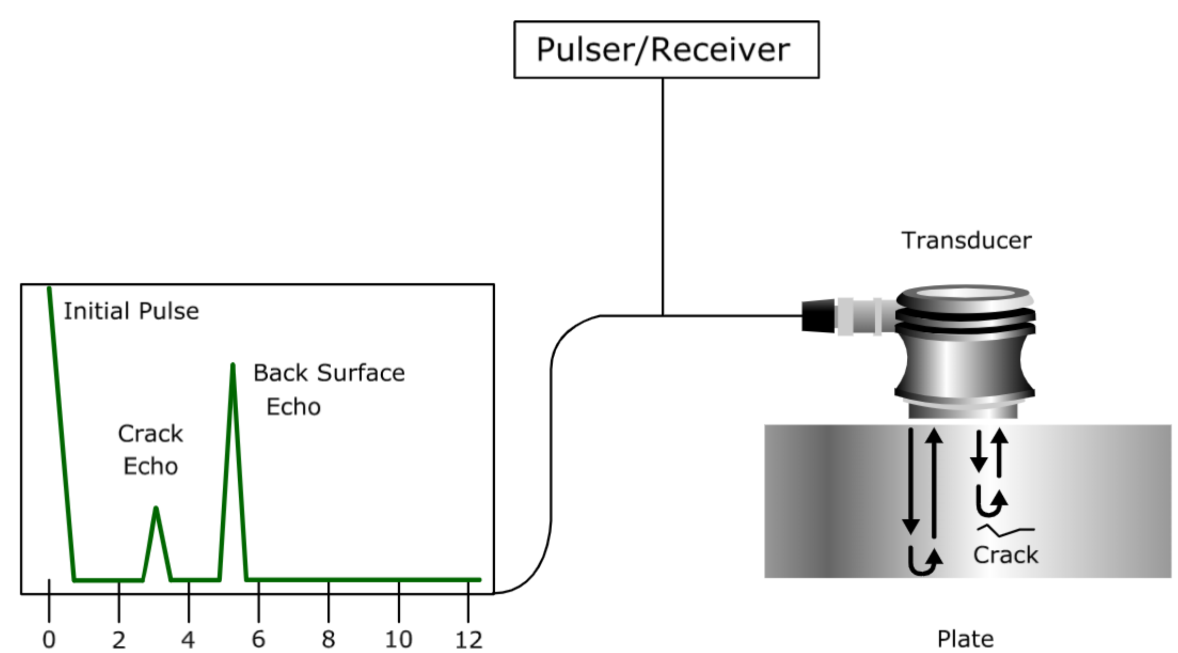
Nondestructive Evaluation Techniques > Ultrasonic Testing > Basic Principles of Ultrasonic Testing

Basic Principles of Ultrasonic Testing

Ultrasonic Testing (UT) uses high frequency sound energy to conduct examinations and make measurements. Ultrasonic inspection can be used for flaw detection/evaluation, dimensional measurements, material characterization, and more. To illustrate the general inspection principle, a typical pulse/echo inspection configuration as illustrated below will be used.

A typical UT inspection system consists of several functional units, such as the pulser/receiver, transducer, and display devices. A pulser/receiver is an electronic device that can produce high voltage electrical pulses. Driven by the pulser, the transducer generates high frequency ultrasonic energy. The sound energy is introduced and propgates through the materials in the form of waves. When there is a discontinuity (such as a crack) in the wave path, part of the energy will be reflected. back from the flaw surface. The reflected wave signal is transformed into an electrical signal by the transducer and is displayed on a screen. In the applet below, the reflected signal strength is displayed versus the time from signal generation to when a echo was received. Signal travel time can be directly related to the distance that the signal traveled. From the signal, information about the reflector location, size, orientation and other features can sometimes be gained.



restart

Ultrasonic Inspection is a very useful and versatile NDT method. Some of the advantages of ultrasonic inspection that are often cited include:

- It is sensitive to both surface and subsurface discontinuities.
- The depth of penetration for flaw detection or measurement is superior to other NDT methods.
- Only single-sided access is needed when the pulse-echo technique is used.
- It is highly accurate in determining reflector position and estimating size and shape.
- Minimal part preparation is required.
- Electronic equipment provides instantaneous results.
- Detailed images can be produced with automated systems.
- It has other uses, such as thickness measurement, in addition to flaw detection.

As with all NDT methods, ultrasonic inspection also has its limitations, which include:

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

The above introduction provides a simplified introduction to the NDT method of ultrasonic testing. However, to effectively perform an inspection using ultrasonics, much more about the method needs to be known. The following pages present information on the science involved in ultrasonic inspection, the equipment that is commonly used, some of the measurement techniques used, as well as other information.

Nondestructive Evaluation Techniques

Ultrasound

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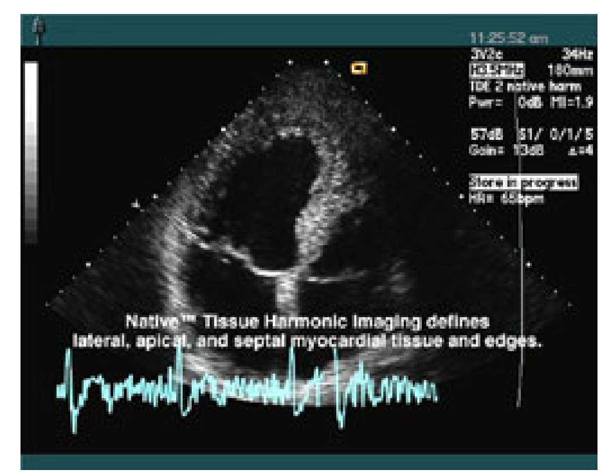
History of Ultrasonics

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 studied 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 the 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 image.

Japan's work in ultrasound was relatively unknown in the United States and Europe until the 1950s. Researchers then 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 the speed and direction of the flow..

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.

Beginnings of Nondestructive Evaluation (NDE)

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 in the NDT field. First, improvements in the technology led to the ability to detect small flaws, which caused more parts to be rejected even though the probability of component failure had not changed. However, the discipline of fracture mechanics emerged, which enabled one to predict whether a crack of a given size will fail under a particular load when a material's fracture toughness properties are known. Other laws were developed to predict the growth rate 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 the new philosophy of "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. The need for quantitative information was particularly strongly in the defense and nuclear power industries and led to the emergence of quantitative nondestructive evaluation (QNDE) as a new engineering/research discipline. A number of research programs around the world were started, such as the Center for Nondestructive Evaluation at Iowa State University (growing out of a major research effort at the Rockwell International Science Center); the Electric Power Research Institute in Charlotte, North Carolina; the Fraunhofer Institute for Nondestructive Testing in Saarbrucken, Germany; and the Nondestructive Testing Centre in Harwell, England.

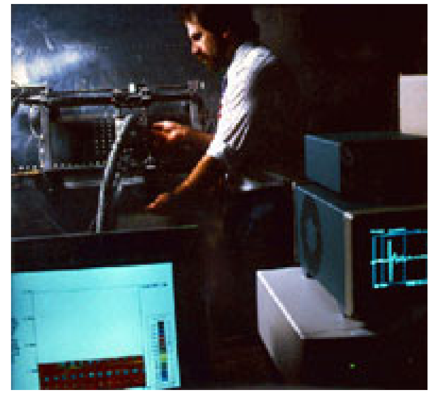
Present State of Ultrasonics

Ultrasonic testing (UT) has been practiced for many decades. Initial rapid developments in instrumentation spurred by the technological advances from the 1950's continue today. Through the 1980's and continuing through the present, computers have provided technicians with smaller and more rugged instruments with greater capabilities.

Thickness gauging is an example application where instruments have been refined make data collection easier and better. Built-in data logging capabilities allow thousands of measurements to be recorded and eliminate the need for a "scribe." Some instruments have the capability to capture waveforms as well as thickness readings. The waveform option allows an operator to view or review the A-scan signal of thickness measurement long after the completion of an inspection. Also, some instruments are capable of modifying the measurement based on the surface conditions of the material. For example, the signal from a pitted or eroded inner surface of a pipe would be treated differently than a smooth surface. This has led to more accurate and repeatable field measurements.

Many ultrasonic flaw detectors have a trigonometric function that allows for fast and accurate location determination of flaws when performing shear wave inspections. Cathode ray tubes, for the most part, have been replaced with LED or LCD screens. These screens, in most cases, are extremely easy to view in a wide range of ambient lighting. Bright or low light working conditions encountered by technicians have little effect on the technician's ability to view the screen. Screens can be adjusted for brightness, contrast, and on some instruments even the color of the screen and signal can be selected. Transducers can be programmed with predetermined instrument settings. The operator only has to connect the transducer and the instrument will set variables such as frequency and probe drive.

Along with computers, motion control and robotics have contributed to the advancement of ultrasonic inspections. Early on, the advantage of a stationary platform was recognized and used in industry. Computers can be programmed to inspect large, complex shaped components, with one or multiple transducers collecting information. Automated systems typically consisted of an immersion tank, scanning system, and recording system for a printout of the scan. The immersion tank can be replaced with a squirter systems, which allows the sound to be transmitted through a water column. The resultant C-scan provides a plan or top view of the component. Scanning of components is considerably faster than contact hand scanning, the coupling is much more consistent. The scan information is collected by a computer for evaluation, transmission to a customer, and archiving.

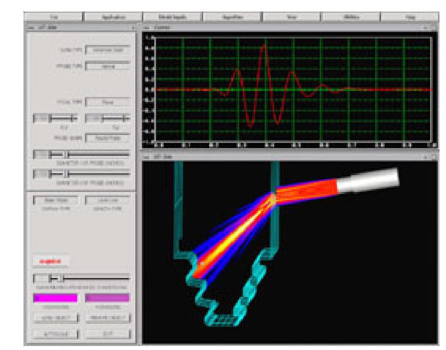


Today, quantitative theories have been developed to describe the interaction of the interrogating fields with flaws. Models incorporating the results have been integrated with solid model descriptions of real-part geometries to simulate practical inspections. Related tools allow NDE to be considered during 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, where anisotropy and inhomogeneity have become important issues. The rapid advances in digitization and computing capabilities have totally changed the faces of many instruments and the type of algorithms that are used in processing the resulting data. High-resolution imaging systems and multiple measurement modalities for characterizing a flaw have emerged. Interest is increasing not only in detecting, characterizing, and sizing defects, but also in characterizing the materials. Goals 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. As technology continues to advance, applications of ultrasound also advance. The high-resolution imaging systems in the laboratory today will be tools of the technician tomorrow.

Nondestructive Evaluation Techniques > Ultrasonic Testing > Future Direction of Ultrasonic Inspection

Future Direction of Ultrasonic Inspection

Looking to the future, those in the field of NDE see an exciting new set of opportunities. The defense and nuclear power industries have played a major role in the emergence of NDE. Increasing global competition has led to dramatic changes in product development and business cycles. At the same time, aging infrastructure, from roads to buildings and aircraft, present a new set of measurement and monitoring challenges for engineers as well as technicians.



Among the new applications of NDE spawned by these changes is the increased emphasis on the use of NDE to improve the productivity of manufacturing processes. Quantitative nondestructive evaluation (QNDE) both increases the amount of information about failure modes and the speed with which information can be obtained and facilitates the development of in-line measurements for process control.

The phrase, "you cannot inspect in quality, you must build it in," exemplifies the industry's focus on avoiding the formation of flaws. Nevertheless, manufacturing flaws will never be completely eliminated and material damage will continue to occur in-service so continual development of flaw detection and characterization techniques is necessary.

Advanced simulation tools that are designed for inspectability and their integration into quantitative strategies for life management will contribute to increase the number and types of engineering applications of NDE. With growth in engineering applications for NDE, there will be a need to expand the knowledge base of technicians performing the evaluations. Advanced simulation tools used in the design for inspectability may be used to provide technical students with a greater understanding of sound behavior in materials. UTSIM, developed at Iowa State University, provides a glimpse into what may be used in the technical classroom as an interactive laboratory tool.

As globalization continues, companies will seek to develop, with ever increasing frequency, uniform international practices. In the area of NDE, this trend will drive the emphasis on standards, enhanced educational offerings, and simulations that can be communicated electronically. The coming years will be exciting as NDE will continue to emerge as a full-fledged engineering discipline.

Nondestructive Evaluation Techniques > Ultrasonic Testing > Ultrasound and Ultrasonic Testing

Ultrasound and Ultrasonic Testing

After reading this section you will be able to do the following:

- Define the acronym "NDT."
- Explain how sound is used in NDT to find flaws.
- Explain how sound is used in NDT to measure material thickness.

Why is it important to understand sound?

There are many uses for sound in the world today. We have already mentioned a few. Musicians can benefit from a greater understanding of sound, architects must understand sound to design effective auditoriums, detectives can use sound to identify people, and many new types of technology apply sound recognition. Another use of sound is in the area of science called Nondestructive testing, or NDT.

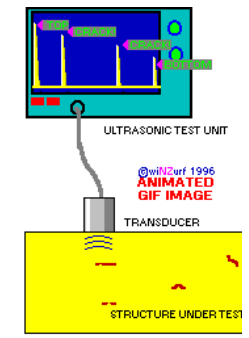
What is NDT?

Nondestructive testing is a method of finding defects in an object without harming the object. Often finding these defects is a very important task. In the aircraft industry, NDT is used to look for internal changes or signs of wear on airplanes. Discovering defects will increase the safety of the passengers. The railroad industry also uses nondestructive testing to examine railway rails for signs of damage. Internally cracked rails could fracture and derail a train carrying wheat, coal, or even people. If an airplane or a rail had to be cut into pieces to be examined, it would destroy their usefulness. With NDT, defects may be found before they become dangerous.

How is ultrasound used in NDT?

Sound with high frequencies, or **ultrasound**, is one method used in NDT. Basically, ultrasonic waves are emitted from a transducer into an object and the returning waves are analyzed. If an impurity or a crack is present, the sound will bounce off of them and be seen in the returned signal. In order to create ultrasonic waves, a transducer contains a thin disk made of a crystalline material with piezoelectric properties, such as quartz. When electricity is applied to piezoelectric materials, they begin to vibrate, using the electrical energy to create movement. Remember that waves travel in every direction from the source. To keep the waves from going backwards into the transducer and interfering with its reception of returning waves, an absorptive material is layered behind the crystal. Thus, the ultrasound waves only travel outward.

One type of ultrasonic testing places the transducer in contact with the test object. If the transducer is placed flat on a surface to locate defects, the waves will go straight into the material, bounce off a flat back wall and return straight to the transducer. The animation on the right, developed by NDTA, Wellington, New Zealand, illustrates that sound waves propagate into a object being tested and reflected waves return from discontinuities along the sonic path. Some of the energy will be absorbed by the material, but some of it will return to the transducer.



Ultrasonic measurements can be used to determine the thickness of materials and determine the location of a discontinuity within a part or structure by accurately measuring the time required for a ultrasonic pulse to travel through the material and reflect from the backsurface or the discontinuity.

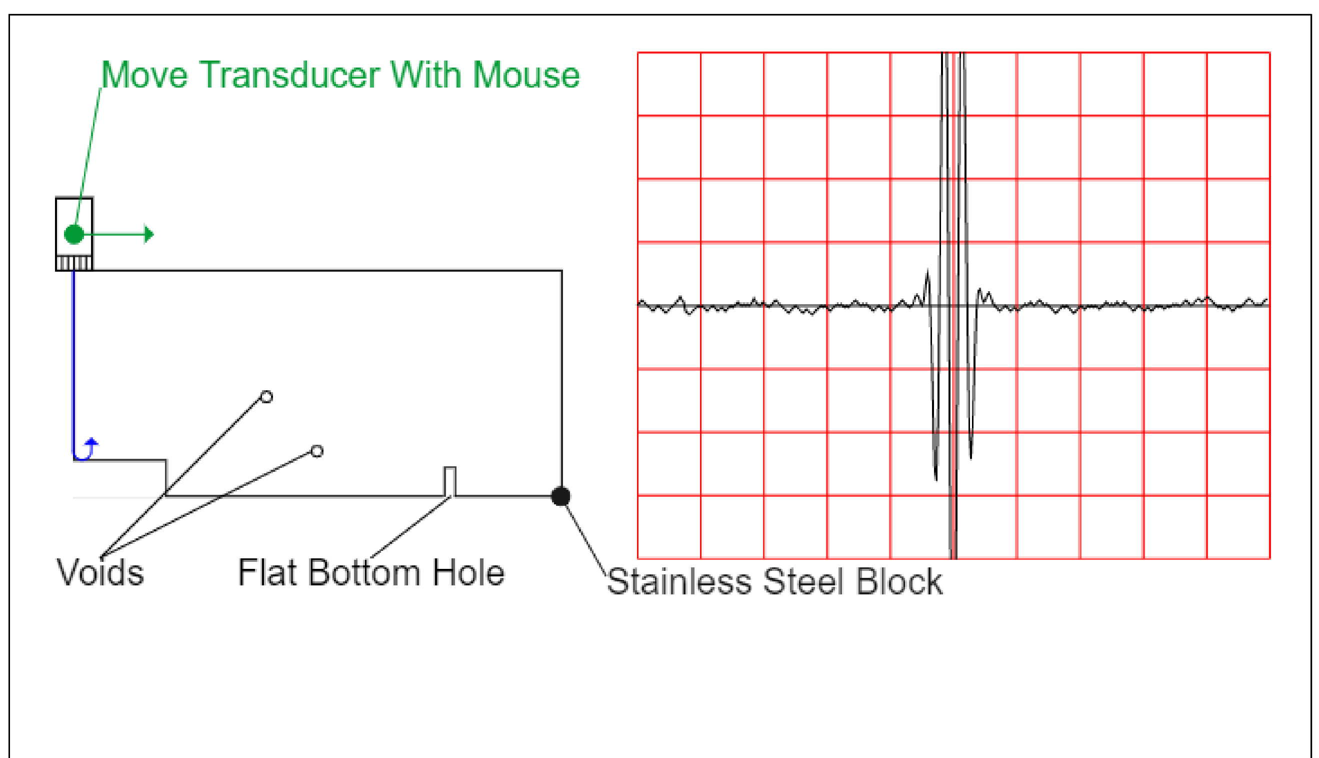
When the mechanical sound energy comes back to the transducer, it is converted into electrical energy. Just as the piezoelectric crystal converted electrical energy into sound energy, it can also do the reverse. The mechanical vibrations in the material couple to the piezoelectric crystal which, in turn, generates electrical current.

Your Turn - Try this normal beam test

A pulse-echo ultrasonic measurement 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. Then it reflects from the back or surface of a discontinuity and is returned to the transducer.

The applet below allows you to move the transducer on the surface of a stainless steel test block and see the reflected echoes as the would appear on an oscilloscope.

Move the transducer along the test piece and observe the oscilloscope reading.



What the graphs tell us?

The ultrasonic tester graphs a peak of energy whenever the transducer receives a reflected wave. As you recall, sound is reflected any time a wave changes mediums. Thus, there will be a peak anytime the waves change mediums. Right when the initial pulse of energy is sent from the tester, some is reflected as the ultrasonic waves go from the transducer into the couplant. The first peak is therefore said to record the energy of the initial pulse. The next peak in a material with no defects is the backwall peak. This is the reflection from waves changing between the bottom of the test material and the material behind it, such as air or the table it is on. The backwall peak will not have as much energy as the first pulse, because some of the energy is absorbed by the test object and some into the material behind it.

The amount of distance between peaks on the graph can be used to locate the defects. If the graph has 10 divisions and the test object is 2 inches thick, each division represents 0.2 inches. If a defect peak occurs at the 8th division, we know the defect is located 1.6 (0.2 x 8) inches into the test object.

What if the thickness is unknown?

If the thickness of the object is unknown, it can be calculated using the amount of time it takes for the back wall peak to occur. The thickness of the object is traveled twice in that time, once to the back wall and once returning to the transducer. If we know the speed of our sound, then we can calculate the distance it traveled, which is the thickness of the object times two.

What happens when a defect is present?

If a defect is present, it will reflect energy sooner also. Another peak would then appear from the defect. Since it reflected energy sooner than the back wall, the defect's energy would be received sooner. This causes the defect peak to appear before the backwall peak. Since some of the energy is absorbed and reflected by the defect, less will reach the backwall. Thus the peak of the backwall will be lower than had there been no defect interrupting the sound wave.

When the wave returns to the transducer, some of its energy bounces back into the test object and heads towards the back wall again. This second reflection will produce peaks similar to the first set of backwall peaks. Some of the energy, however, has been lost, so the height of all the peaks will be lower. These reflections, called multiples, will continue until all the sound energy has been absorbed or lost through transmission across the interfaces.

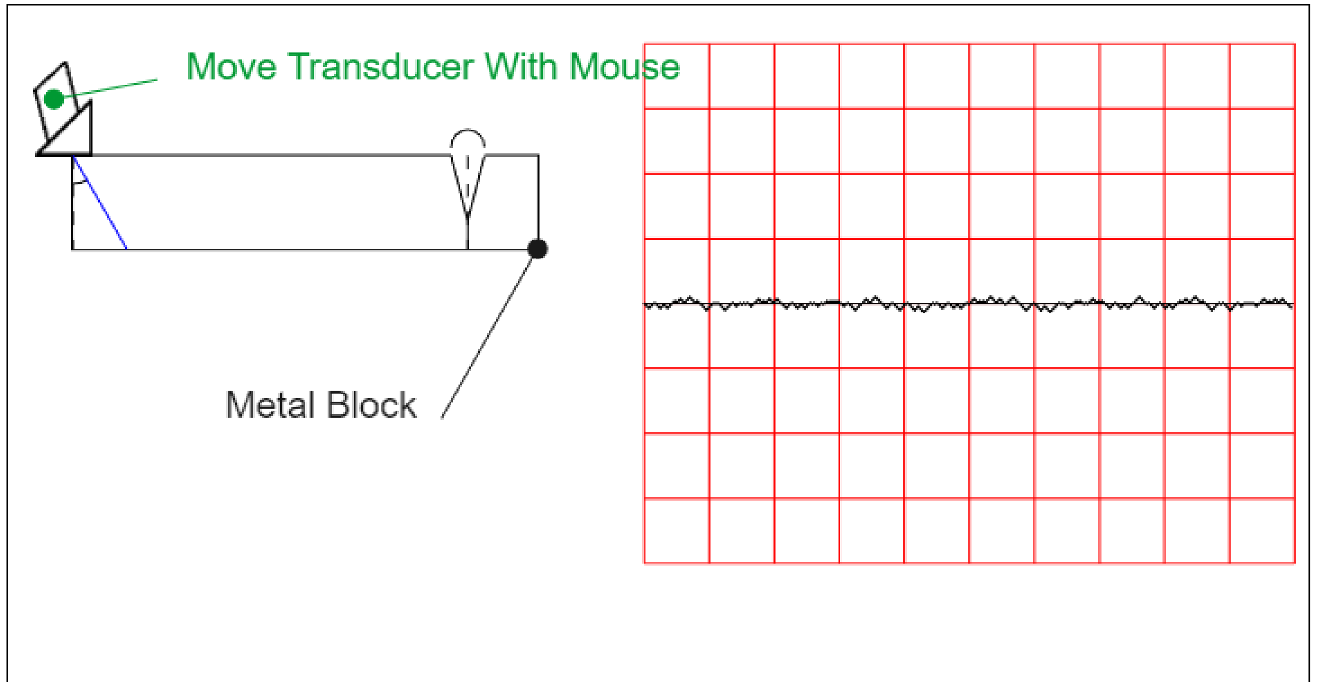
Angle Beam Testing

After reading this section you will be able to do the following:

- Explain why it is important to know about sound refraction and Snell's Law when performing an angle beam inspection.
- Explain what a shear wave is.

