative model for contact and immersion probe inspection that models the liquid-solid in a manner similar to that employed by Ying and Baudry and by Birchak and Serabian. This model further predicts transducer radiation patterns using the Gauss-Hermite model, which has been used extensively for simulation of immersion mode inspections. The resulting model allows computationally efficient prediction of the full ultrasonic fields in the component for (a) any frequency, including broadband measurements; (b) both circular and rectangular crystal shapes; (c) general component surface curvature: and (d) both normal and oblique incidence (e.g., angle beam wedges) transducers. When coupled with analytical models for defect scattering amplitudes, the model can be used to predict actual flaw waveforms.

Example: Curvature Correction Factor Calculations #4 Flat Bottom Hole

The "correction" values are the change in amplitude needed to bring signals from a curved surface measurement to the DAC (flat surface) value. A 3.25" water path is assumed. The plotted data shows the DAC curve and a radius correction factor. The DAC curve drops monotonically since a 3.25" water path ensures that the near field is in the water. The correction factor starts out negative because of the focusing effect of the curved surface. At greater depths, the correction factor is positive because of the increased beam

5.3 References & Standards

What are standards?

Standards are documented agreements containing technical specifications or other precise criteria to be used consistently as rules, guidelines, or definitions of characteristics, to ensure that materials, products, processes and services are fit for their purpose.

For example, the format of the credit cards, phone cards, and "smart" cards that have become commonplace is derived from an ISO International Standard. Adhering to the standard, which defines such features as an optimal thickness (0.76 mm), means that the cards can be used worldwide.

An important source of practice codes, standards, and recommendations for NDT is given in the ***Annual Book of the American Society of Testing and Materials, ASTM***. The **Volume 03.03 *Nondestructive Testing*** is revised annually, covering acoustic emission, eddy current, leak testing, liquid penetrants, magnetic particle, radiography, thermography, and ultrasonics.

There are many efforts on the part of the National Institute of Standards and Technology (NIST) and other standards organizations, both national and international, to work through technical issues and harmonize national and international standards.

6.0 Selected Applications

6.1 Weldments (Welded Joints)

The most commonly occurring defects in welded joints are porosity, slag inclusions, lack of side-wall fusion, lack of inter-run fusion, lack of root penetration, undercutting and longitudinal or transverse cracks.

With the exception of single gas pores all the defects listed are usually well detectable by ultrasonics. Most applications are on low-alloy construction quality steels, however, welds in aluminum can also be tested. Ultrasonic flaw detection has long been the preferred method for nondestructive testing in welding applications. This safe, accurate and simple technique has pushed ultrasonics to the forefront of inspection technology.

Ultrasonic weld inspections are typically performed using a straight beam transducer in conjunction with an angle beam transducer and wedge. 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, as 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. Angle beam transducers use the principles of refraction and mode conversion to produce refracted shear or longitudinal waves in the test material. [Note: Many AWS inspections are performed using refracted shear waves. However, material having a large grain structure, such as stainless steel may require refracted longitudinal waves for successful inspections.] 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. With proper angle beam techniques, echoes returned from the weld zone may allow the operator to determine the location and type of discontinuity.

To determine the proper scanning area for the weld, the inspector must first calculate the location of the sound beam in the test material. Using the refracted angle, beam index point and material thickness, the V-path and skip distance of the sound beam is found. Once they have been calculated, the inspector can identify the transducer locations on the surface of the material corresponding to the crown, sidewall, and root of the weld.