Often straight beam testing will not find a defect. For example, if the defect is vertical and thin enough, it will not reflect enough sound back to the transducer to let the tester know that it exists. In cases like this, another method of ultrasound testing must be used. The other method of ultrasound testing is angle beam testing. **Angle beam testing** uses an incidence of other than 90 degrees. In contact testing, an angled plastic block is place between the transducer and the object to create the desired angle. For angle beam testing in immersion systems, a plastic block is not needed because the transducer can simply be angled in the water.

If the angle of incidence is changed to be anything other than 90 degrees, longitudinal waves and a second type of sound wave are produced. These other waves are called **shear waves**. Because the wave entered at an angle, it does not all travel directly through the material. Molecules in the test object are attracted to each other because solids have strong molecular bonds. The molecules carrying the sound are attracted to their surrounding molecules. Because of the angle, those sound carrying molecules get pulled by attracting forces in a direction perpendicular to the direction of the wave. This produces shear waves, or waves whose molecules travel perpendicular to the direction of the wave.



Refraction Angle: 30 Thickness: 1
Surface Distance: 0.577
Depth (1st Leg): 1.000

Angle beam testing and a change in the angle of incidence also creates further complications. Remember that when a wave hits a surface at an angle, it will be refracted, or bent, when it enters the new medium. Thus, the shear waves and the longitudinal waves will be refracted in the test object. The amount of refraction depends on the speed of sound in the two mediums between which the wave is traveling. Since the speed of shear waves is slower than the speed of longitudinal waves, their angles of refraction will be different. By using Snell's law, we can calculate the angle of refraction if we know the speed of sound in our material.

Review

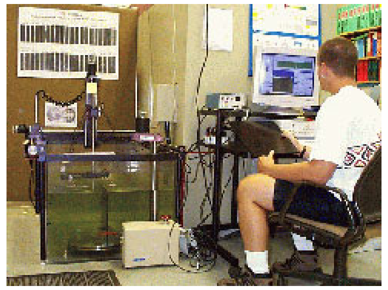
1. An angle beam test cannot be performed unless the angle of refraction is calculated using Snell's law, and the speed of sound must be known too.
2. Shear waves are produced when the angle of incidence is not 90 degrees.

Nondestructive Evaluation Techniques > Ultrasonic Testing > Immersion Ultrasonic Testing

Immersion Ultrasonic Testing

After reading this section you will be able to do the following:

- Explain what an immersion ultrasonic test is and why they are needed in NDT.



Another way to couple the sound from transducer to a test object is coupling the sound with water. This can be done with squirters where the sound travels through a jet of water or by immersing the transducer and test object in a tank of water. Both techniques are called immersion testing. In **immersion testing**, the transducer is placed in the water, above the test object, and a beam of sound is projected.

The graph of peaks using the immersion method is slightly different. Between the initial pulse and the back wall peaks there will be an additional peak caused by the sound wave going from the water to the test material. This additional peak is called the front wall peak. The ultrasonic tester can be adjusted to ignore the initial pulse peak, so the first peak it will show is the front wall peak. Some energy is lost when the waves hit the test material, so the front wall peak is slightly lower than the peak of the initial pulse.

Ultrasonic testing is an NDT test technique that interrogates components and structures to detect internal and surface breaking defects, and measures wall thickness on hard (typically metallic or ceramic) components and structures.

How does ultrasonic testing work?

Ultrasonic operates on the principle of injecting a very short pulse of ultrasound (typically between 0.1 MHz and 100 Mhz) into a component or structure, and then receiving and analyzing any reflected sound pulses.

Conventionally, an operator scans a transducer over the surface of the component in such a way that he inspects all the area that is required to be tested by means of a scanning motion. The inspection relies on the training and integrity of the operator to ensure that he has inspected all that is necessary.

The image on the left is the result of an immersion ultrasound test. A photograph of the object is in the image on the right.

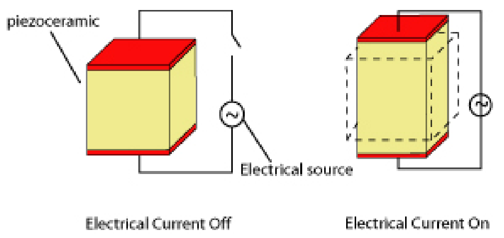
Sound pulses reflected from features within the component or structure are conventionally displayed on a screen. The operator also has to interpret these signals and report if the component or structure is defective or acceptable according to the test specification that he is given.

Typical detection limits for fine grained steel structures or components (hand scanning) are single millimeter sized defects. Smaller defects can be detected by immersion testing and a programmed scan pattern with higher frequency ultrasound (slower testing). Detection limits are in the order of 0.1 to 0.2 mm, although smaller defects (typically 0.04mm diameter) can be detected under laboratory conditions.

Review

1. Immersion testing is completed with squirters where the sound travels through a jet of water or by taking the transducer and test object and immersing them in a tank of water.

Piezoelectric Transducers



The conversion of electrical pulses to mechanical vibrations and the conversion of returned mechanical vibrations back into electrical energy is the basis for ultrasonic testing. The active element is the heart of the transducer as it converts the electrical energy to acoustic energy, and vice versa. The active element is basically a piece of polarized material (i.e. some parts of the molecule are positively charged, while other parts of the molecule are negatively charged) with electrodes attached to two of its opposite faces. When an electric field is applied across the material, the polarized molecules will align themselves with the electric field, resulting in induced dipoles within the molecular or crystal structure of the material. This alignment of molecules will cause the material to change dimensions. This phenomenon is known as electrostriction. In addition, a permanently-polarized material such as quartz (SiO2) or barium titanate (BaTiO3) will produce an electric field when the material changes dimensions as a result of an imposed mechanical force. This phenomenon is known as the piezoelectric effect. Additional information on why certain materials produce this effect can be found in the linked presentation material, which was produced by the Valpey Fisher Corporation.

Piezoelectric Effect (PPT, 89kb) Piezoelectric Elements (PPT, 178kb)

> **Piezoelectric**: The generation of electricity or of electric polarity in ceramic dielectric crystals subjected to mechanical stress, or the generation of stress in such ceramic crystals subjected to an applied voltage.
>
> **Magnetostrictive**: Deformation of a ferromagnetic material (such as iron and steel) subjected to a magnetic field.

The active element of most acoustic transducers used today is a **piezoelectric** ceramic, which can be cut in various ways to produce different wave modes. A large piezoelectric ceramic element can be seen in the image of a sectioned low frequency transducer. Preceding the advent of piezoelectric ceramics in the early 1950's, piezoelectric crystals made from quartz crystals and **magnetostrictive** materials were primarily used. The active element is still sometimes referred to as the crystal by old timers in the NDT field. When piezoelectric ceramics were introduced, they soon became the dominant material for transducers due to their good piezoelectric properties and their ease of manufacture into a variety of shapes and sizes. They also operate at low voltage and are usable up to about 300°C. The first piezoceramic in general use was barium titanate, and that was followed during the 1960's by lead zirconate titanate compositions, which are now the most commonly employed ceramic for making transducers. New materials such as piezo-polymers and composites are also being used in some applications.

The thickness of the active element is determined by the desired frequency of the transducer. A thin wafer element vibrates with a wavelength that is twice its thickness. Therefore, piezoelectric crystals are cut to a thickness that is 1/2 the desired radiated wavelength. The higher the frequency of the transducer, the thinner the active element. The primary reason that high frequency contact transducers are not produced is because the element is very thin and too fragile.

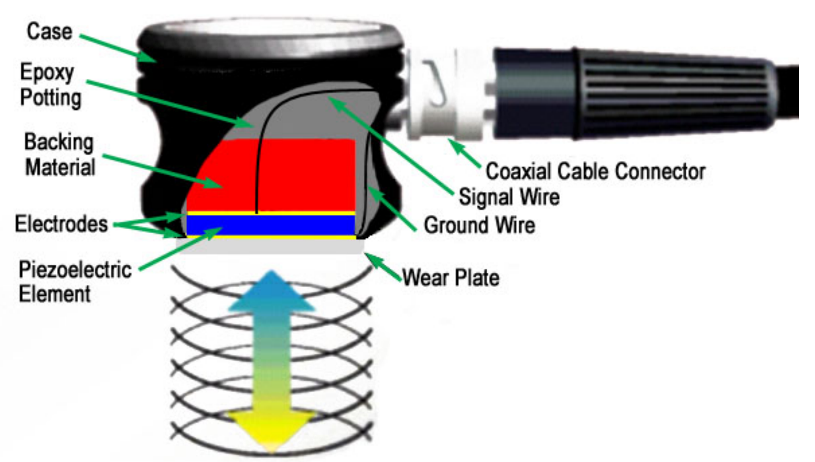
Characteristics of Piezoelectric Transducers

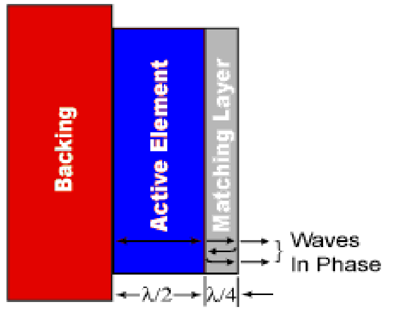
The transducer is a very important part of the **ultrasonic** instrumentation system. As discussed on the previous page, the **transducer** incorporates a **piezoelectric element**, which converts electrical signals into mechanical vibrations (transmit mode) and mechanical vibrations into electrical signals (receive mode). Many factors, including material, mechanical and electrical construction, and the external mechanical and electrical load conditions, influence the behavior of a transducer. Mechanical construction includes parameters such as the radiation surface area, mechanical damping, housing, connector type and other variables of physical construction. As of this writing, transducer manufacturers are hard pressed when constructing two transducers that have identical performance characteristics.

Ultrasonic: Sound frequencies that are higher that detectable with the human ear.

Transducer: A device that converts one form of energy into another. In ultrasonics, electrical energy is converted to mechanical (sound) energy and visa versa.

Piezoelectric Element: Electricity produced by mechanical pressure on a crystal with low symmetry atomic structure.





A cut away of a typical contact transducer is shown above. It was previously learned that the piezoelectric element is cut to 1/2 the desired wavelength. To get as much energy out of the transducer as possible, an impedance matching is placed between the active element and the face of the transducer. Optimal impedance matching is achieved by sizing the matching layer so that its thickness is 1/4 of the desired wavelength. This keeps waves that were reflected within the matching layer in phase when they exit the layer (as illustrated in the image to the right). For contact transducers, the matching layer is made from a material that has an acoustical impedance between the active element and steel. Immersion transducers have a matching layer with an acoustical impedance between the active element and water. Contact transducers also incorporate a wear plate to protect the matching layer and active element from scratching.

The backing material supporting the crystal has a great influence on the damping characteristics of a transducer. Using a backing material with an impedance similar to that of the active element will produce the most effective damping. Such a transducer will have a wider bandwidth resulting in higher sensitivity. As the mismatch in impedance between the active element and the backing material increases, material penetration increases but transducer sensitivity is reduced.

Transducer Efficiency, Bandwidth and Frequency

Some transducers are specially fabricated to be more efficient transmitters and others to be more efficient receivers. A transducer that performs well in one application will not always produce the desired results in a different application. For example, sensitivity to small defects is proportional to the product of the efficiency of the transducer as a transmitter and a receiver. Resolution, the ability to locate defects near the surface or in close proximity in the material, requires a highly damped transducer.

It is also important to understand the concept of bandwidth, or range of frequencies, associated with a transducer. The frequency noted on a transducer is the central or center frequency and depends primarily on the backing material. Highly damped transducers will respond to frequencies above and below the central frequency. The broad frequency range provides a transducer with high resolving power. Less damped transducers will exhibit a narrower frequency range and poorer resolving power, but greater penetration. The central frequency will also define the capabilities of a transducer. Lower frequencies (0.5MHz-2.25MHz) provide greater energy and penetration in a material, while high frequency crystals (15.0MHz-25.0MHz) provide reduced penetration but greater sensitivity to small discontinuities. High frequency transducers, when used with the proper instrumentation, can improve flaw resolution and thickness measurement capabilities dramatically. Broadband transducers with frequencies up to 150 MHz are commercially available.

Transducers are constructed to withstand some abuse, but they should be handled carefully. Misuse, such as dropping, can cause cracking of the wear plate, element, or the backing material. Damage to a transducer is often noted on the A-scan presentation as an enlargement of the initial pulse.

Nondestructive Evaluation Techniques

Ultrasound

- Basic Principles of Ultrasonic Testing
- History of Ultrasonics
- Present State of Ultrasonics
- Future Direction of Ultrasonic Inspection
- Ultrasound and Ultrasonic Testing
- Angle Beam Testing
- Immersion Ultrasonic Testing
- Piezoelectric Transducers
- Characteristics of Piezoelectric Transducers
- **Radiated Fields of Ultrasonic Transducers**
- Transducer Beam Spread
- Transducer Types
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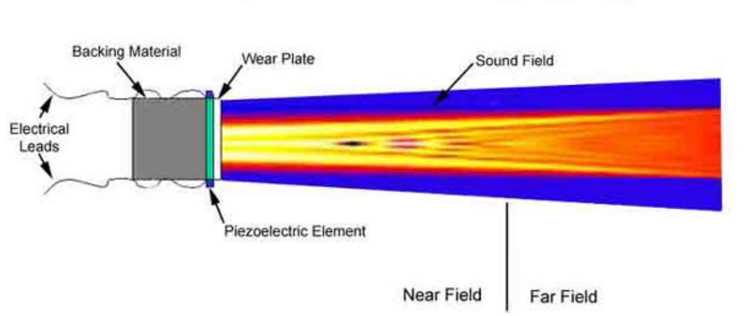
- Transducer Modeling
- Couplant
- Pulser-Receivers
- Tone Burst Generators in Research
- Arbitrary Function Generators
- Electrical Impedance Matching and Termination
- Data Presentation
- Error Analysis
- Normal Beam Inspection
- Angle Beams I
- Angle Beams II
- Crack Tip Diffraction

Nondestructive Evaluation Techniques > Ultrasonic Testing > Radiated Fields of Ultrasonic Transducers

Radiated Fields of Ultrasonic Transducers

The sound that emanates from a piezoelectric transducer does not originate from a point, but instead originates from most of the surface of the piezoelectric element. Round transducers are often referred to as piston source transducers because the sound field resembles a cylindrical mass in front of the transducer. The sound field from a typical piezoelectric transducer is shown below. The intensity of the sound is indicated by color, with lighter colors indicating higher intensity.



Since the ultrasound originates from a number of points along the transducer face, the ultrasound intensity along the beam is affected by constructive and destructive wave interference as discussed in a previous page on wave interference. These are sometimes also referred to as diffraction effects. This wave interference leads to extensive fluctuations in the sound intensity near the source and is known as the near field. Because of acoustic variations within a near field, it can be extremely difficult to accurately evaluate flaws in materials when they are positioned within this area.

The pressure waves combine to form a relatively uniform front at the end of the near field. The area beyond the near field where the ultrasonic beam is more uniform is called the far field. In the far field, the beam spreads out in a pattern originating from the center of the transducer. The transition between the near field and the far field occurs at a distance, **N**, and is sometimes referred to as the "natural focus" of a flat (or unfocused) transducer. The near/far field distance, **N**, is significant because amplitude variations that characterize the near field change to a smoothly declining amplitude at this point. The area just beyond

Example Calculation

Calculate the end of the near field when using a 5 MHz, 0.375 inch diameter transducer to inspect a component made of brass. The sound velocity in brass is 0.1685x106 inch/second

The near field formula is: $N = \frac{D^2}{4\lambda}$ or $N = \frac{D^2 F}{4V}$

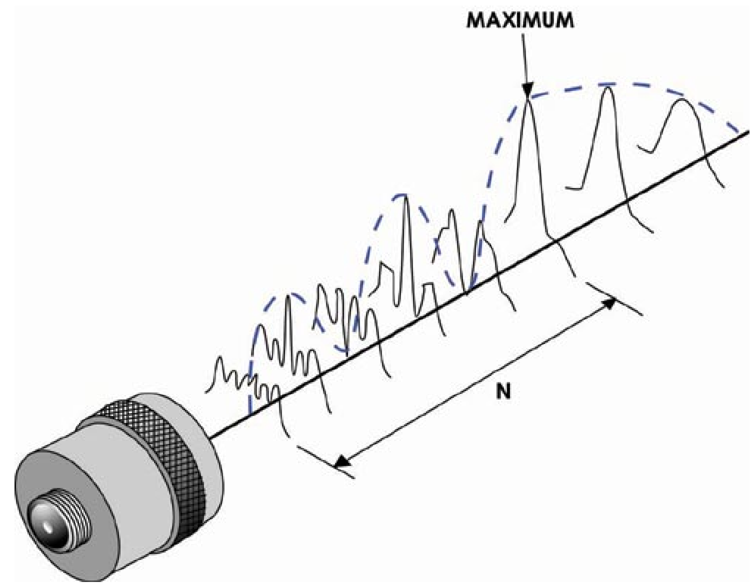
Where: N = Near Field Length
D = Diameter of the Transducer
F = Frequency of the Transducer
I = Wavelength (cycles/second)
Note: MHz is used in the Java applet for ease of use.
V = Velocity of Sound in the Material

Note: Sometimes the radius of the transducer is used (like in the Java calculator). When the radius is used, the four in the denominator go away because the diameter squared divided by four is equal to the radius squared.

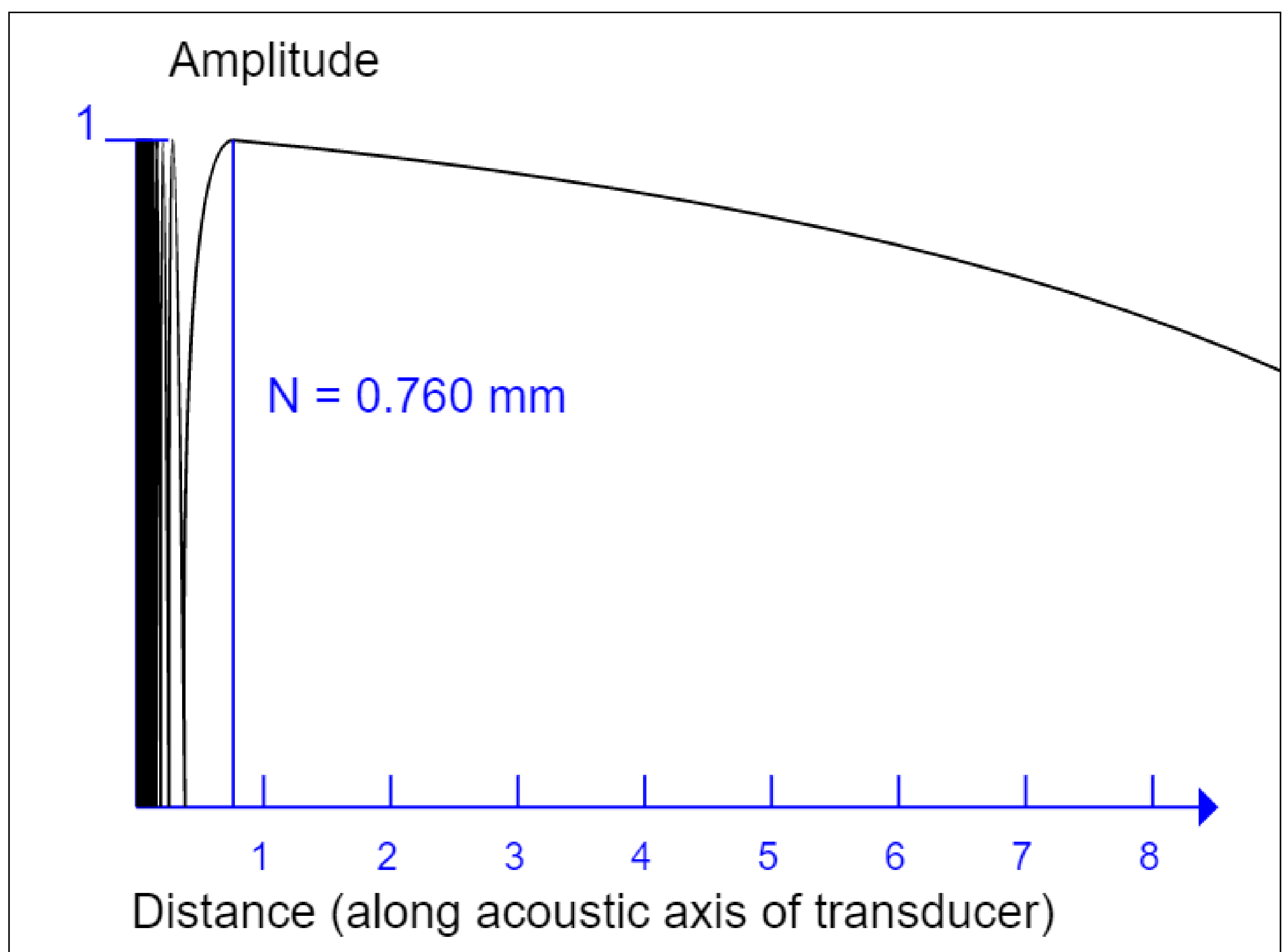
Substitute the values into the formula:
$N = \frac{(.0375 inch)^2 (5.0\times10^6 sec^{-1})}{4(0.1685\times10^6 inch/sec)}$

Solve to get $N = 1.04$ inches

the near field is where the sound wave is well behaved and at its maximum strength. Therefore, optimal detection results will be obtained when flaws occur in this area.



For a piston source transducer of radius (**a**), frequency (**f**), and velocity (**V**) in a liquid or solid medium, the applet below allows the calculation of the near/far field transition point. In the Java applet below, the radius (a) and the near field/far field distance can be in metric or English units (e.g. mm or inch), the frequency (f) is in MHz and the sound velocity (V) is in metric or English length units per second (e.g. mm/sec or inch/sec). Just make sure the length units used are consistent in the calculation.



N = 0.760 mm   Radius (mm) 0.300

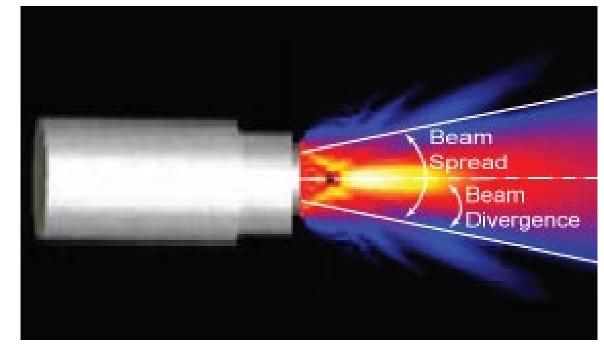
Frequency (MHz) 5.000   Velocity (mm/sec) 0.148

$$\frac{\text{radius}^2 * \text{frequency}}{4 * \text{velocity}} = \frac{0.300^2 * 5.000}{4 * 0.148}$$

Change the radius, frequency, and velocity of the transducer and observe the effective working distance.

Spherical or cylindrical focusing changes the structure of a transducer field by "pulling" the *N* point nearer the transducer. It is also important to note that the driving excitation normally used in NDT applications are either spike or rectangular pulsars, not a single frequency. This 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.

Transducer Beam Spread



As discussed on the previous page, round transducers are often referred to as piston source transducers because the sound field resembles a cylindrical mass in front of the transducer. However, the energy in the beam does not remain in a cylinder, but instead spreads out as it propagates through the material. The phenomenon is usually referred to as beam spread but is sometimes also referred to as beam divergence or ultrasonic diffraction. It should be noted that there is actually a difference between beam spread and beam divergence. Beam spread is a measure of the whole angle from side to side of the main lobe of the sound beam in the far field. Beam divergence is a measure of the angle from one side of the sound beam to the central axis of the beam in the far field. Therefore, beam spread is twice the beam divergence.

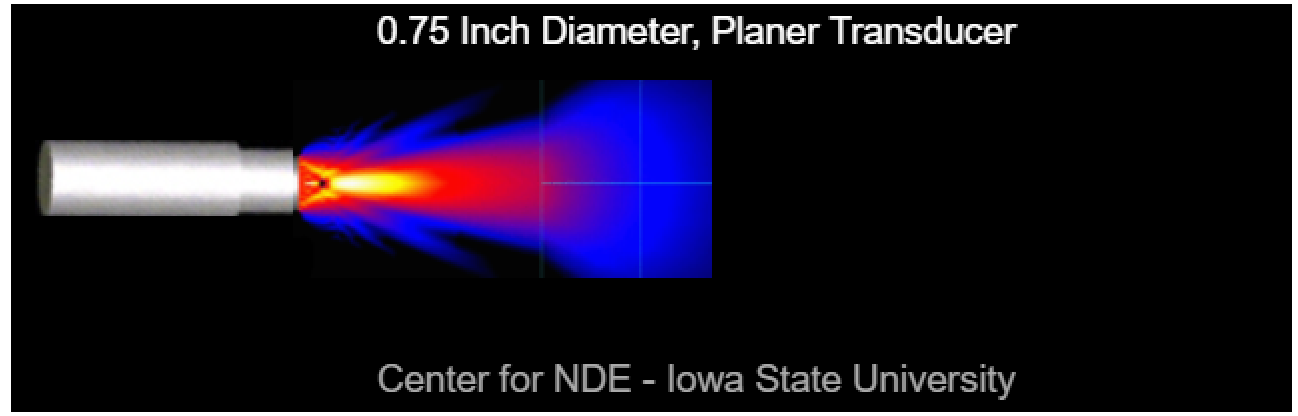
Although beam spread must be considered when performing an ultrasonic inspection, it is important to note that in the far field, or **Fraunhofer** zone, the maximum sound pressure is always found along the acoustic axis (centerline) of the transducer. Therefore, the strongest reflections are likely to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

Fraunhofer Diffraction : A form of diffraction in which the light source and the receiving screen are in effect at infinite distances from the diffracting object, so the the wave fronts can be treated as planar rather than spherical.

Piezoelectric: Electricity produced by mechanical pressure on a crystal with low symmetric atomic structure.

Beam spread occurs because the vibrating particle of the material (through which the wave is traveling) do not always transfer all of their energy in the direction of wave propagation. Recall that waves propagate through the transfer of energy from one particle to another in the medium. If the particles are not directly aligned in the direction of wave propagation, some of the energy will get transferred off at an angle. (Picture what happens when one ball hits another ball slightly off center). In the near field, constructive and destructive wave interference fill the sound field with fluctuation. At the start of the far field, however, the beam strength is always greatest at the center of the beam and diminishes as it spreads outward.

As shown in the applet below, beam spread is largely determined by the frequency and diameter of the transducer. Beam spread is greater when using a low frequency transducer than when using a high frequency transducer. As the diameter of the transducer increases, the beam spread will be reduced.



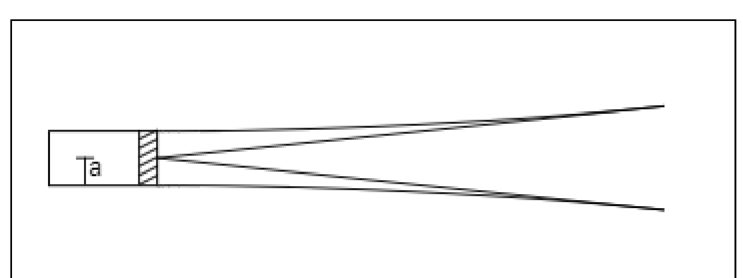
1 MHz 2 MHz 3 MHz 4 MHz 5 MHz 6 MHz 7 MHz 8 MHz
9 MHz

Choose different frequencies to see how the beam divergence changes.

Beam angle is an important consideration in transducer selection for a couple of reasons. First, beam spread lowers the amplitude of reflections since sound fields are less concentrated and, thereby weaker. Second, beam spread may result in more difficulty in interpreting signals due to reflections from the lateral sides of the test object or other features outside of the inspection area. Characterization of the sound field generated by a transducer is a prerequisite to understanding observed signals.

Numerous codes exist that can be used to standardize the method used for the characterization of beam spread. American Society for Testing and Materials ASTM E-1065, addresses methods for ascertaining beam shapes in Section A6, Measurement of Sound Field Parameters. However, these measurements are limited to immersion probes. 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 receiver, which allows the sound field of the probe to be assessed for the entire volume in front of the probe.

For a flat piston source transducer, an approximation of the beam spread may be calculated as a function of the transducer diameter (D), frequency (F), and the sound velocity (V) in the liquid or solid medium. The applet below allows the beam divergence angle (1/2 the beam spread angle) to be calculated. This angle represents a measure from the center of the acoustic axis to the point where the sound pressure has decreased by one half (-6 dB) to the side of the acoustic axis in the far field.



Beam Spread (-6dB)
Velocity (mm/sec) 0.148
Radius (mm) 0.300
Frequency (MHz) 5.000
Θ = 2.906
0.514 * velocity

$$\frac{}{2 * \text{radius} * \text{frequency}} =$$

$$\frac{0.514 * 0.148}{2 * 0.300 * 5.000}$$

$$\sin(\Theta / 2) = \frac{0.514 * 0.148}{2 * 0.300 * 5.000}$$

Change the velocity, radius, and frequency setting to see how the beam spread will change.

Note: This applet uses the equation:

$$\sin\frac{\theta}{2} = \frac{0.514V}{2aF}$$

Where: θ = Beam divergence angle from centerline to point where signal is at half strength.

V = Sound velocity in the material. (inch/sec or cm/sec)[1]

a = Radius of the transducer. (inch or cm)[1]

F = Frequency of the transducer. (cycles/second)

Note 1: Units must be consistent throughout calculation (i.e. inch or cm but not both)

An equal, but perhaps more common version of the formula is:

$$\sin\theta = 1.2\frac{V}{DF}$$

Where: θ = Beam divergence angle from centerline to point where signal is at half strength.

V = Sound velocity in the material. (inch/sec or cm/sec)

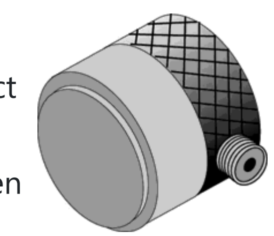
D = Diameter of the transducer. (inch or cm)

F = Frequency of the transducer. (cycles/second)

Transducer Types

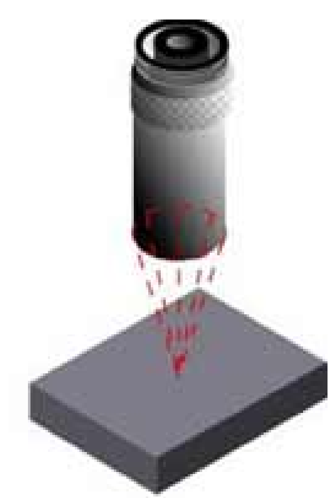
Ultrasonic transducers are manufactured for a variety of applications and can be custom fabricated when necessary. Careful attention must be paid to selecting the proper transducer for the application. A previous section on Acoustic Wavelength and Defect Detection gave a brief overview of factors that affect defect detectability. From this material, we know that it is important to choose transducers that have the desired frequency, bandwidth, and focusing to optimize inspection capability. Most often the transducer is chosen either to enhance the sensitivity or resolution of the system.

Transducers are classified into groups according to the application.



- **Contact transducers** are used for direct contact inspections, and are generally hand manipulated. They have elements protected in a rugged casing to withstand sliding contact with a variety of materials. These transducers have an ergonomic design so that they are easy to grip and move along a surface. They often have replaceable wear plates to lengthen their useful life. Coupling materials of water, grease, oils, or commercial materials are used to remove the air gap between the transducer and the component being inspected.
- **Immersion transducers** do not contact the component. These transducers are designed to operate in a liquid environment and all connections are watertight. Immersion transducers usually have an impedance matching layer that helps to get more sound energy into the water and, in turn, into the component being inspected. Immersion transducers can be purchased with a planer, cylindrically focused or spherically focused lens. A focused transducer can improve the sensitivity and axial resolution by concentrating the sound energy to a smaller area. Immersion transducers are typically used inside a water tank or as part of a squirter or bubbler system in scanning applications.

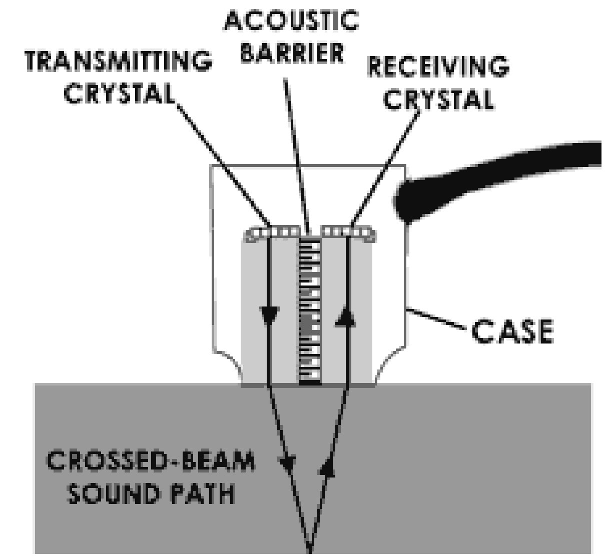
Cylindrical Focus



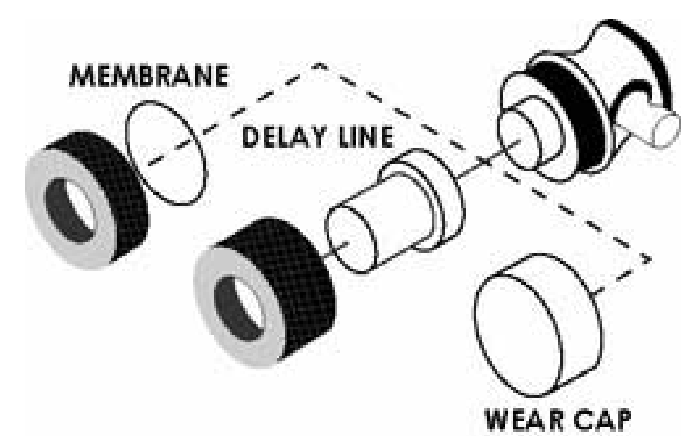
Spherical Focus

More on Contact Transducers

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

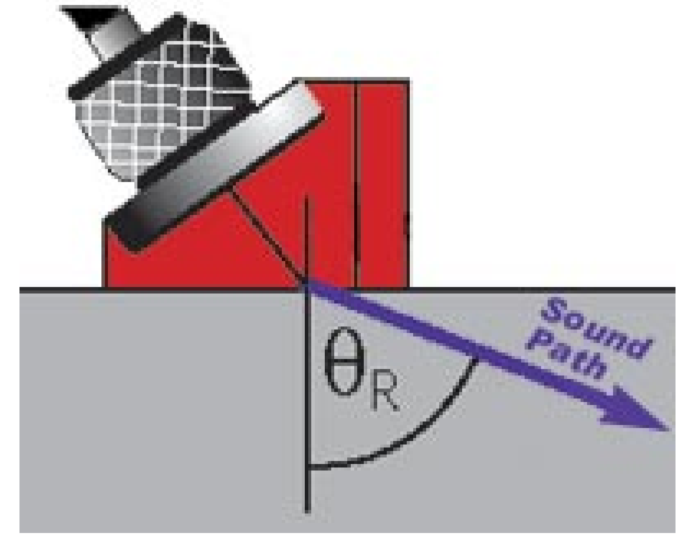


Dual element transducers contain two independently operated elements in a single housing. One of the elements transmits and the other receives the ultrasonic signal. Active elements can be chosen for their sending and receiving capabilities to provide a transducer with a cleaner signal, and transducers for special applications, such as the inspection of course grained material. Dual element transducers are especially well suited for making measurements in applications where reflectors are very near the transducer since this design eliminates the ring down effect that single-element transducers experience (when single-element transducers are operating in pulse echo mode, the element cannot start receiving reflected signals until the element has stopped ringing from its transmit function). Dual element transducers are very useful when making thickness measurements of thin materials and when inspecting for near surface defects. The two elements are angled towards each other to create a crossed-beam sound path in the test material.



Delay line transducers provide versatility with a variety of replaceable options. Removable delay line, surface conforming membrane, and protective wear cap options can make a single transducer effective for a wide range of applications. As the name implies, the primary function of a delay line transducer is to introduce a time delay between the generation of the sound wave and the arrival of any reflected waves. This allows the transducer to complete its "sending" function before it starts its "listening" function so that near surface resolution is improved. They are designed for use in applications such as high precision thickness gauging of thin materials and delamination checks in composite materials. They are also useful in high-temperature measurement applications since the delay line provides some insulation to the piezoelectric element from the heat.

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



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

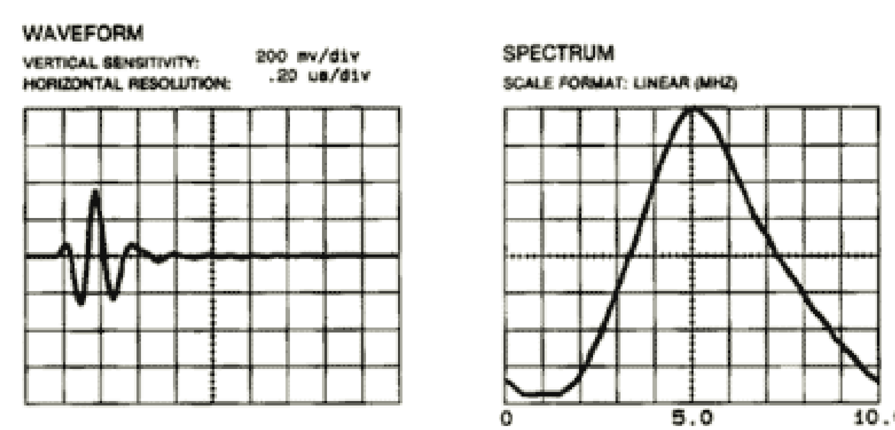
Paint brush transducers are used to scan wide areas. These long and narrow transducers are made up of an array of small crystals that are carefully matched to minimize variations in performance and maintain uniform sensitivity over the entire area of the transducer. Paint brush transducers make it possible to scan a larger area more rapidly for discontinuities. Smaller and more sensitive transducers are often then required to further define the details of a discontinuity.

Transducer Testing

Some transducer manufacturers have lead in the development of transducer characterization techniques and have participated in developing 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 manufacturers 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.

Manufacturers 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 the following:

- **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.

Nondestructive Evaluation Techniques > Ultrasonic Testing > Transducer Testing II

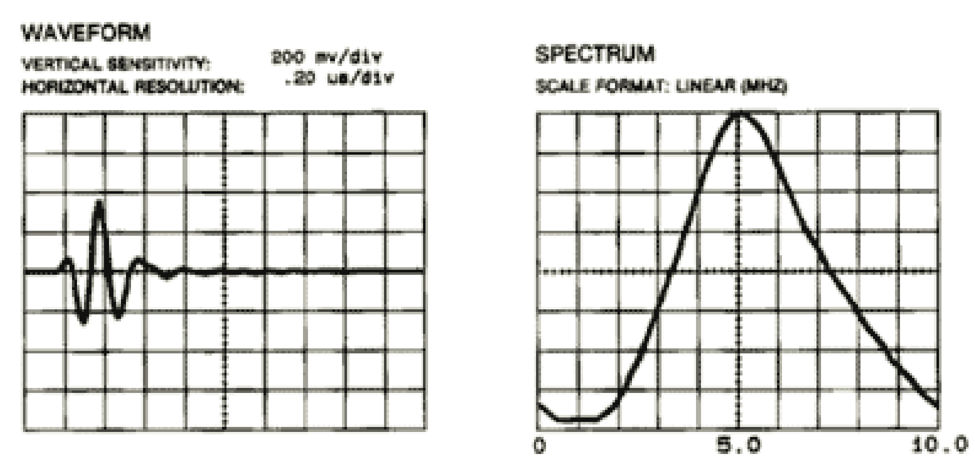
Transducer Testing II

As noted in the ASTM E1065 Standard Guide for Evaluating Characteristics of Ultrasonic Transducers, the acoustic and electrical characteristics which can be described from the data, are obtained from specific procedures that are listed below:

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

Relative Pulse-Echo Sensitivity--The relative pulse-echo sensitivity may be obtained from the frequency response data by 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 to 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 (3.3 to 7.3 MHz) is measured at the -6 dB points, or 50% 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 provide the magnitude and phase of the 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 specifications given by the instrument manufacturer. The value of the magnitude of the complex electrical impedance may also be 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, and flat and curved transducers. These measurements are often achieved by scanning the sound field with a hydrophone transducer to map the sound field in three dimensional space. An alternative approach to sound field measurements is a measure of the transducer's radiating surface motion using laser interferometry.

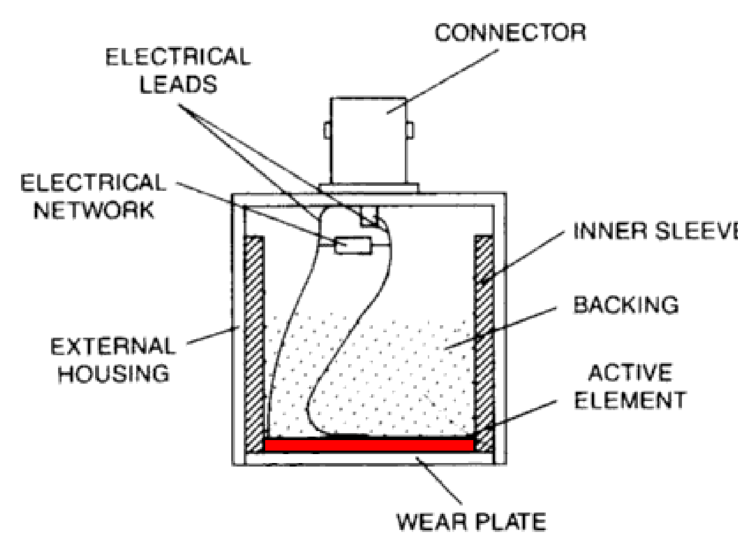
Nondestructive Evaluation Techniques > Ultrasonic Testing > Transducer Modeling

Transducer Modeling

In high-technology manufacturing, part design and simulation of part inspection is done in the virtual world of the computer. Transducer modeling is necessary to make accurate predictions of how a part or component might be inspected, prior to the actual building of that part. Computer modeling is also used to design ultrasonic transducers.

As noted in the previous section, an ultrasonic transducer may be characterized by detailed measurements of its electrical and sound radiation properties. Such measurements can completely determine the response of any one individual transducer.

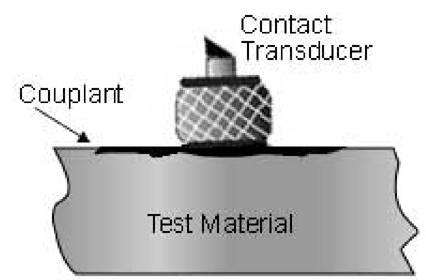
There is ongoing research to develop general models that relate electrical inputs (voltage, current) to mechanical outputs (force, velocity) and vice-versa. These models can be very robust in giving accurate prediction of transducer response, but suffer from a lack of accurate modeling of physical variables inherent in transducer manufacturing. These electrical-mechanical response models must take into account the physical and electrical components in the figure below.



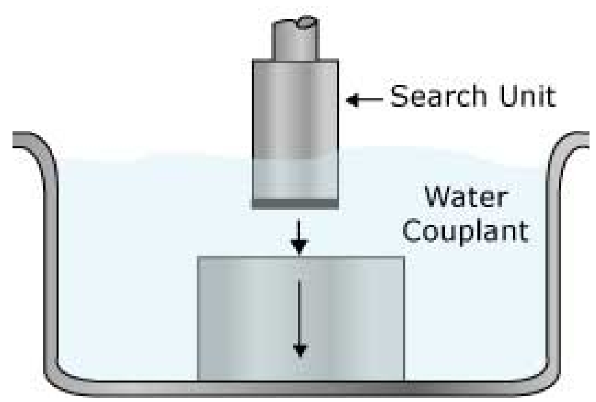
The Thompson-Gray Measurement Model, which makes very accurate predictions of ultrasonic scattering measurements made through liquid-solid interfaces, does not attempt to model transducer electrical-mechanical response. The Thompson-Gray Measurement Model approach makes use of reference data taken with the same transducer(s) to deconvolve electro-physical characteristics specific to individual transducers. See Thompson-Gray Measurement Model.

The long term goal in ultrasonic modeling is to incorporate accurate models of the transducers themselves as well as accurate models of pulser-receivers, cables, and other components that completely describe any given inspection setup and allow the accurate prediction of inspection signals.

Couplant



A couplant is a material (usually liquid) that facilitates the transmission of ultrasonic energy from the transducer into the test specimen. Couplant is generally necessary because the acoustic impedance mismatch between air and solids (i.e. such as the test specimen) is large. Therefore, nearly all of the energy is reflected and very little is transmitted into the test material. The couplant displaces the air and makes it possible to get more sound energy into the test specimen so that a usable ultrasonic signal can be obtained. In contact ultrasonic testing a thin film of oil, glycerin or water is generally used between the transducer and the test surface.



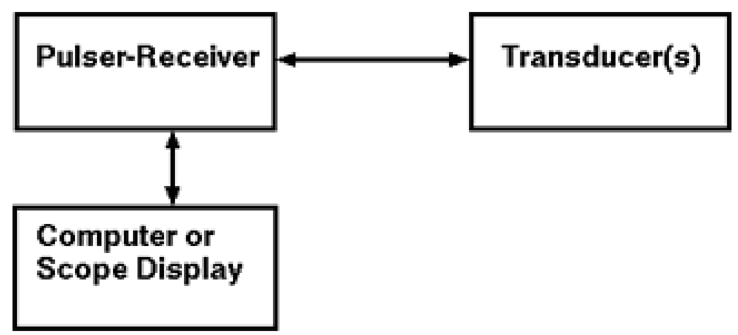
When scanning over the part or making precise measurements, an immersion technique is often used. In immersion ultrasonic testing both the transducer and the part are immersed in the couplant, which is typically water. This method of coupling makes it easier to maintain consistent coupling while moving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

Piezoelectric: The generation of electricity or of electric polarity in ceramic dielectric crystals subjected to mechanical stress, or the generation of stress in such ceramic crystals subjected to an applied voltage.

Magnetostrictive: Deformation of a ferromagnetic material (such as iron and steel) subjected to a magnetic field.

Pulser-Receivers

Ultrasonic pulser-receivers are well suited to general purpose ultrasonic testing. Along with appropriate transducers and an oscilloscope, they can be used for flaw detection and thickness gauging in a wide variety of metals, plastics, ceramics, and composites. Ultrasonic pulser-receivers provide a unique, low-cost ultrasonic measurement capability.



The pulser section of the instrument generates short, large amplitude electric pulses of controlled energy, which are converted into short ultrasonic pulses when applied to an ultrasonic transducer. Most pulser sections have very low impedance outputs to better drive transducers. Control functions associated with the pulser circuit include:

- Pulse length or damping (The amount of time the pulse is applied to the transducer.)
- Pulse energy (The voltage applied to the transducer. Typical pulser circuits will apply from 100 volts to 800 volts to a transducer.)

In the receiver section the voltage signals produced by the transducer, which represent the received ultrasonic pulses, are amplified. The amplified radio frequency (RF) signal is available as an output for display or capture for signal processing. Control functions associated with the receiver circuit include

- Signal rectification (The RF signal can be viewed as positive half wave, negative half wave or full wave.)
- Filtering to shape and smooth return signals
- Gain, or signal amplification

Impedance: The apparent resistance in an electric circuit to the flow of an alternating current, analogous to the actual electrical resistance to a direct current, being the ratio of electromotive force to the current.

Elastic Modulus: The ratio of the applied stress to the change in shape of an elastic body.

Stepless Gate: An instrument or algorithm that allows a portion of a time-varying signal to be selected or rejected. Stepless gates are often used to select the desired portion of a signal while rejecting unwanted noise or events.

- Reject control

The pulser-receiver is also used in material characterization work involving sound velocity or attenuation measurements, which can be correlated to material properties such as elastic modulus. In conjunction with a stepless gate and a spectrum analyzer, pulser-receivers are also used to study frequency dependent material properties or to characterize the performance of ultrasonic transducers.

Tone Burst Generators In Research

Tone burst generators are often used in high power ultrasonic applications. They take low-voltage signals and convert them into high-power pulse trains for the most power-demanding applications. Their purpose is to transmit bursts of acoustic energy into a test piece, receive the resulting signals, and then manipulate and analyze the received signals in various ways. High power radio frequency (RF) burst capability allows researchers to work with difficult, highly attenuative materials or inefficient transducers such as EMATs. A computer interface makes it possible for systems to make high speed complex measurements, such as those involving multiple frequencies.

Resonance: Reinforcement and prolongation of a sound or musical tone by reflection or by sympathetic vibration of other bodies.

Superheterodyne Receiver : Donating a device or method of radio reception in which beats are produced by superimposing a locally generated radio wave on an incoming wave. In the superheterodyne receiver the intermediate frequency is amplified and demodulated.

Nondestructive Evaluation Techniques > Ultrasonic Testing

Tone Burst Generators In Research

Tone burst generators are often used in high power ultrasonic applications. They take low-voltage signals and convert them into high-power pulse trains for the most power-demanding applications. Their purpose is to transmit bursts of acoustic energy into a test piece, receive the resulting signals, and then manipulate and analyze the received signals in various ways. High power radio frequency (RF) burst capability allows researchers to work with difficult, highly attenuative materials or inefficient transducers such as EMATs. A computer interface makes it possible for systems to make high speed complex measurements, such as those involving multiple frequencies.

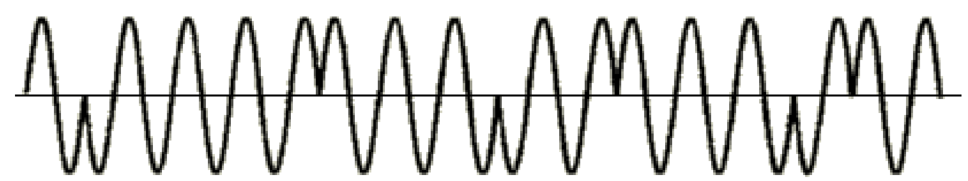
Resonance: Reinforcement and prolongation of a sound or musical tone by reflection or by sympathetic vibration of other bodies.

Superheterodyne Receiver : Donating a device or method of radio reception in which beats are produced by superimposing a locally generated radio wave on an incoming wave. In the superheterodyne receiver the intermediate frequency is amplified and demodulated.

Arbitrary Function Generators

Arbitrary waveform generators permit the user to design and generate virtually any waveform in addition to the standard function generator signals (i.e. sine wave, square wave, etc.). Waveforms are generated digitally from a computer's memory, and 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 provided by many common pulser/receiver units. The lightly damped transducers used in high power generation, for example, require a narrowband tone-burst excitation from a separate generator unit. Sometimes the same transducer will be excited differently, such as in the study of 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 (see spread spectrum page), encoded sound is generated by an arbitrary waveform generator continuously transmitting 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 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).

Nondestructive Evaluation Techniques > Ultrasonic Testing > Electrical Impedance Matching and Termination

Electrical Impedance Matching and Termination

When computer systems were first introduced decades ago, they were large, slow-working 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 that are used in ultrasonics?

Data Signals: Input versus Output

Consider the signal going to and from ultrasonic transducers. When you transmit data through a 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 the cable's 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 page, we can only review these characteristics very generally, however, we will discuss capacitance in more detail.

Impedance: The quantity that measures the opposition of a circuit to the passage of a current and therefore determines the amplitude of the current.

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.

Attenuation: A loss of intensity suffered by sound, radiation, etc., as it passes through a medium.

Shielding: A barrier surrounding a region to exclude it from the influence of an energy field.

Capacitance: The property of a conductor or system of conductors that describes its ability to store electric charge.

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 have a double shield. Cable shields usually have two functions: to act as a barrier to keep external signals from getting in and internal signals from getting out, and 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 a 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.

Recommendations:

- Observe manufacturer's recommended practices for cable impedance, cable length, impedance matching, and any requirements for termination in characteristic impedance.
- If possible, use the same cables and cable dressing for all inspections.

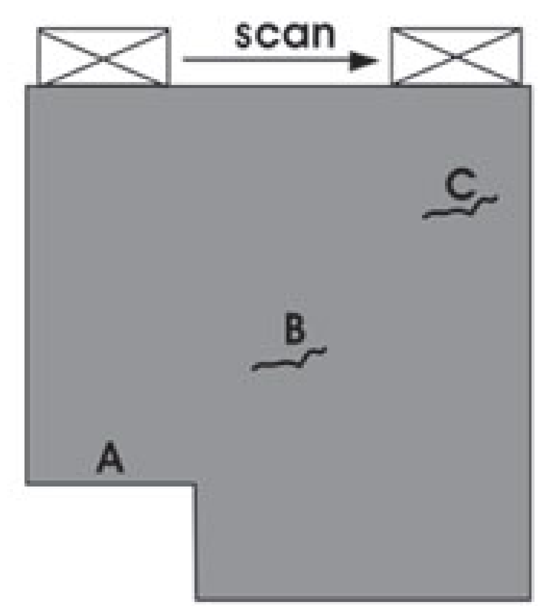
Nondestructive Evaluation Techniques > Ultrasonic Testing > Data Presentation

Data Presentation

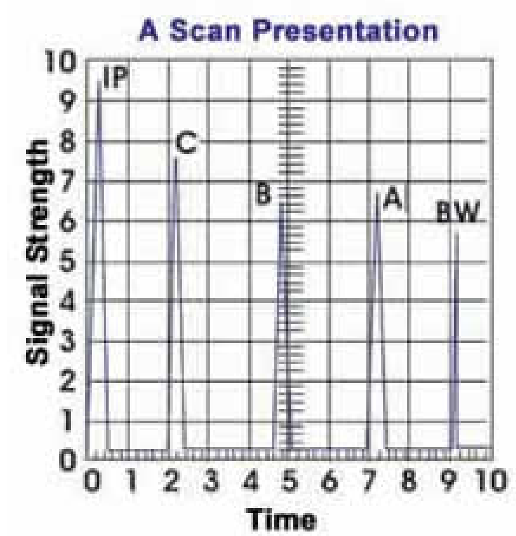
Ultrasonic data can be collected and displayed in a number of different formats. The three most common formats are know in the NDT world as **A-scan**, **B-scan** and **C-scan** presentations. Each presentation mode provides a different way of looking at and evaluating the region of material being inspected.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

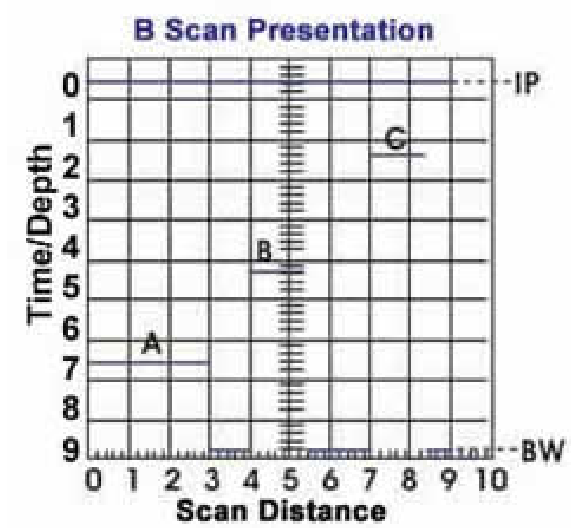
A-Scan Presentation

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



In the illustration of the A-scan presentation to the right, the initial pulse generated by the transducer is represented by the signal *IP*, which is near time zero. As the transducer is scanned along the surface of the part, four other signals are likely to appear at different times on the screen. When the transducer is in its far left position, only the *IP* signal and signal *A*, the sound energy reflecting from surface *A*, will be seen on the trace. As the transducer is scanned to the right, a signal from the backwall *BW* will appear later in time, showing that the sound has traveled farther to reach this surface. When the transducer is over flaw *B*, signal **B** will appear at a point on the time scale that is approximately halfway between the **IP** signal and the **BW** signal. Since the **IP** signal corresponds to the front surface of the material, this indicates that flaw *B* is about halfway between the front and back surfaces of the sample. When the transducer is moved over flaw *C*,





signal *C* will appear earlier in time since the sound travel path is shorter and signal *B* will disappear since sound will no longer be reflecting from it.

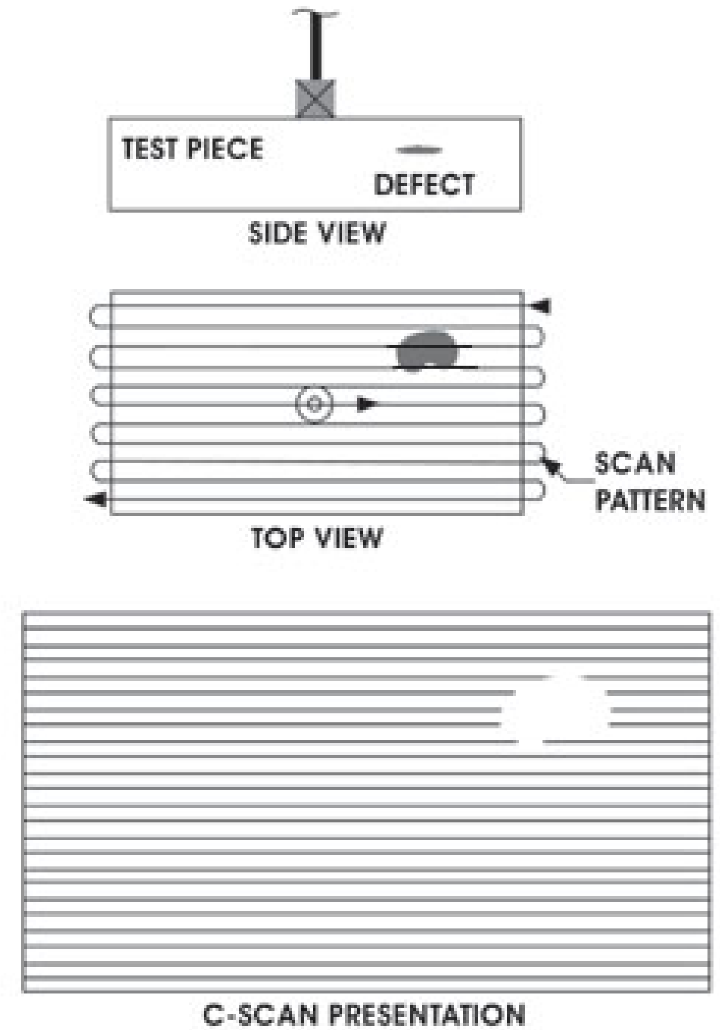
B-Scan Presentation

The B-scan presentations is a profile (cross-sectional) view of the test specimen. In the B-scan, the time-of-flight (travel time) of the sound energy is displayed along the vertical axis and the linear position of the transducer is displayed along the horizontal axis. From the B-scan, the depth of the reflector and its approximate linear dimensions in the scan direction can be determined. The B-scan is typically produced by establishing a trigger gate on the A-scan. Whenever the signal intensity is great enough to trigger the gate, a point is produced on the B-scan. The gate is triggered by the sound reflecting from the backwall of the specimen and by smaller reflectors within the material. In the B-scan image above, line **A** is produced as the transducer is scanned over the reduced thickness portion of the specimen. When the transducer moves to the right of this section, the backwall line **BW** is produced. When the transducer is over flaws **B** and *C*, lines that are similar to the length of the flaws and at similar depths within the material are drawn on the B-scan. It should be noted that a limitation to this display technique is that reflectors may be masked by larger reflectors near the surface.

C-Scan Presentation

The C-scan presentation provides a plan-type view of the location and size of test specimen features. The plane of the image is parallel to the scan pattern of the transducer. C-scan presentations are produced with an automated data acquisition system, such as a computer controlled immersion scanning system. Typically, a data collection gate is established on the A-scan and the amplitude or the time-of-flight of the signal is recorded at regular intervals as the transducer is scanned over the test piece. The relative signal amplitude or the time-of-flight is displayed as a shade of gray or a color for each of the positions where data was recorded. The C-scan presentation provides an image of the features that reflect and scatter the sound within and on the surfaces of the test piece.

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



Error Analysis

All measurements, including ultrasonic measurements, however careful and scientific, are subject to some uncertainties. Error analysis is the study and evaluation 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. Because ultrasonics depends on measurements, evaluation and minimization of uncertainties is crucial.

In science the word "error" does not mean "mistake" or "blunder" but rather the inevitable uncertainty of all measurements. Because they cannot be avoided, errors in this context are not, strictly speaking, "mistakes." At best, they can be made as small as reasonably possible, and their size can be reliably estimated.

To illustrate the inevitable occurrence of uncertainties surrounding attempts at measurement, let us consider 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, she 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 she wanted a more accurate measurement, she would use a tape measure, and she might find that the height is 211.3 cm. This measurement is certainly more precise than her original estimate, but it is obviously still subject to some uncertainty, since it is inconceivable that she 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 enough care were taken. For example, one source of uncertainty might be that poor lighting is making it difficult to read the tape; this could be corrected by improved lighting.

On the other hand, some sources of uncertainty are intrinsic to the process of measurement and can never be entirely removed. For instance, 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 she 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 her tape, and this necessity causes some uncertainty in her answer.

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

Furthermore, as the carpenter strives for greater precision, she will encounter an important problem of principle. She will certainly find that the height is different in different places. Even in one place, she will find that the height varies if the temperature and humidity vary, or even if she accidentally rubs off a thin layer of dirt. In other words, she 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 are simply 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 her door, she 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 will not leak out, and her concern with error analysis will come to an end.

Nondestructive Evaluation Techniques > Ultrasonic Testing > Normal Beam Inspection

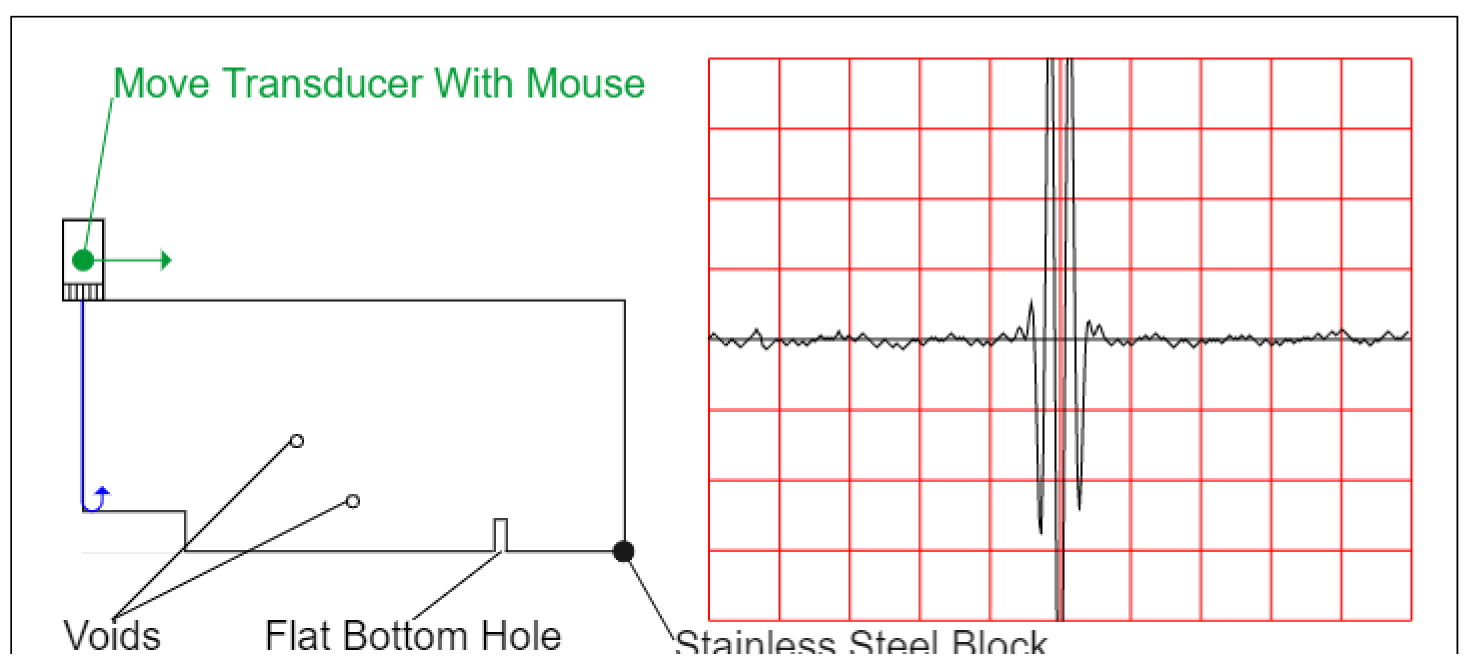
Normal Beam Inspection

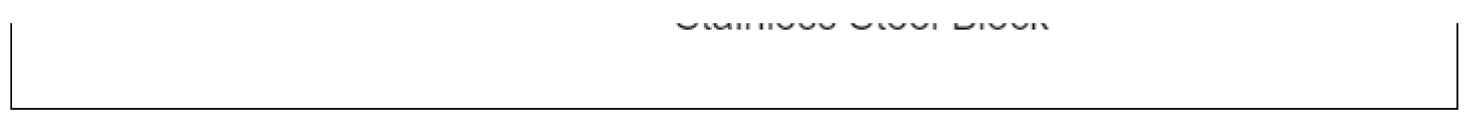
Pulse-echo ultrasonic measurements can determine the location of a discontinuity in a part or structure by accurately measuring the time required for a short ultrasonic pulse generated by a transducer to travel through a thickness of material, reflect from the back or the surface of a discontinuity, and be returned to the transducer. In most applications, this time interval is a few microseconds or less. The two-way transit time measured is divided by two to account for the down-and-back travel path and multiplied by the velocity of sound in the test material. The result is expressed in the well-known relationship

$$d = \frac{vt}{2}$$

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

The diagram below allows you to move a transducer over the surface of a stainless steel test block and see return echoes as they would appear on an oscilloscope. The transducer employed is a 5 MHz broadband transducer 0.25 inches in diameter. The signals were generated with computer software similar to that found in the Thompson-Gray Measurement Model and UTSIM developed at the Center for Nondestructive Evaluation at Iowa State University.





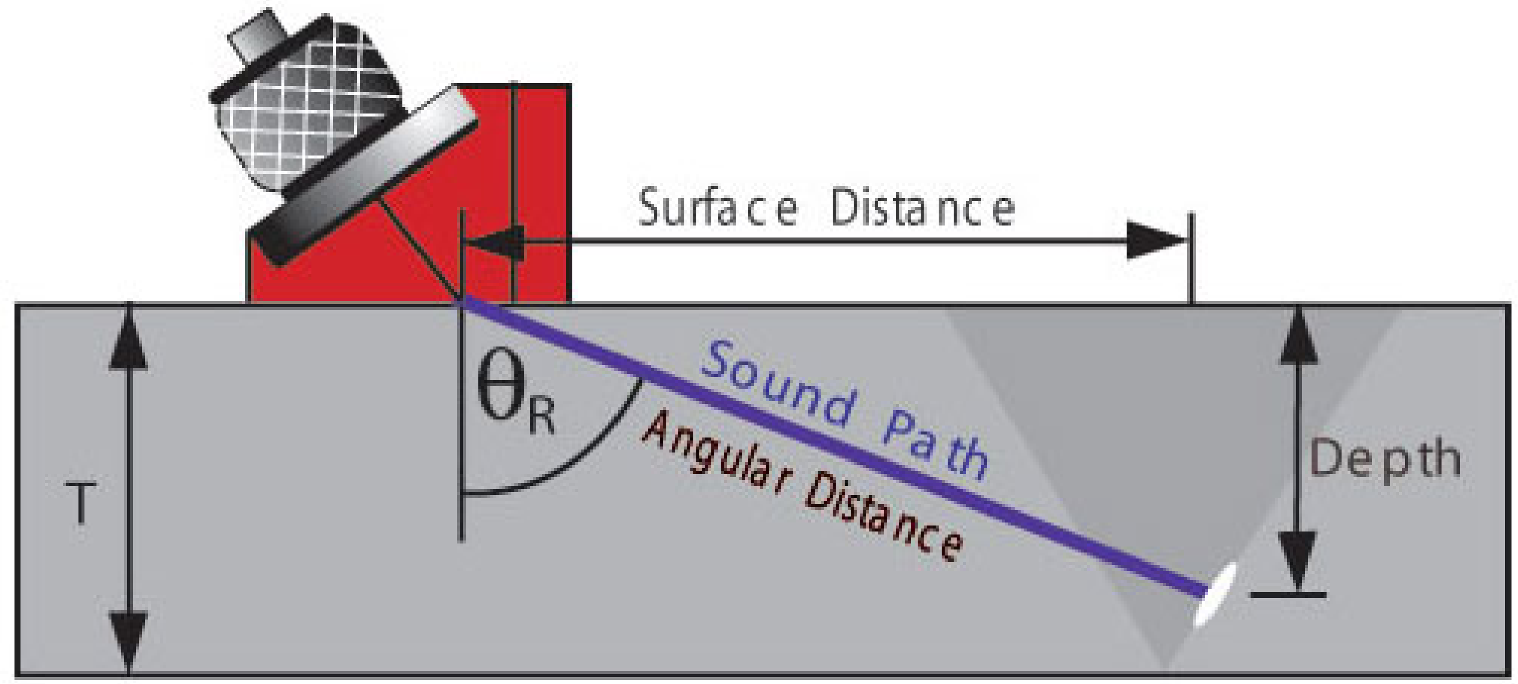
Precision ultrasonic thickness gages usually operate at frequencies between 500 kHz and 100 MHz, by means of piezoelectric transducers that generate bursts of sound waves when excited by electrical pulses. A wide variety of transducers with various acoustic characteristics have been developed to meet the needs of industrial applications. Typically, lower frequencies are used to optimize penetration when measuring thick, highly attenuating or highly scattering materials, while higher frequencies will be recommended to optimize resolution in thinner, non-attenuating, non-scattering materials.

In thickness gauging, ultrasonic techniques permit quick and reliable measurement of thickness without requiring access to both sides of a part. Accuracy's as high as ±1 micron or ±0.0001 inch can be achieved in some applications. It is possible to measure most engineering materials ultrasonically, including metals, plastic, ceramics, composites, epoxies, and glass as well as liquid levels and the thickness of certain biological specimens. On-line or in-process measurement of extruded plastics or rolled metal often is possible, as is measurements of single layers or coatings in multilayer materials. Modern handheld gages are simple to use and very reliable.

Angle Beams I

Refraction: The change of direction suffered by wavefront as it passes obliquely from one medium to another in which its speed of propagation is altered.

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

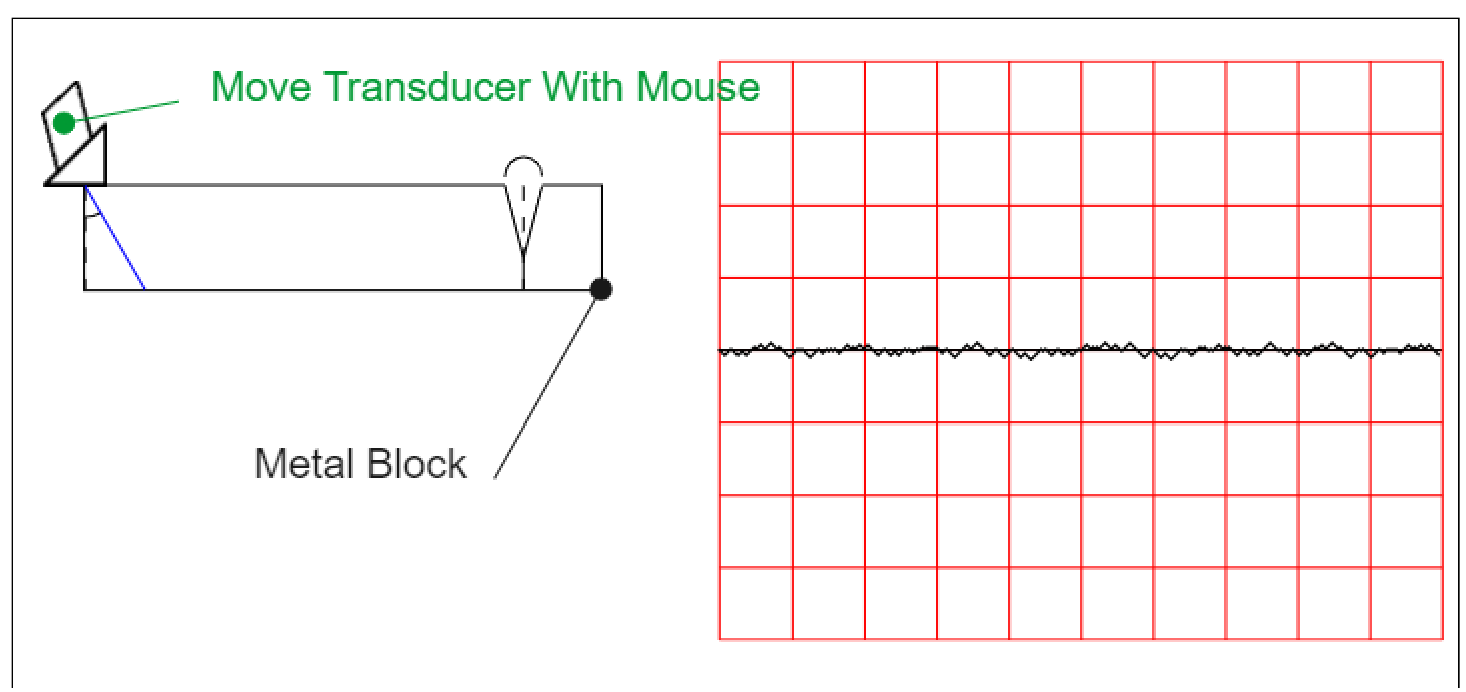


θ_R = Angle of Refraction

T = Material Thickness

Surface Distance = Sinθ_Rx Sound Path

Depth (1st Leg) = Cosθ_Rx Sound Path



Refraction Angle: 30 Thickness: 1

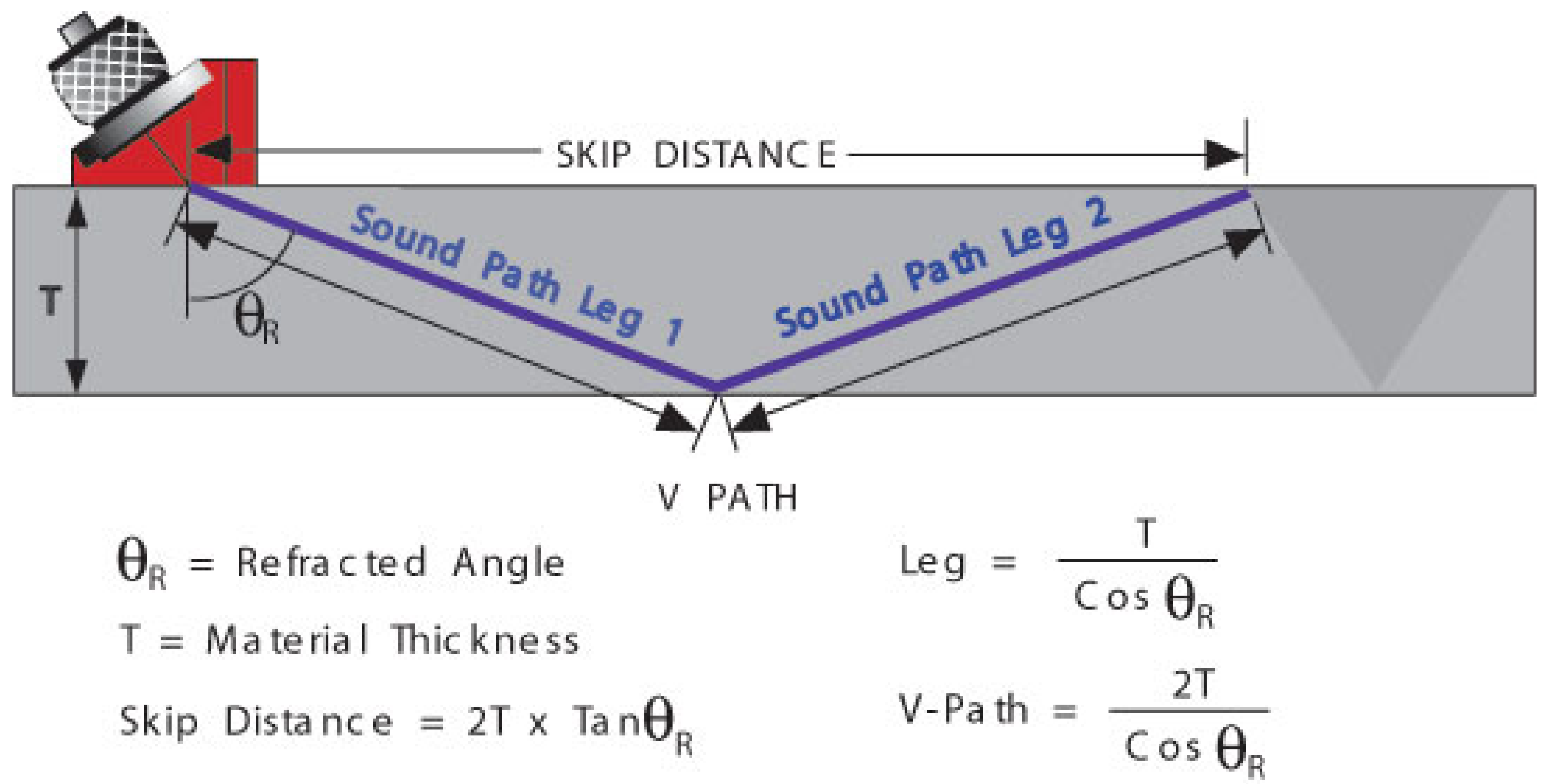
Surface Distance: 0.577

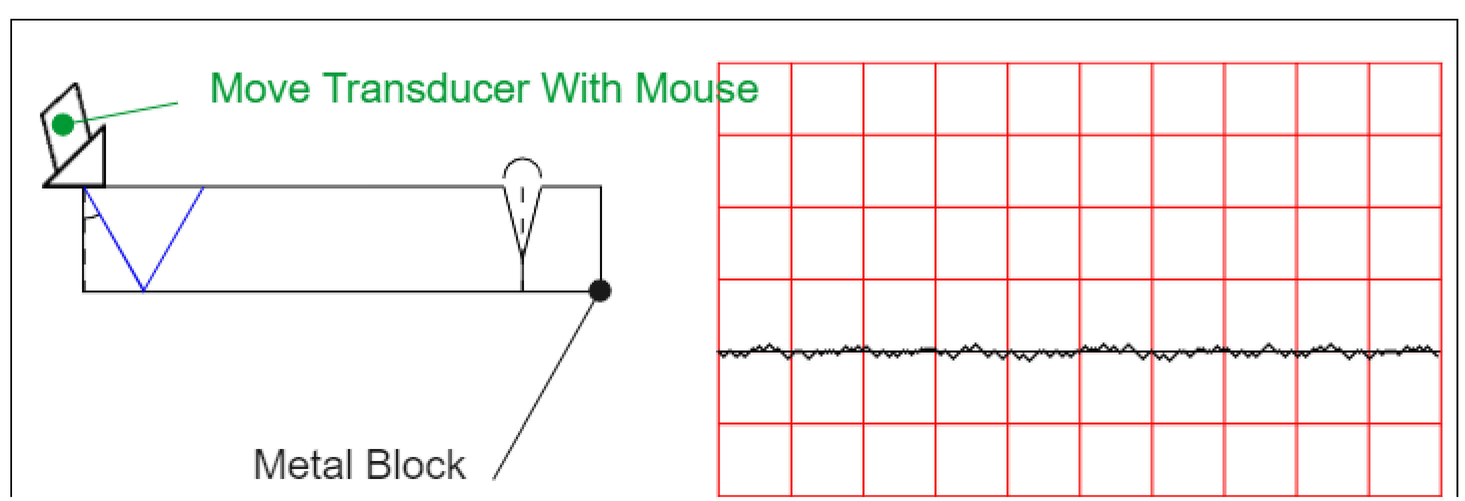
Depth (1st Leg): 1.000

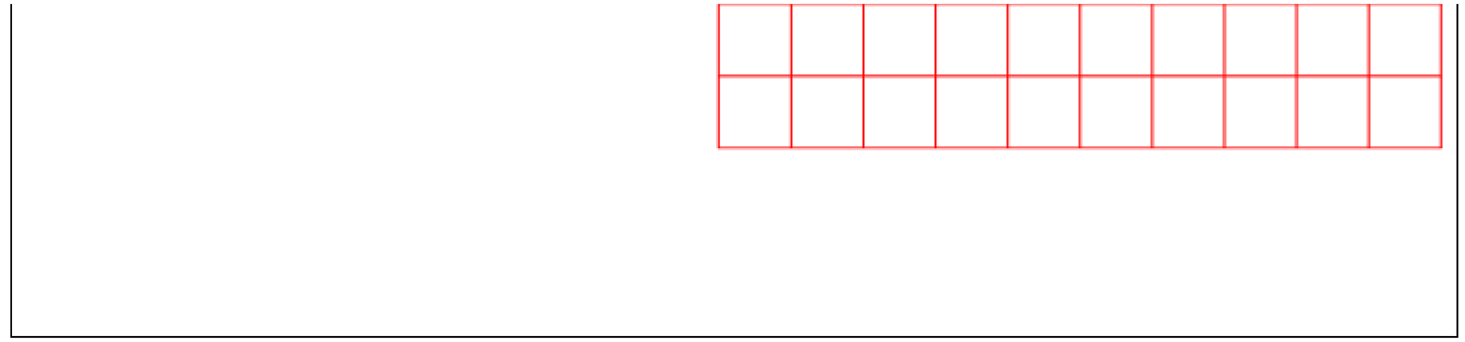
Nondestructive Evaluation Techniques > Ultrasonic Testing > Angle Beams II

Angle Beams II

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







Refraction Angle: 30 Thickness: 1
Surface Distance: 1.155
V-Path: 2.309 Depth (2nd Leg): 0

Nondestructive Evaluation Techniques

Ultrasound

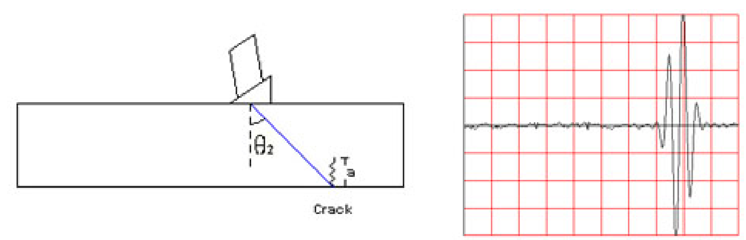
- Basic Principles of Ultrasonic Testing
- History of Ultrasonics
- Present State of Ultrasonics
- Future Direction of Ultrasonic Inspection
- Ultrasound and Ultrasonic Testing
- Angle Beam Testing
- Immersion Ultrasonic Testing
- Piezoelectric Transducers
- Characteristics of Piezoelectric Transducers
- Radiated Fields of Ultrasonic Transducers
- Transducer Beam Spread
- Transducer Types
- Transducer Testing
- Transducer Testing II
- Transducer Modeling
- Couplant
- Pulser-Receivers
- Tone Burst Generators in Research
- Arbitrary Function Generators
- Electrical Impedance Matching and Termination
- Data Presentation
- Error Analysis
- Normal Beam Inspection

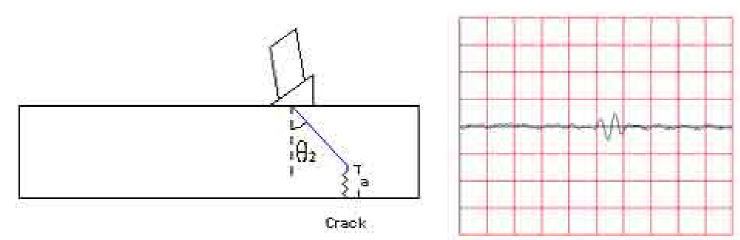
Nondestructive Evaluation Techniques > Ultrasonic Testing > Crack Tip Diffraction

Crack Tip Diffraction

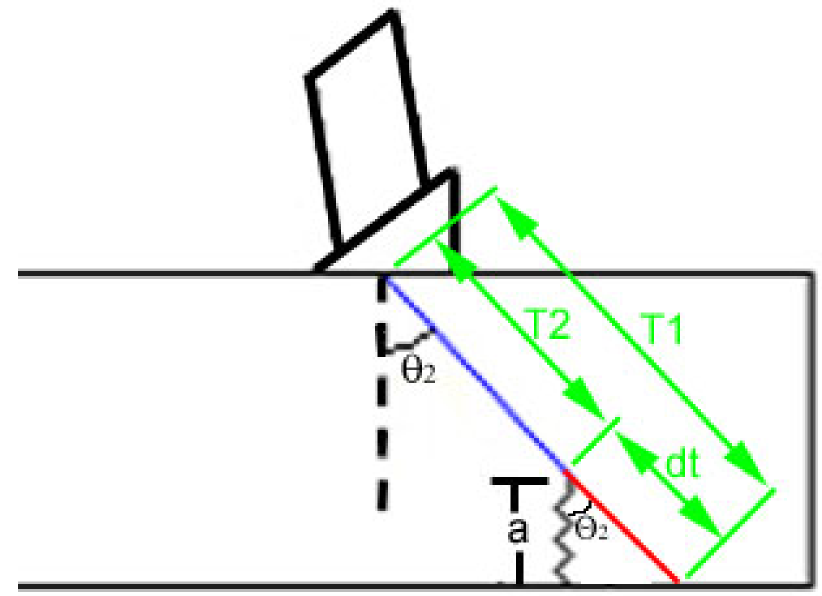
Diffraction: The spreading or bending of waves as they pass through an aperture (transducer) or round the edge of a barrier.

When the geometry of the part is relatively uncomplicated and the orientation of a flaw is well known, the length ***(a)*** of a crack can be determined by a technique known as tip **diffraction**. One common application of the tip diffraction technique is to determine the length of a crack originating from on the backside of a flat plate as shown below. In this case, when an angle beam transducer is scanned over the area of the flaw, the principle echo comes from the base of the crack to locate the position of the flaw (Image 1). A second, much weaker echo comes from the tip of the crack and since the distance traveled by the ultrasound is less, the second signal appears earlier in time on the scope (Image 2).





Crack height *(a)* is a function of the ultrasound velocity (**v**) in the material, the incident angle (Q_2) and the difference in arrival times between the two signal **(dt)**. Since the incident angle and the thickness of the material is the same in both measurements, two similar right triangle are formed such that one can be overlayed on the other. A third similar right triangle is made, which is comprised on the crack, the length **dt** and the angle Q_2. The variable **dt** is really the difference in time but can easily be converted to a distance by dividing the time in half (to get the one-way travel time) and multiplying this value by the velocity of the sound in the material. Using trigonometry an equation for estimating crack height from these variables can be derived as shown below.



Crack

$$\cos\theta = \frac{a}{dt}$$

Solving for "a" the equation becomes

$$a = \cos\theta \times dt$$

The equation is complete once distance dt is calculated by dividing the difference in time between the two signals (dt) by two and multiplying this value by the sound velocity.

$$a = \cos\theta \times \frac{dt \times v}{2}$$

Automated Scanning

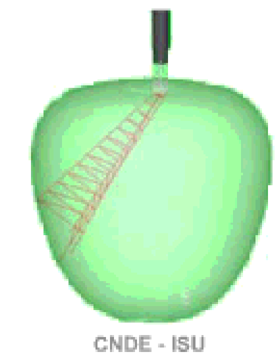
Ultrasonic scanning systems are used for automated data acquisition and imaging. They typically integrate a ultrasonic instrumentation, a scanning bridge, and computer controls. The signal strength and/or the time-of-flight of the signal is measured for every point in the scan plan. The value of the data is plotted using colors or shades of gray to produce detailed images of the surface or internal features of a component. Systems are usually capable of displaying the data in A-, B- and C-scan modes simultaneously. With any ultrasonic scanning system there are two factors to consider:

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

The most common ultrasonic scanning systems involve the use of an immersion tank as shown in the image above. The ultrasonic transducer and the part are placed under water so that consistent coupling is maintained by the water path as the transducer or part is moved within the tank. However, scanning systems come in a large variety of configurations to meet specific inspection needs. In the image to the right, an engineer aligns the heads of a squirter system that uses a through-transmission technique to inspect aircraft composite structures. In this system, the ultrasound travels through columns of forced water which are scanned about the part with a robotic system. A variation of the squirter system is the "Dripless Bubbler" scanning system, which is discussed below.

It is often desirable to eliminate the need for the water coupling and a number of state-of-the-art UT scanning systems have done this. Laser ultrasonic systems use laser beams to generate the ultrasound and collect the resulting signals in an noncontact mode. Advances in transducer technology has lead to the development of an inspection technique known as air-coupled ultrasonic inspection. These systems are capable of sending ultrasonic energy through air and getting enough energy into the part to have a useable signal. These system typically use a through-transmission technique since reflected energy from discontinuities are too weak to detect.

The second major consideration is how to scan the transducer(s) with respect to the part being inspected. When the sample being inspected has a flat surface, a simple raster-scan can be performed. If the sample is cylindrical, a turntable can be used to turn the sample while the transducer is held stationary or scanned in the axial direction of the cylinder. When the sample is irregular shaped, scanning becomes more difficult. As illustrated in the beam modeling animation, curved surface can steer, focus and defocus the ultrasonic beam. For inspection applications involving parts having complex curvatures, scanning systems capable of performing contour following are usually necessary.



Precision Velocity Measurements

Changes in ultrasonic wave propagation speed, along with energy losses, from interactions with a materials microstructures are often used to nondestructively gain information about a material's properties. Measurements of sound velocity and ultrasonic wave attenuation can be related to the elastic properties that can be used to characterize the texture of polycrystalline metals. These measurements enable industry to replace destructive microscopic inspections with nondestructive methods.

Of interest in velocity measurements are **longitudinal wave**, which propagate in gases, liquids, and solids. In solids, also of interest 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 wavelength. The transverse velocity is affected little by the physical dimensions of the sample.

Longitudinal Wave: A wave composed of alternate surfaced of compression and rarefaction traveling perpendicular to these surfaces. Particle motion is in the direction of travel.

Transverse Wave: The particle displacement at each point in a material is perpendicular to the direction of wave propagation. Transverse waves are not supported by liquids and gasses.

Transducer: A device that converts one form of energy into another. In ultrasonics, electrical energy is converted to mechanical (sound) energy and visa versa.

Pulse-Echo and Pulse-Echo-Overlap Methods

Rough ultrasonic velocity measurements 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). Another method is to compare the phase of the detected sound wave with a reference signal: slight changes in the transducer separation are seen as slight phase changes, from which the sound velocity can be calculated. 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)

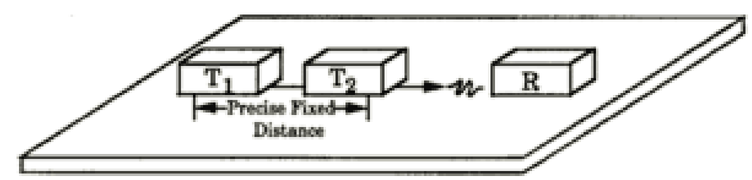
Electromagnetic-acoustic transducers (EMAT) generate ultrasound in the material being investigated. When a wire or coil is placed near to the surface of an electrically conducting object and is driven by a current at the desired ultrasonic frequency, eddy currents will be induced in a near surface region. If a static magnetic field is also present, these currents will experience Lorentz forces of the form

$$F = J \times B$$

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:



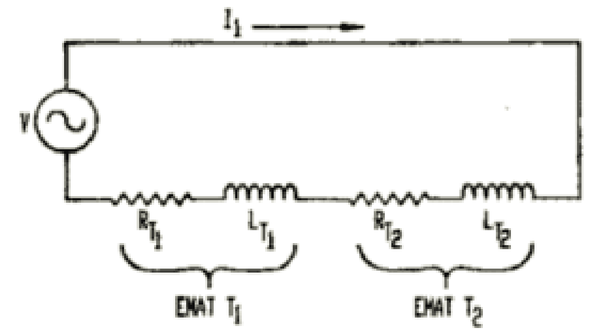
	Texture	Stress	
Ferrous	0, 45, 90	0, 90	Pulsed Magnets
Non-Ferrous	0, 45, 90	0, 90	Permanent Magnets
	S_0	SH_0	

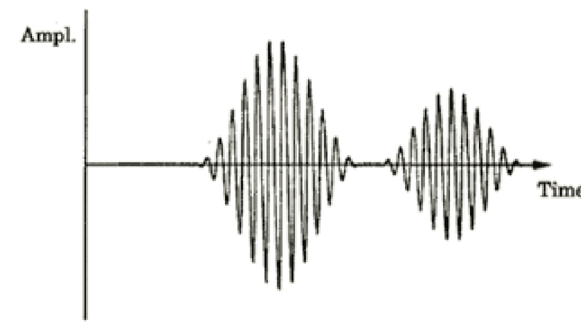
EMAT Driver Frequency: 450-600 KHz (nominal)
Sampling Period: 100 ns
Time Measurement Accuracy:

- 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

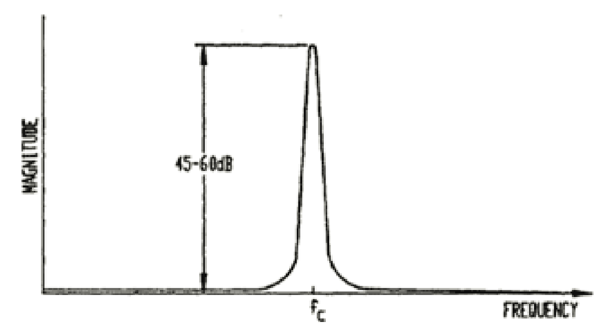
Time Measurement Technique

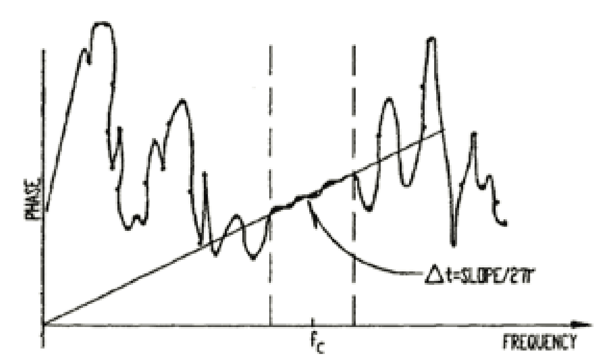
Fourier Transform-Phase-Slope determination of delta time between received RF bursts (T**2**-R) - (T**1**-R), where T**2** and T**1** EMATs are driven in series to eliminate differential phase shift due to probe liftoff.





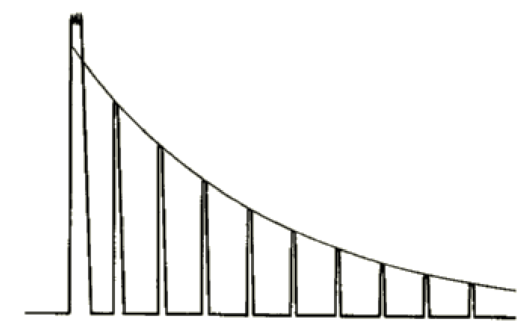
Received Waveforms from T_1 and T_2





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).

Attenuation Measurements



Ultrasonic wave propagation is influenced by the microstructure of the material through which it propagates. The velocity of the ultrasonic waves is influenced by the elastic moduli and the density of the material, which in turn are mainly governed by the amount of various phases present and the damage in the material. Ultrasonic attenuation, which is the sum of the absorption and the scattering, is mainly dependent upon the damping capacity and scattering from the grain boundary in the material. However, to fully characterize the attenuation required knowledge of a large number of thermo-physical parameters that in practice are hard to quantify.

Relative measurements such as the change of attenuation and simple qualitative tests are easier to make than absolute measure. Relative attenuation measurements can be made by examining the exponential decay of multiple back surface reflections. However, significant variations in microstructural characteristics and mechanical properties often produce only a relatively small change in wave velocity and attenuation.

Absolute measurements of attenuation are very difficult to obtain because the echo amplitude depends on factors in addition to amplitude. The most common method used to get quantitative results is to use an ultrasonic source and detector transducer separated by a known distance. By varying the separation distance, the attenuation can be measured from the changes in the amplitude. To get accurate results, the influence of coupling conditions must be carefully addressed. To overcome the problems related to conventional ultrasonic attenuation measurements, ultrasonic spectral parameters for frequency-dependent attenuation measurements, which are independent from coupling conditions are also used. For example, the ratio of the amplitudes of higher frequency peak to the lower frequency peak, has been used for microstructural characterization of some materials.

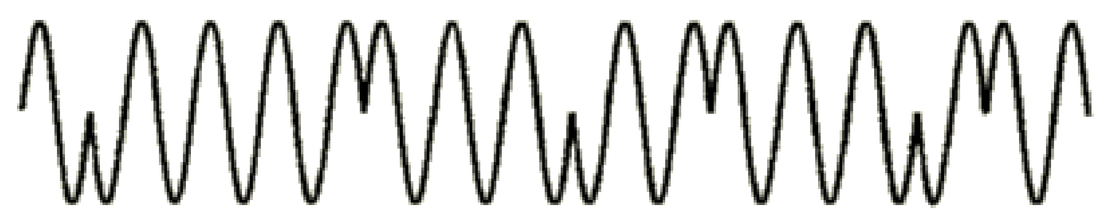
Spread Spectrum Ultrasonics

Spread **spectrum** ultrasonics makes use of the correlation of continuous signals rather than pulse-echo or pitch-catch techniques.

Spectrum: The distribution of energy over a range of frequencies of a particular source.

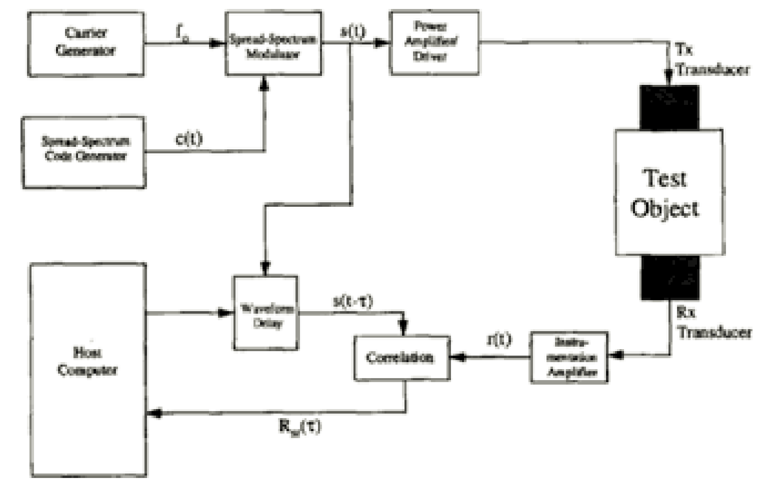
Spread spectrum ultrasonics is a patented new broad band spread-spectrum ultrasonic nondestructive evaluation method. In conventional ultrasonics, a pulse or tone burst is transmitted, then received echoes or through-transmission signals are received and analyzed.

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 of energy.

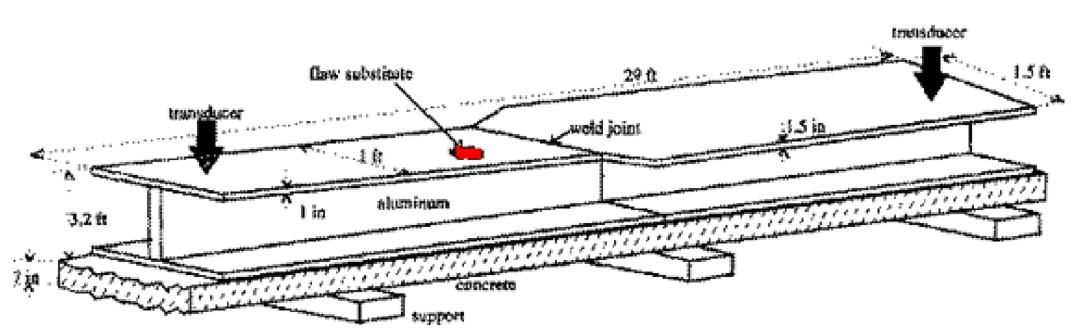


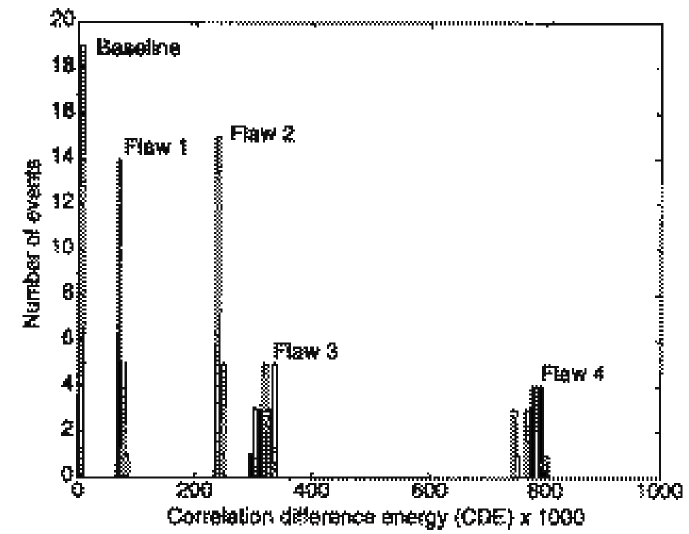
Two significant applications of Spread Spectrum Ultrasonics are:

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 such as temperature, load, vibration, or environmental coupling, it is necessary to filter out these effects to obtain the correct measurements of defects.

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

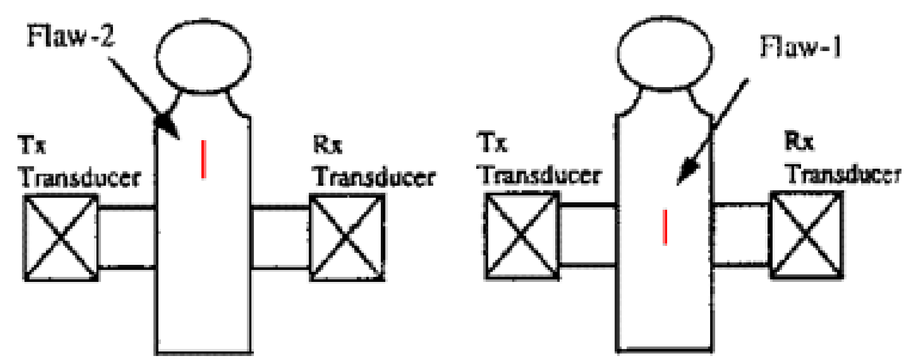
Trial	Setup	Contact Area
Baseline	No Flaw	--
Flaw 1	One block laying flat on girder	12.5 sq in
Flaw 2	One block standing on its long side	1.25 sq in
Flaw 3	Both blocks standing on their long sides	2.50 sq in
Flaw 4	Both blocks laying flat on girder	25.0 sq in



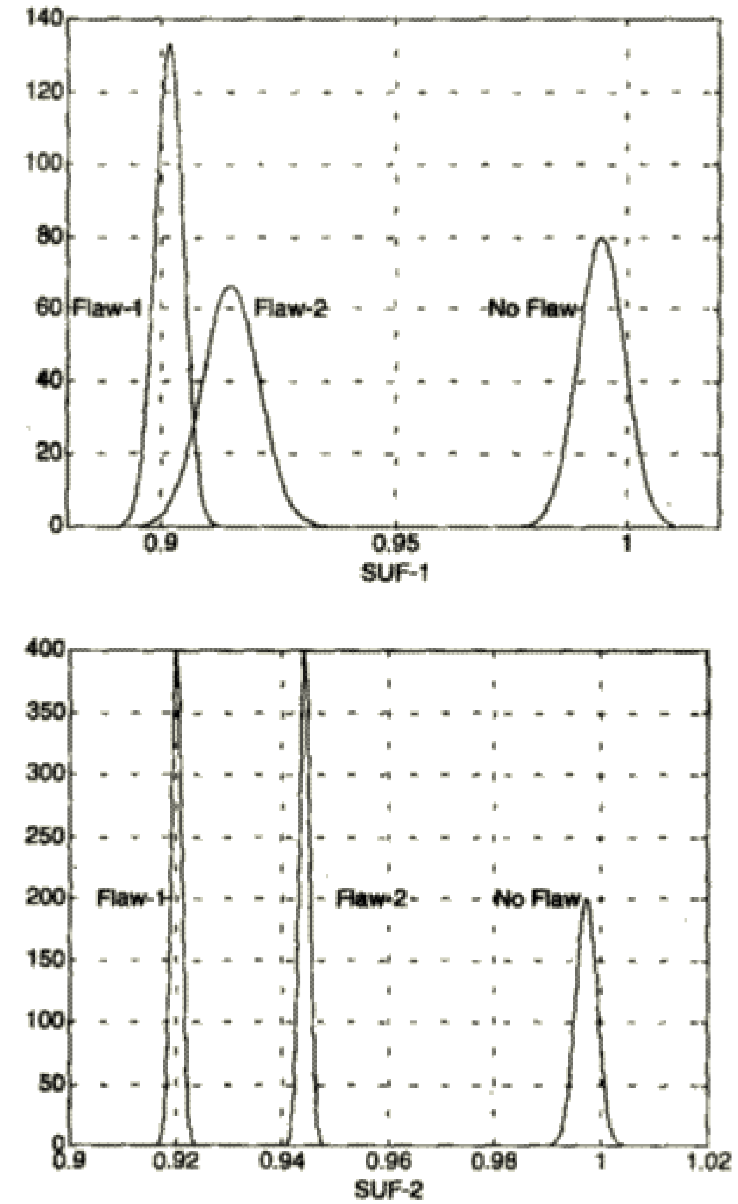


2. **Piece-part assembly line environments** where transducers and couplant may be precisely controlled, eliminating significant variations in transducer registration and couplant. Acoustic correlation signatures may be statistically compared to an ensemble of known "good" parts for sorting or accepting/rejecting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

Impurities in the incoming steel used to forge 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 technique are tested here, which are 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 economic unfeasible.

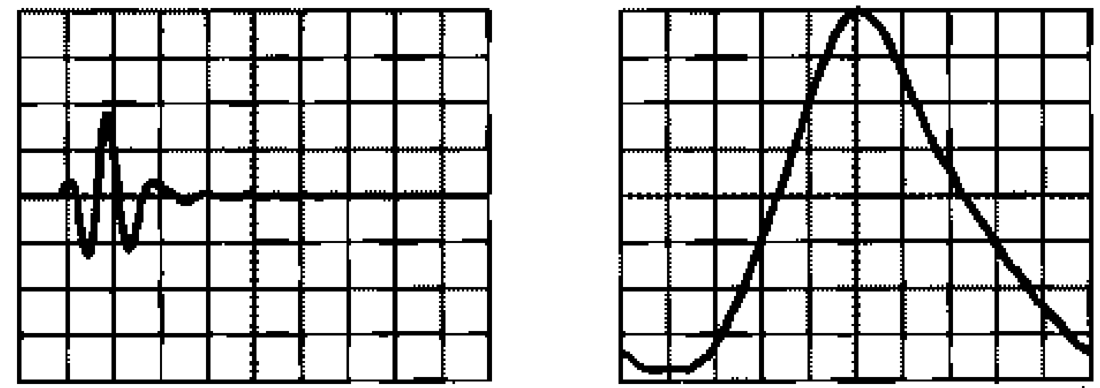


[Nondestructive Evaluation Techniques](#) > [Ultrasonic Testing](#) > [Signal Processing Techniques](#)

Signal Processing Techniques

Signal processing involves techniques that improve our understanding of information contained in received ultrasonic data. Normally, when a signal is measured with an oscilloscope, it is viewed in the time domain (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. Simple signal processing often involves the use of gates to isolate the signal of interest or frequency filters to smooth or reject unwanted frequencies.

When the frequency content of the signal is of interest, it makes sense to view the signal graph in the frequency domain. In the frequency domain, the vertical axis is still voltage but the horizontal axis is frequency.



Time Domain (left) and Frequency Domain Magnitude (right)

The frequency domain display shows how much of the signal's energy is present as a function of frequency. For a simple signal such as a sine wave, the frequency domain representation does not usually show us much additional information. However, with more complex signals, such as the response of a broad bandwidth transducer, the frequency domain gives a more useful view of the signal.

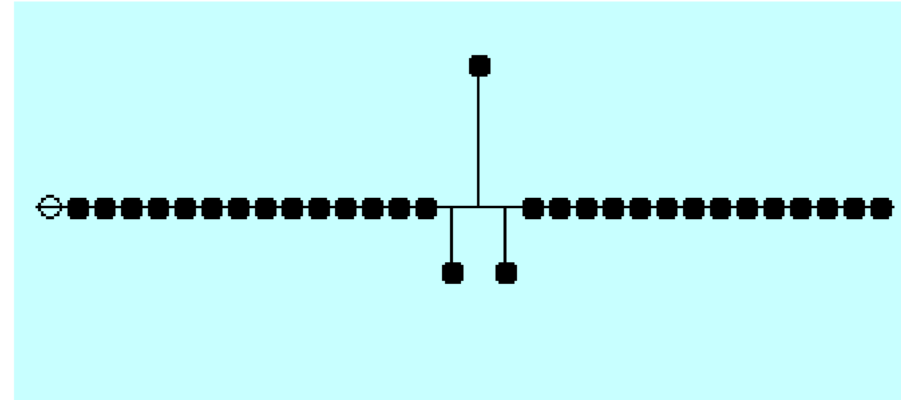
Fourier theory says that any complex periodic waveform can be decomposed into a set of sinusoids with different amplitudes, frequencies and phases. The process of doing this is called Fourier Analysis, and the result is a set of amplitudes, phases, and frequencies for each of the sinusoids that makes up the complex waveform. Adding these sinusoids together again will reproduce exactly the original waveform. A plot of the frequency or phase of a sinusoid against amplitude is called a spectrum.

The following Fourier Java applet, adapted with permission of Stanford University, allows the user to manipulate discrete time domain or frequency domain components and see the relationships between signals in time and frequency domains.

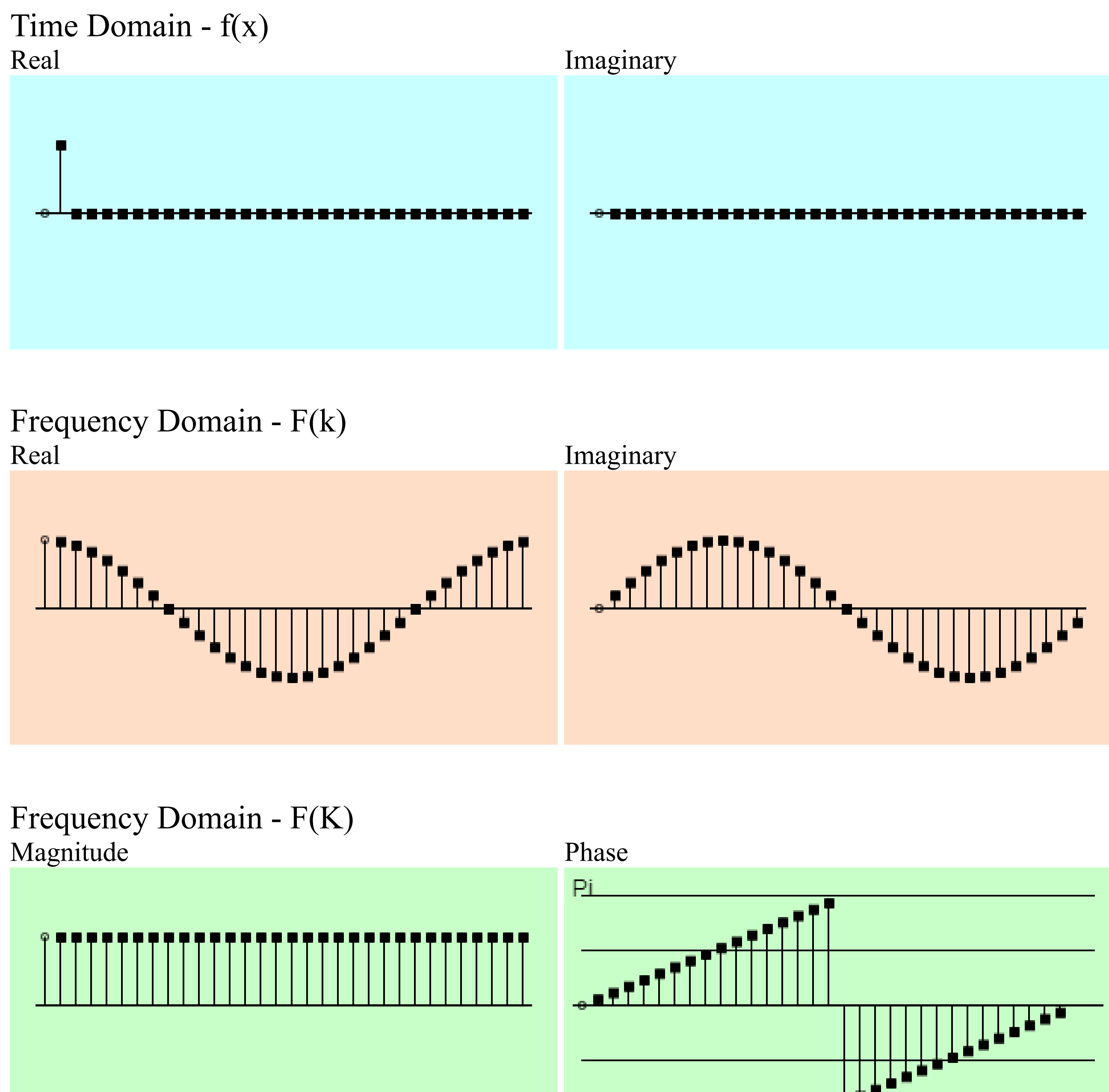
The top row (light blue color) represents the real and imaginary parts of the time domain. Normally the imaginary part of the time domain signal is identically zero.

The middle row (peach color) represents the the real and imaginary parts of the frequency domain.

The bottom row (light green color) represents the magnitude (amplitude) and phase of the frequency domain signal. Magnitude is the square root of the sum of the squares of the real and imaginary components. Phase is the angular relationship of the real and imaginary components. Ultrasonic transducer manufactures often provide plots of both time domain and frequency domain (magnitude) signals characteristic of each transducer. Use this applet to explore the relationship between time and frequency domains.



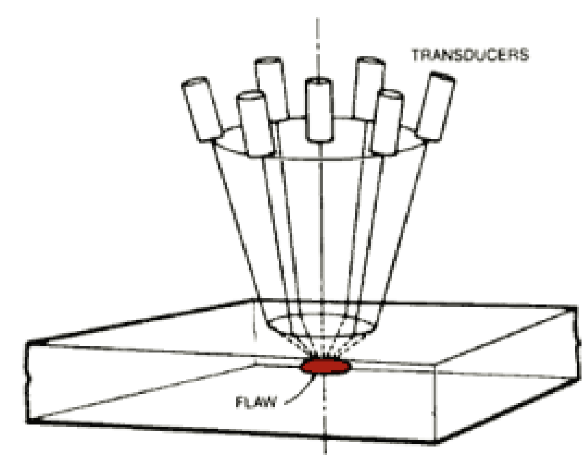
Exercise: Try replicating time domain signal in the upper left box in the app with a pattern similar to the image above. Note the resulting bandwidth in the frequency domain (magnitude) in the lower left box. Next try changing the magnitude, perhaps more of a "mountain" shape tapering to zero. Note that "narrowing" the magnitude, results in more cycles in the time domain signal.



Origin Centered Length: 32 Editing: Draw Zero All

Flaw Reconstruction Techniques

In nondestructive evaluation of structural material defects, the size, shape, and orientation are important flaw parameters in structural integrity assessment. To illustrate flaw reconstruction, a multiviewing ultrasonic transducer system is shown below. A single probe moved sequentially to achieve different perspectives would work equally as well. The apparatus and the signal-processing algorithms were specifically designed at the Center for Nondestructive Evaluation to make use of the theoretical developments in elastic wave scattering in the long and intermediate wavelength regime.

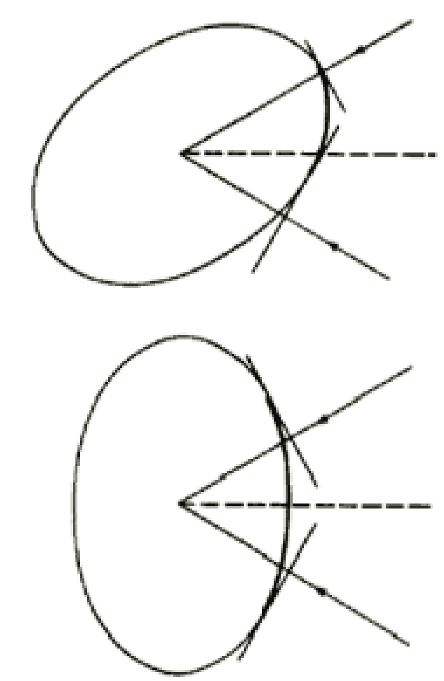


Depicted schematically at the right is the multiprobe system consisting of a sparse array of seven unfocused immersion transducers. This system can be used to "focus" onto a target flaw in a solid by refraction at the surface. The six perimeter transducers are equally spaced on a 5.08 cm diameter ring, surrounding a center transducer. Each of the six perimeter transducers may be independently moved along its axis to allow an equalization of the propagation time for any pitch-catch or pulse-echo combinations. The system currently uses 0.25 in diameter transducers with a nominal center frequency of 10 MHz and a bandwidth extending from approximately 2 to 16 MHz. The axis of the aperture cone of the transducer assembly normally remains vertical and perpendicular to the part surface.

The flaw reconstruction algorithm normally makes use of 13 or 19 backscatter waveforms acquired in a conical pattern within the aperture. The data-acquisition and signal-processing protocol has four basic steps.

1. Step one involves the experimental setup, the location and focusing on a target flaw, and acquisition (in a predetermined pattern) of pitch-catch and pulse-echo backscatter waveforms.
2. Step two employs a measurement model to correct the backscatter waveforms for effects of attenuation, diffraction, interface losses, and transducer characteristics, thus resulting in absolute scattering amplitudes.
3. Step three employs a one-dimensional **inverse Born approximation** to extract a tangent plane to centroid radius estimate for each of the scattering amplitudes.
4. In step four the radius estimates and their corresponding look angles are used in a regression analysis program to determine the six ellipsoidal parameters, three semiaxes, and three Euler angles, defining an ellipsoid which best fits the data.

The inverse Born approximation sizes the flaw by computing the characteristic function of the flaw (defined as unity inside the flaw and zero outside the flaw) as a Fourier transform of the ultrasonic scattering amplitude. The one-dimensional inverse Born algorithm treats scattering data in each interrogation direction independently and has been shown to yield the size of ellipsoidal flaws (both voids and inclusions) in terms of the distance from the center of the flaw to the wavefront that is tangent to the front surface of the flaw. Using the multiprobe ultrasonic system, the 1-D inverse Born technique is used to reconstruct voids and inclusions that can be reasonably approximated by an equivalent ellipsoid. So far, the investigation has been confined to convex flaws with a center of inversion symmetry. The angular scan method described in this paper is capable of locating the bisecting symmetry planes of a flaw. The utility of the multiprobe system is, therefore, expanded since two-dimensional elliptic reconstruction may now be made for the central slice. Additionally, the multiprobe system is well suited for the 3-D flaw reconstruction technique using 2-D slices.



The model-based reconstruction method has been previously applied to voids and incursion flaws in solids. Since the least-squares regression analysis leading to the "best fit" ellipsoid is based on the tangent plane to centroid distances for the interrogation directions confined within a finite aperture. The success of reconstruction depends on the extent of the flaw surface "illuminated" by the various viewing directions. The extent of coverage of the flaw surface by the tangent plane is a function of the aperture size, flaw shape, and the flaw orientation. For example, a prolate spheroidal flaw with a large aspect ratio oriented along the axis of the aperture cone will only have one tip illuminated (i.e., covered by the tangent planes) and afford a low reconstruction reliability. For the same reason, orientation of the flaw also has a strong effect on the reconstruction accuracy.

The diagram on the right shows the difference in surface coverage of a tilted flaw and an untilted flaw subjected to the same insonification aperture. Both the experimental and simulation studies of the aperture effect reported before were conducted for oblate and prolate spheroids oriented essentially symmetrically with respect to the part surface and hence the aperture cone. From a flaw reconstruction standpoint, an oblate spheroid with its axis of rotational symmetry perpendicular to the part surface represents a high leverage situation. Likewise, a prolate spheroid with its symmetry axis parallel to the part surface also affords an easier reconstruction than a tilted prolate spheroid. In this CNDE project, we studied effects of flaw orientation on the reconstruction and derived a new data-acquisition approach that will improve reliability of the new reconstruction of arbitrarily oriented flaws.

The orientation of a flaw affects reconstruction results in the following ways.

1. For a given finite aperture, a change in flaw orientation will change the insonified surface area and hence change the "leverage" for reconstruction.
2. The scattering signal amplitude and the signal/noise ratio for any given interrogation direction depends on the flaw orientation.
3. Interference effects, such as those due to tip diffraction phenomena or flash points may be present at certain orientations. Of course, interdependencies exist in these effects, but for the sake of convenience they are discussed separately in the following.

Aperture

To assess the effects of finite aperture size on flaws of different orientation, computer simulations were performed for an oblate spheroid with semi-axes of 400, 400, and 200 μm that is tilted and untilted with respect to the part surface. For each of the 13 scattering directions, the exact radius estimates Re (i.e. the tangent plane to centroid distances) were first computed, and a random error in sizing was then introduced to simulate the experimental situation. The radius estimate used was then taken to be

$$Re' = Re(I+n)$$

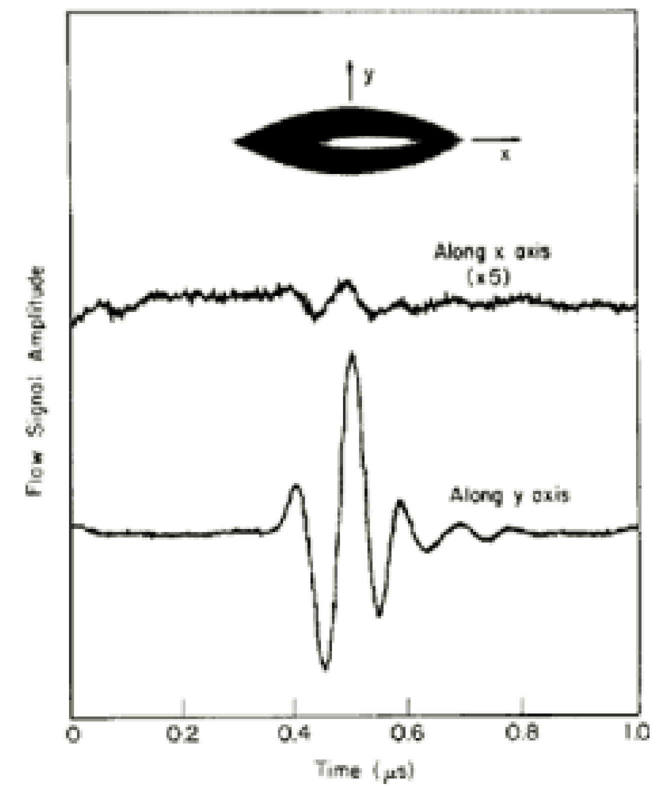
where **n** is a randomly generated number between ±0.1. Using the **Re'** values for the various directions, a best fit ellipsoid is determined using a regression program. This process is repeated 100 times for each aperture angle and mean standard deviation of the three semiaxes is expressed as a percentage of the expected values. The simulation was performed for the untilted case with the 400 x 400 μm plane parallel to the part surface and for a

2 : 1 Oblate Spheroid

Aperture Half-Angle (°)	Tilt = 0° (percent)	Tilt = 40° (percent)
20	11.6	39.0
30	6.9	18.2
40	4.5	10.9
50	4.3	7.6
60	4.1	5.8
70	4.1	4.6
80	4.1	4.0

The mean values for the ellipsoidal semi-axes converge to expected values, while the standard deviations converge to some asymptotic minimum. The values in Table I show that for a small aperture, the standard deviation as a percentage of expected value (an indication of the reconstruction error) is much higher for the oblate spheroid tilted at 40ƒ with respect to the horizontal than is the 0ƒ untilted case. As the aperture increases, the difference in reconstruction error approaches zero because surface illumination is sufficient to ensure a reliable reconstruction. Due to the combined effect of finite aperture and a prior unknown flaw orientation, a large aperture is desirable to increase reliability of reconstruction results.

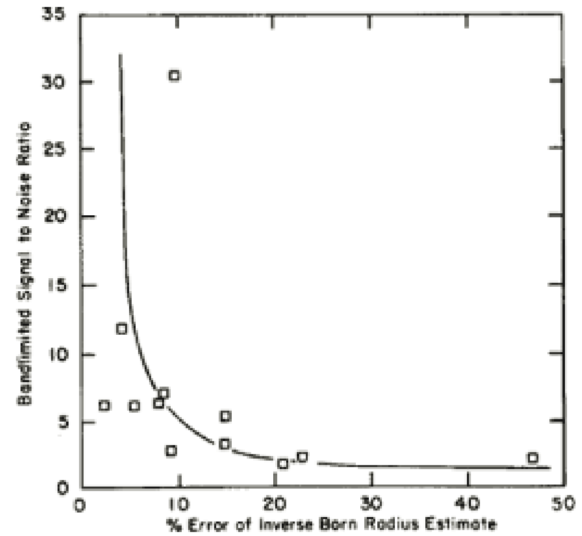
Note that in this simulation only the aperture angle is increased, and the number of interrogation directions remains unchanged. The number of look directions is kept the same because the multiviewing system is intended for acquiring a sparse array of data based on speed considerations.



Signal/Noise Ratio

For a given scattering direction amplitude of the scattering amplitude and, therefore, the signal/noise ratio depend on orientation of the flaw. In the short wavelength limit scattering amplitude is proportional to square root of (R1 R2) with R1 and R2 being the principal radii of curvature of the flaw for the scattering direction used. This dependence is found to be important in the intermediate frequency regime as well. To illustrate this effect, the figure at the right shows the scattered signal amplitudes from a football-shaped prolate spheroidal void with two cusp-like tips in two directions: broadside and along the tips. The profile of the tips can increase the ratio of the two signal amplitudes as large as 35.

To investigate the correlation between the accuracy of flaw sizing and signal/noise ratio of the flaw waveform at different scattering directions, a 400 x 400 x 200 µm oblate spheroidal void in titanium with its axis of rotational symmetry tilted at a 30ƒ angle from normal to the part surface was reconstructed using the multiviewing transducer system. It was found that sizing results were generally more accurate for the scattering directions with a higher signal/noise ratio, as expected. Furthermore, the directions that gave the poorest signal/noise ratios



were often ones closest to being in an edge-on perspective. The figure on the right shows the relationship between the percentage error of the radius estimate and signal/noise ratio of the flaw waveform. Reconstruction results of the oblate spheroid void tilted at 30ƒ are listed in Table II.

TABLE II
RECONSTRUCTION RESULTS FOR A 2 : 1 OBLATE SPHEROID IN TITANIUM WITH A 30° TILT USING AN APERTURE OF 52° HALF-ANGLE[a]

		Obtained from Full Set of 13 Backscatter Waveforms	Obtained from Best Nine Back-scatter Wave-forms Based on S/N Ratio	Expected Values
Ellipsoid semi-axis (μm)	A_x	456	400	400
	A_y	351	380	400
	A_z	177	184	200
Euler angles (°)	θ	−51	−36	30
	ϕ	79	73	−90
	ψ	9	28	0

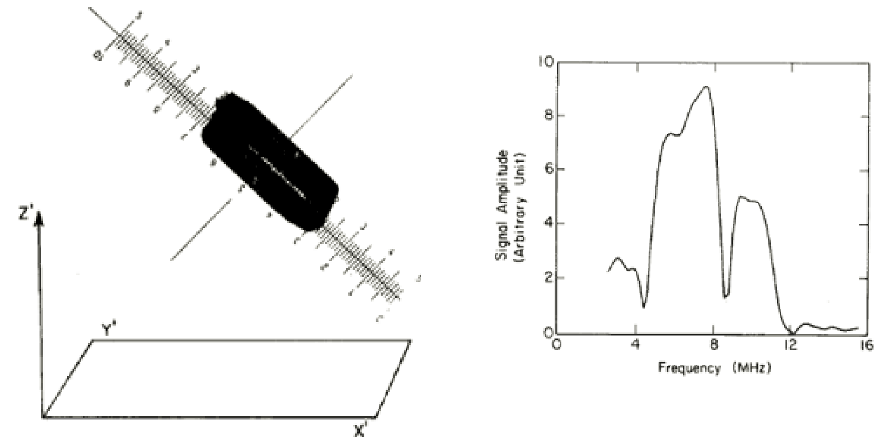
[a]When comparing the flaw orientation in terms of Euler angles, the entire set of angles should be used . The flaw orientations in the last two columns are, in fact, quite close to being equivalent.

The reconstruction results of both the semi-axes length and tilt angle were improved by rejecting four data points with the lowest signal/noise ratios. Since multiviewing transducer system provides a maximum of 19 independent look angles for a given tilt angle of the transducers, rejecting a small subset of the data points based on signal/noise consideration still leaves a sufficient number of data points for the ellipsoidal regression step which requires a minimum of six data points.

Flash Point Interference

The multiview transducer system and associated signal-processing algorithms reconstruct a flaw based on a general ellipsoid model. For ellipsoids with a large aspect ratio and flaw shapes that approach those of a flat crack or a long needle, edge or tip diffractions due to points of stationary phase (flash points) governed by, geometric acoustics become important. When such phenomena are present within the transducer bandwidth, the scattered signal frequency spectrum contains strong interference maxima and minima and renders radius estimates by the 1-D inverse Born difficult or impossible.

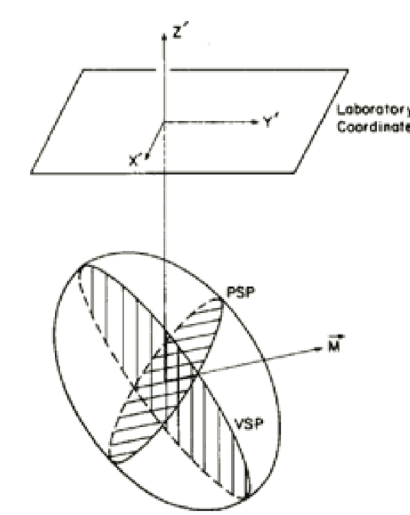
The figures below show a test flaw in the form of a copper wire segment embedded in a transparent thermoplastic disk and tilted at 45ƒ with respect to the disk surface and the frequency spectrum of the wire inclusion at a scattering angle of 21ƒ from the wire axis. The strong interference pattern prevented the I-D inverse Born algorithm from yielding a meaningful radius estimate. However, when the spectrum was analyzed on assumption of flash point interference (without having to use the angle information), 321 μm was obtained for a path length difference of the stationary phase points in the scattering direction; this compared reasonably well with 374 μm for twice the tangent plane distance in this orientation.



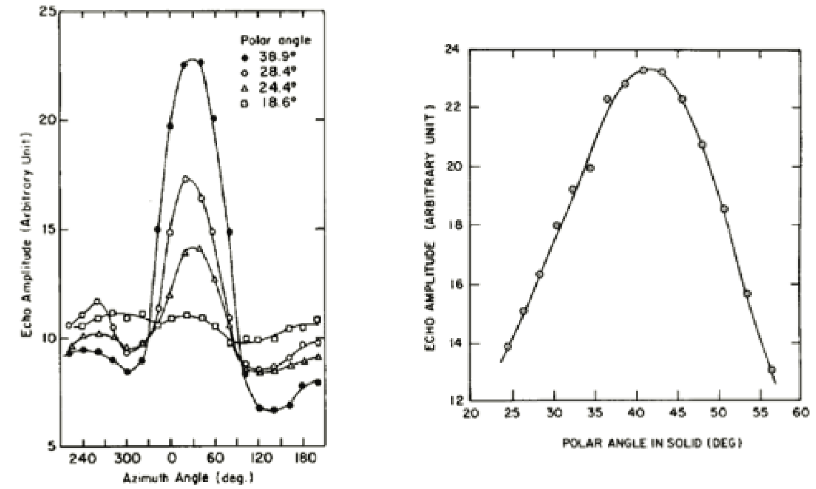
In the photomicrograph of copper wire segment titled at 45ƒ and embedded in thermoplastic. Each minor division of scale is 10 μm, and wire segment is approximately prolate spheroid with semi-axes Ax = 80 μm, Ay = 80 μm, and Az = 200 μm.

Spatial Data-acquisition Pattern For Arbitrarily Oriented Flaw

From the investigation described earlier, it is clear that reliable reconstruction of an arbitrarily oriented flaw generally requires a large aperture. However, a large viewing aperture perpendicular to the part surface may still contain scattering directions hampered by weak flaw signal amplitude (poor signal-to-noise ratio) and, in certain cases, flash point interference. A predetermined data-acquisition pattern that is relatively free from such disadvantages can improve reconstruction reliability. In this work we explored a method to predetermine a spatial pattern for data acquisition. This pattern affords a high leverage for reliable reconstruction for arbitrarily oriented flaws that can be approximated by the shape of a spheroid.



Consider a tilted prolate spheroid as shown on the right. We may define a vertical sagittal plane (VSP) as the plane that bisects the flaw and contains the z axis. We further define a perpendicular sagittal plane (PSP) as the plane bisecting the spheroid and perpendicular to the VSP. The intersection of the VSP and PSP (direction M in diagram) then corresponds to a direction of maximum flaw signal amplitude. The orientation of the VSP can be located by a series of azimuthal scans at different polar angles. A maximum in the signal amplitude should be observed at the azimuthal angle of the VSP. This definition of the VSP and PSP and their relationship to backscattered flaw signal amplitude also holds true for an oblate spheroid. Below shows the azimuthal scans at four different polar angles for the 2.5:1 prolate spheroid (wire segment) flaw. Once the azimuthal angle of the VSP is determined (30ƒ in this case), a polar scan below at the azimuthal angle of the VSP determines the tilt angle of the wire segment to be 41ƒ, as compared to 45ƒ from optical measurement.



Flaw signal amplitude as a function of azimuthal and polar angles.

The angular scans serve two very useful functions. First, they provide some information about the shape and orientation of the flaw. For example, a scan in the perpendicular sagittal plane can distinguish a prolate spheroid from an oblate spheroid by changing the polar angle and the azimuthal angle simultaneously. A scan in the PSP of the 2:1 oblate spheroid tilted at 30ƒ showed a peak in flaw signal amplitude at the intersection of the VSP and the PSP (direction M), whereas a scan in the PSP of the tilted 2.5:1 prolate spheroid showed a constant flaw signal amplitude.

Second, it provides a basis for predetermining a spatial data-acquisition pattern that is equivalent to a tilted aperture cone centered at direction M. This data-acquisition pattern not only ensures good signal-to-noise ratio, avoids possible flash point interference due to end-on or edge-on perspectives, and provides a maximum illuminated area on the flaw surface, but also allows one to reconstruct the flaw with two mutually orthogonal elliptical cross sections in the VSP and PSP.

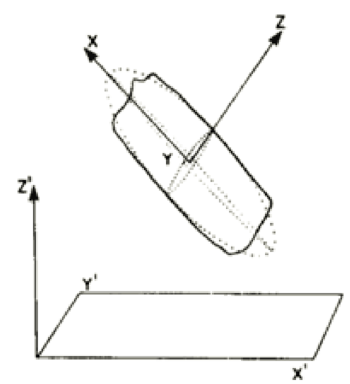
So far, the discussion of angular scans has been confined to flaws that are approximately spheroidal in shape. For a general ellipsoid with three unequal semi-axes and oriented arbitrarily in space, the angular scan results will be more complicated. For example, an azimuthal scan at different polar angles is not expected to show a peak at the same azimuthal angle. Shape and orientation information, in principle, can still be extracted from such data, and further investigations are underway for the general case.

Reconstruction Results

To verify the reconstruction method using the new spatial data-acquisition configuration experimentally, reconstructions were performed on two test specimens. The first flaw was the 400 μm long 80 μm radius copper wire segment embedded in a thermoplastic disk. This flaw was used to approximate a prolate spheroid with a 2.5:1 aspect ratio. The axis of the wire segment was at a 45ƒ angle relative to the part surface. The second flaw was a 400 x 200 µm oblate spheroidal void tilted at a 30ƒ angle in a diffusion bonded titanium disk, as just described.

The flaw reconstruction procedure using an aperture cone perpendicular to the part surface was first carried out for the 2.5:1 prolate inclusion (copper wire) tilted at a 45ƒ angle. Difficulties due to a poor signal-to-noise ratio and flash point interference associated with look directions close to the end-on perspective prevented a successful reconstruction; in fact, enough inconsistencies occurred in the tangent plane distance estimates that the regression step failed to converge.

Based on orientations of the sagittal planes determined in the angular scans, the new data-acquisition pattern equivalent to tilting the aperture axis to the direction of maximum signal strength was used. The ellipsoidal reconstruction gave a tilt angle of 42ƒ and three semiaxes of 257, 87, and 81 µm. These results compared very favorably with the actual tilt angle of 45ƒ and the actual semi-axes of 200, 80, and 80 µm.



The new data-acquisition pattern also allows one to reconstruct an arbitrarily tilted spheroidal flaw with the two mutually orthogonal elliptical cross-sectional cuts in the VSP and PSP. This was done for the copper wire inclusion. After identifying the vertical sagittal plane and the perpendicular sagittal plane, a series of tangent plane distance estimates were made for scattering directions confined in these two planes. Using these results, the two mutually orthogonal elliptical cross sections in the VSP and PSP were reconstructed using a similar regression program in 2-D. The two reconstructed ellipses were 266 x 83 µm and 80 x 75 µm, respectively, and the tilt angle was found to be 51ƒ. Table III shows the results of the 3-D reconstruction using 19 look perspectives and the 2-D reconstruction of the ellipses in the VSP and PSP. Both reconstructions compared very favorably with the expected values. The greatest discrepancy is in the value of the semi-axis Ax; this is to be expected because the wire segment is approximately a prolate spheroid with two ends truncated.

TABLE III
COPPER WIRE INCLUSION AS PROLATE SPHEROID

		3-D Reconstruction	2-D Reconstruction	Expected Values
Ellipsoid semi-axis (µm)	A_x	257	266	200
	A_y	87	80, 83	80
	A_z	81	75	80
Euler angles (°)	θ	42	51	45
	ϕ	103	—	—
	ψ	74	—	—

The 2:1 oblate spheroidal void tilted at a 30ƒ angle in a titanium disk was investigated, again, following the procedure of predetermining a favorable data-acquisition pattern based on angular scan results. Table IV shows the reconstruction results using the new data-acquisition pattern equivalent to an aperture cone centered on the direction of maximum backscatter signal. As a comparison, reconstruction results using an aperture cone normal to the part surface (described earlier) are also shown. As can be seen, the improvement of the reconstruction by using the new data-acquisition pattern is not as dramatic as the prolate inclusion case. This is consistent with the

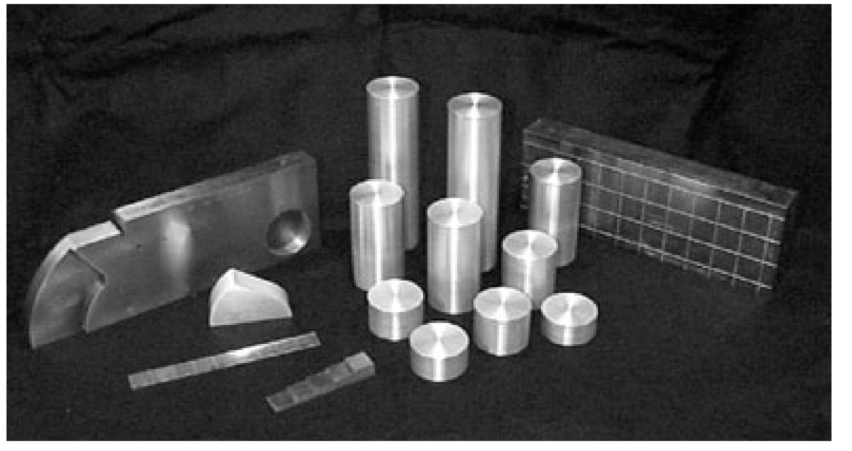
fact that the oblate spheroid has a smaller aspect ratio and a smaller tilt angle and is therefore not nearly a "low leverage" flaw to reconstruct using the normal (untilted) data-acquisition pattern.

TABLE IV
RECONSTRUCTION RESULTS FOR A 2 : 1 OBLATE SPHEROID IN TITANIUM WITH A 30° TILT USING AN APERTURE OF 52°

		Aperture Cone Normal to Part Surface (Based on Nine Look Directions)	Aperture Cone in the Direction of Maximum Backscatter Signal	Expected Values
Ellipsoid semi-axis (μm)	A_x	400	394	400
	A_y	380	419	400
	A_z	184	191	200
Euler angles (°)	θ	−36	31	30
	ϕ	73	−89	−90
	ψ	28	3	0

The reliability problem of reconstructing arbitrarily oriented flaws using the multiviewing transducer system and associated model-based algorithm has been studied. An arbitrarily oriented flaw may afford a low leverage for reconstructing the entire flaw based on limited surface area covered by the tangent planes in a finite aperture and, therefore, requires a greater aperture for a reliable reconstruction. However, the aperture size has practical limits in a single-side access inspection situation and a larger aperture does not necessarily alleviate such difficulties as poor signal-to-noise ratio and flash point interference associated with certain interrogation directions. In our study of reconstructing approximately spheroidal flaws oriented at some arbitrary angle, it was found beneficial to predetermine a spatial data-acquisition pattern based on angular dependence of the flaw signal amplitude. The new data-acquisition pattern is equivalent to tilting the interrogation aperture cone to compensate for the particular orientation of the flaw and restore the leverage for a more reliable reconstruction. This method worked well on two test cases.

Calibration Methods



Calibration refers to the act of evaluating and adjusting the precision and accuracy of measurement equipment. In ultrasonic testing, several forms of calibration must occur. First, the electronics of the equipment must be calibrated to ensure that they are performing as designed. This operation is usually performed by the equipment manufacturer and will not be discussed further in this material. It is also usually necessary for the operator to perform a "user calibration" of the equipment. This user calibration is necessary because most ultrasonic equipment can be reconfigured for use in a large variety of applications. The user must "calibrate" the system, which includes the equipment settings, the transducer, and the test setup, to validate that the desired level of precision and accuracy are achieved. 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.

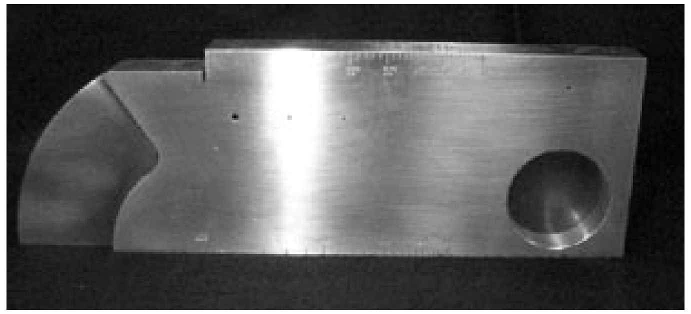
In ultrasonic testing, there is also a need for reference standards. Reference standards are used to establish a general level of consistency in measurements and to help interpret and quantify the information contained in the received signal. Reference standards are used to validate that the equipment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

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. Be aware that there 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. Computer programs that allow the inspector to create computer simulated models of the part and flaw may one day lessen this limitation.

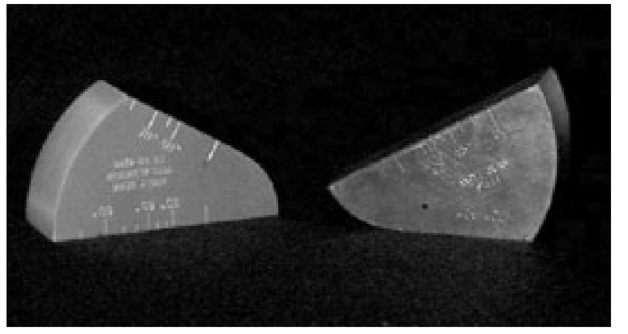
The IIW Type Calibration Block



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 (to be precise, killed, open hearth or electric furnace, low-carbon steel in the normalized condition with a grain size of McQuaid-Ehn #8) 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 below in the figure on the left. The IIW type US-2 block was developed for US Air Force application and is shown below in the center. A Mini version also exists.

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 setups. 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

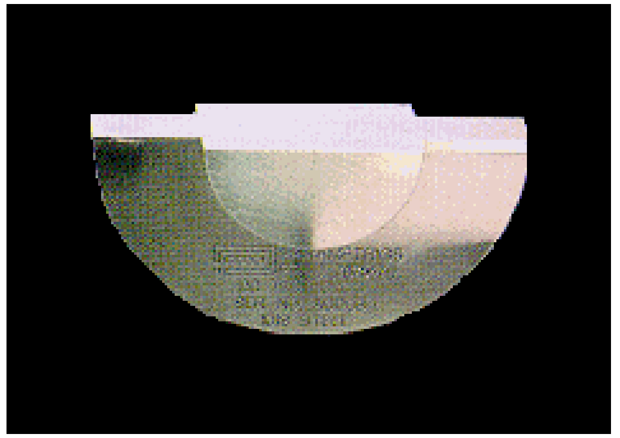


The miniature angle-beam is a calibration block that was designed for the US Air Force for use in the field for instrument calibration. The block is much smaller and lighter than the IIW block but performs many of the same functions. The miniature angle-beam block can be used to check the beam angle 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 setups.

AWS Shear Wave Distance/Sensitivity Calibration (DSC) Block

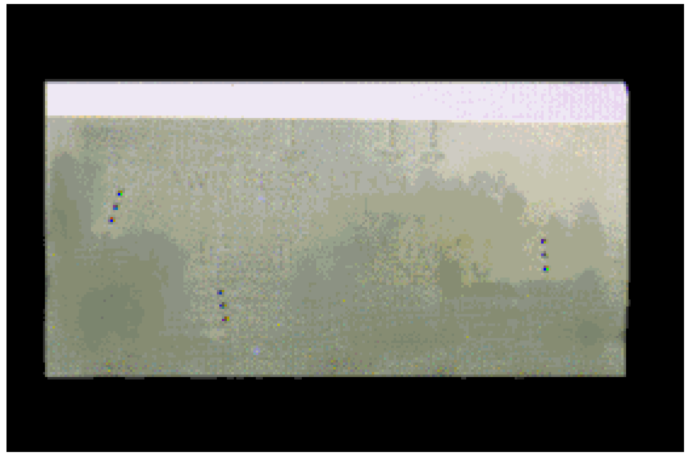
A block that closely resembles the miniature angle-beam block and is used in a similar way is the DSC AWS Block. This block is used to determine the beam exit point and refracted angle of angle-beam transducers and to calibrate distance and set the sensitivity for both normal and angle beam inspection setups. 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



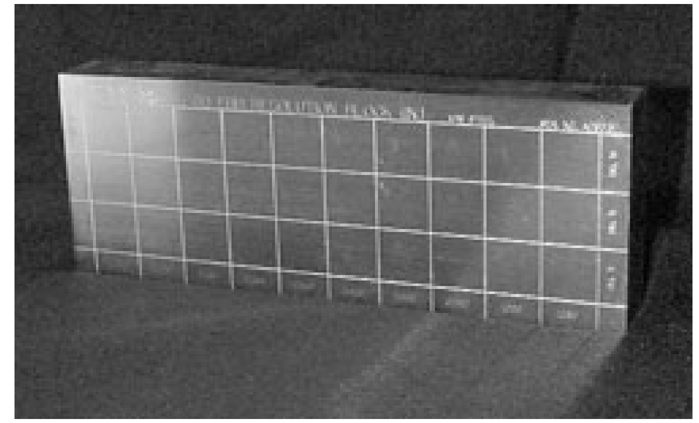
The DC AWS Block is a metal path distance and beam exit point calibration standard that conforms to the requirements of the American Welding Society (AWS) and the American Association of State Highway and Transportation Officials (AASHTO). Instructions on using the DC block can be found in the annex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

AWS Resolution Calibration (RC) Block



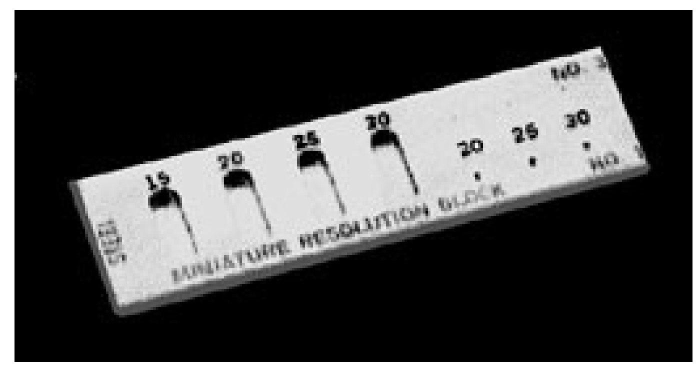
The RC Block is used to determine the resolution of angle beam transducers per the requirements of AWS and AASHTO. Engraved Index markers are provided for 45, 60, and 70 degree refracted angle beams.

30 FBH Resolution Reference Block

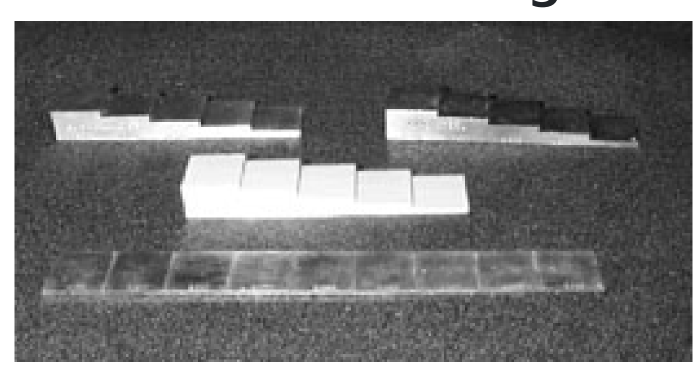


The 30 FBH resolution reference block is used to evaluate the near-surface resolution and flaw size/depth sensitivity of a normal-beam setup. The block contains number 3 (3/64"), 5 (5/64"), and 8 (8/64") ASTM flat bottom holes at ten metal-distances ranging from 0.050 inch (1.27 mm) to 1.250 inch (31.75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

Miniature Resolution Block

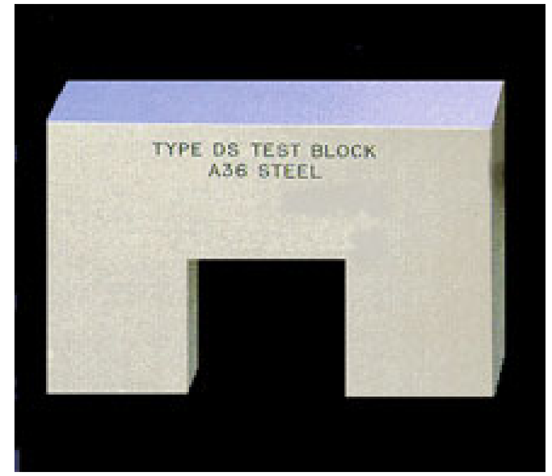


Step and Tapered Calibration Wedges



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 used to check the horizontal linearity and the dB accuracy per requirements of AWS and AASHTO.

Distance/Area-Amplitude Blocks


Distance/area amplitude correction blocks typically are purchased as a ten-block set, as shown above. Aluminum sets are manufactured per the requirements of ASTM E127 and steel sets per ASTM E428. Sets can also be purchased in titanium. 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.

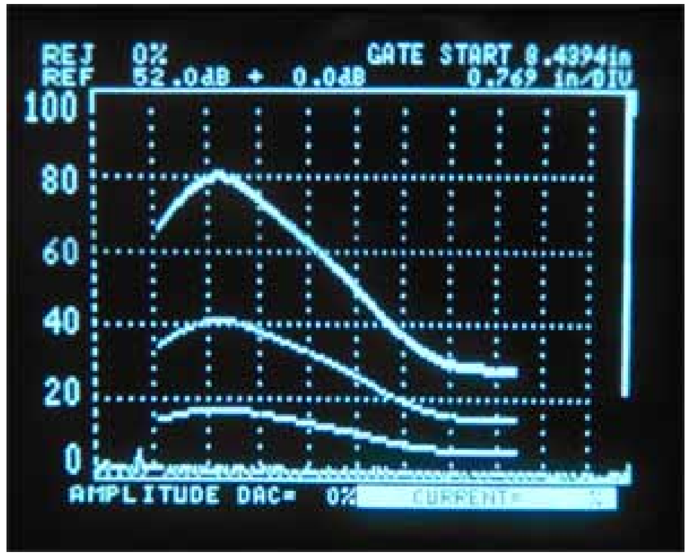
Area-Amplitude Blocks

Area-amplitude blocks are also usually purchased in an eight-block set and look very similar to Distance/Area-Amplitude Blocks. However, area-amplitude blocks have a constant 3-inch metal path distance and the hole sizes are 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 very similar to the distance/area-amplitude blocks pictured above. Nineteen 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.

Distance Amplitude Correction (DAC)



Acoustic signals from the same reflecting surface will have different amplitudes at different distances from the transducer. Distance amplitude correction (DAC) provides a means of establishing a graphic 'reference level sensitivity' as a function of sweep distance on the A-scan display. The use of DAC allows signals reflected from similar discontinuities to be evaluated where signal attenuation as a function of depth has been correlated. Most often DAC will allow for loss in amplitude over material depth (time), graphically on the A-scan display but can also be done electronically by certain instruments. Because near field length and beam spread vary according to transducer size and frequency, and materials vary in attenuation and velocity, a DAC curve must be established for each different situation. DAC may be employed in both longitudinal and shear modes of operation as well as either contact or immersion inspection techniques.

A distance amplitude correction curve is constructed from the peak amplitude responses from reflectors of equal area at different distances in the same material. A-scan echoes are displayed at their non-electronically compensated height and the peak amplitude of each signal is marked on the flaw detector screen or, preferably, on a transparent plastic sheet attached to the screen. Reference standards which incorporate side drilled holes (SDH), flat bottom holes (FBH), or notches whereby the reflectors are located at varying depths are commonly used. It is important to recognize that regardless of the type of reflector used, the size and shape of the reflector must be constant. Commercially available reference standards for constructing DAC include ASTM Distance/Area Amplitude and ASTM E1158 Distance Amplitude blocks, NAVSHIPS Test block, and ASME Basic Calibration Blocks.

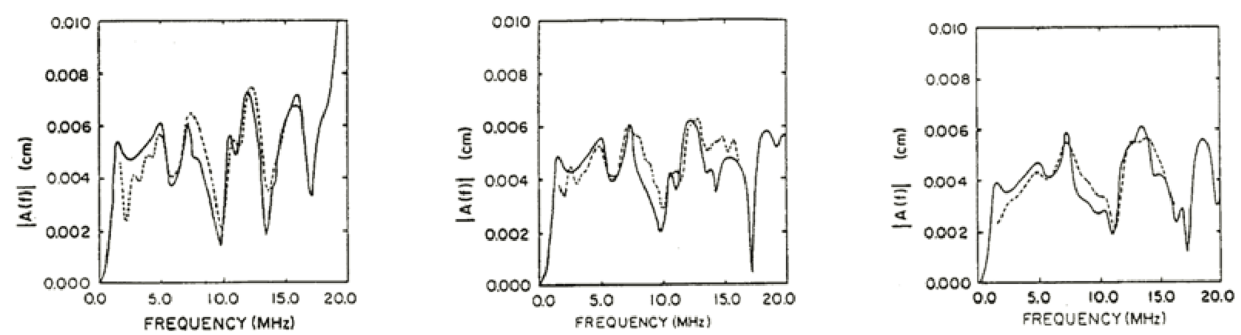
The following applet shows a test block with a side drilled hole. The transducer was chosen so that the signal in the shortest pulse-echo path is in the far-field. The transducer may be moved finding signals at depth ratios of 1, 3, 5, and 7. Red points are "drawn" at the peaks of the signals and are used to form the distance amplitude correction curve drawn in blue. Start by pressing the green "Test now!" button. After determining the amplitudes for various path lengths (4), press "Draw DAC" and then press the green "Test now!" button.

Thompson-Gray Measurement Model

The Thompson-Gray Measurement Model allows the approximate prediction of ultrasonic scattering measurements made through liquid-solid interfaces. Liquid-solid interfaces are common in physical inspection scenarios. The model allows us to make predictions about received ultrasonic signals scattered from various classes of defects. The model predicts an absolute scattering amplitude in the sense that amplitudes are correct and transducer and system characteristics are removed by deconvolution techniques.

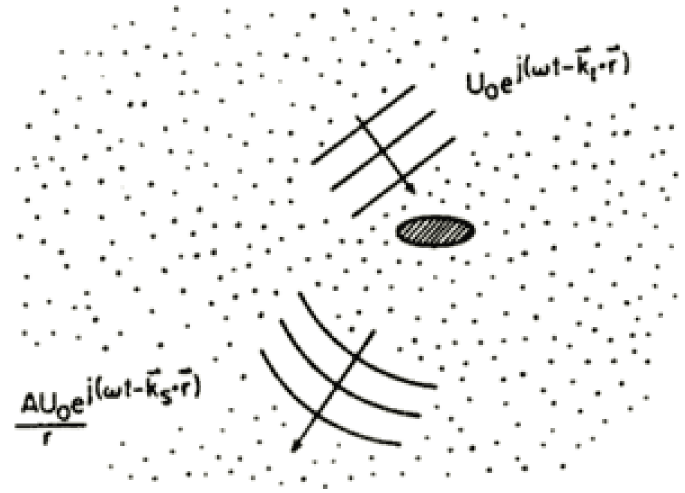
Work begun in the early 1980's continues to be refined and has resulted into an increasingly valuable working tool for comparison of ultrasonic theory and experiment. The Thompson-Gray Measurement Model is at the heart of UTSIM (see section 5.4 Ultrasonic Simulation - UTSIM).

The validity of any model rests on how well its predictions agree with experiment. Shown below are three examples taken from the *J. Acoust. Soc. Am.*, 74(4) October 1983 entitled, "A model relating ultrasonic scattering measurements through liquid-solid interfaces to unbounded medium scattering amplitudes."



Comparison of theory and experimental magnitude of longitudinal pitch-catch scattering amplitude for a 114 µm radius tin-lead solder sphere in a Lucite cylindrical disk. Illumination was at normal incidence and reception at an 8° angle (15° in the solid) (left), 15.7° angle (30° in the solid) (center), and a 22.5° angle (45° in the solid) (right).

The relationship between scattering data (obtained from ultrasonic experiments in which the waves are excited and detected in a finite measurement geometry) and unbounded medium, farfield scattering amplitudes, forms the basis of an ultrasonic measurement model.



The associated amplitudes are:

$$U_{0}e^{i(\omega t- \vec{k}_{s}\cdot \vec{r})}$$

for the incoming sound waves and

$$\frac{AU_{0}e^{i(\omega t- \vec{k}_{s}\cdot \vec{r})}}{r}$$

for the scattered wave.

scatterer is located in an elastic solid which, along with the ultrasonic transducer, is immersed in a fluid medium.

The scattering of elastic waves by a flaw in, an unbounded solid, e.g., a crack, void, or inclusion, is often characterized by a scattering amplitude **A** which defines the spherically spreading wave scattered into the farfield when the flaw is "illuminated" by a unit amplitude plane wave, as schematically illustrated in the above diagram. However, measurements of scattering are always made with transducers of finite aperture, at finite distances from the scatterer. Furthermore, the transducer is often immersed in a fluid medium and the wave has passed through the liquid-solid interface twice during the measurement.

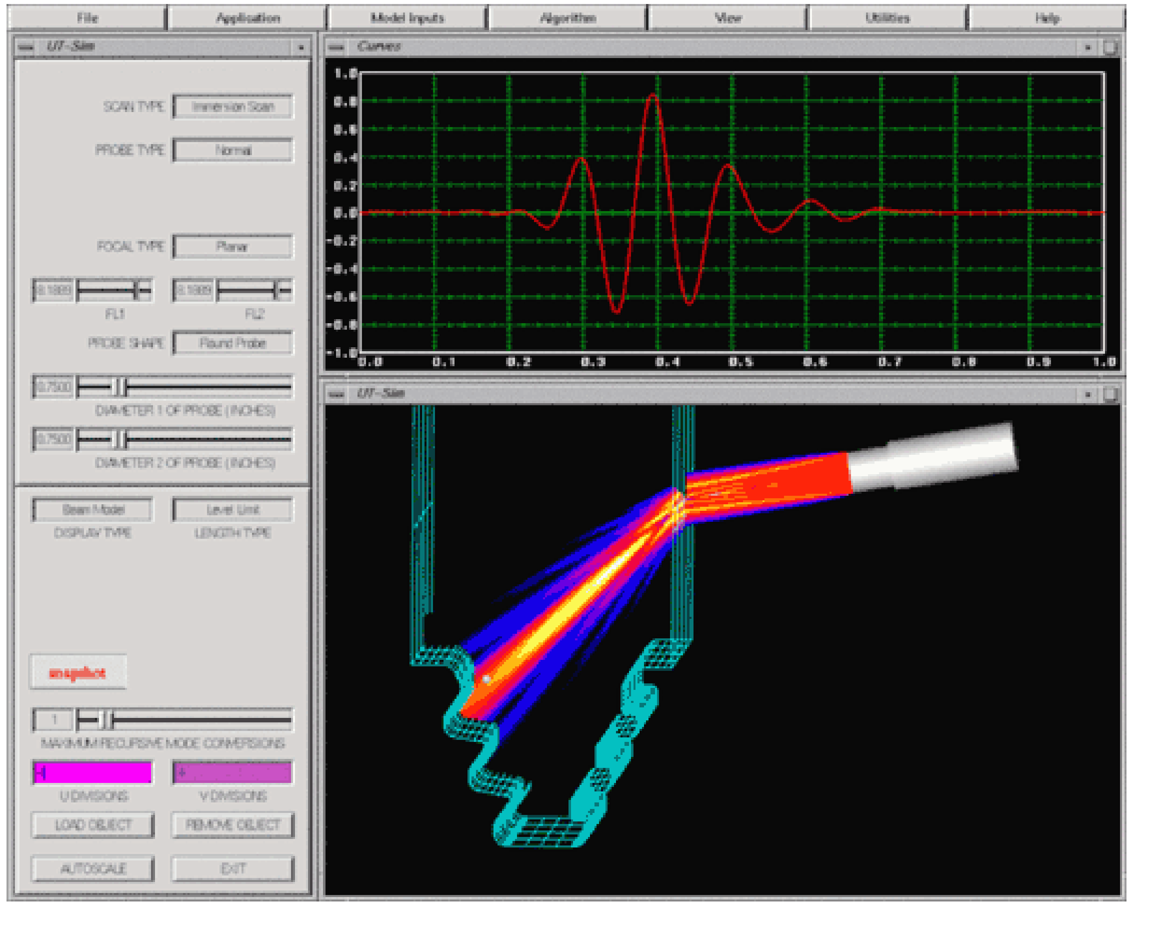
In principle, complete theoretical scattering solutions can be developed for this more complex scattering situation. However, even the introduction of the liquid-solid interface significantly complicates the elastic wave scattering and further introduction of finite beam effects in an exact manner would generally lead to computational complexity, which would severely restrict the use of the results in the routine interpretation of experiments.

An alternative point of view would be to view the unbounded medium scattering amplitude **A** as a canonical solution and to develop approximate expressions, which relate this to the solutions for the more complex measurement geometries. This point of view is routinely adopted in studies of the acoustic scattering (e.g. sonar) from various obstacles. In this case, the problem is greatly simplified by the fact that: (a) the fluid medium only supports a single wave type, (b) the waves do not pass through a refracting and mode converting interface, and (c) calibration experiments can be performed with arbitrary relative positions of transducers and reflecting surfaces to eliminate diffraction effects.

Nondestructive Evaluation Techniques > Ultrasonic Testing > Ultrasonic Simulation - UTSIM

Ultrasonic Simulation - UTSIM

UTSIM is a user interface integrating a CAD model representing a part under inspection and an ultrasound beam model. The beam model can accurately predict fields for focused or planar beams, through curved or flat interfaces in a 3D space. Isotropic materials are required for the current implementation. Within UTSIM, the geometrical boundary conditions are automatically set up when the user points the virtual probe at the 3D solid model. It is fast enough to generate waveforms from flaws in real time.



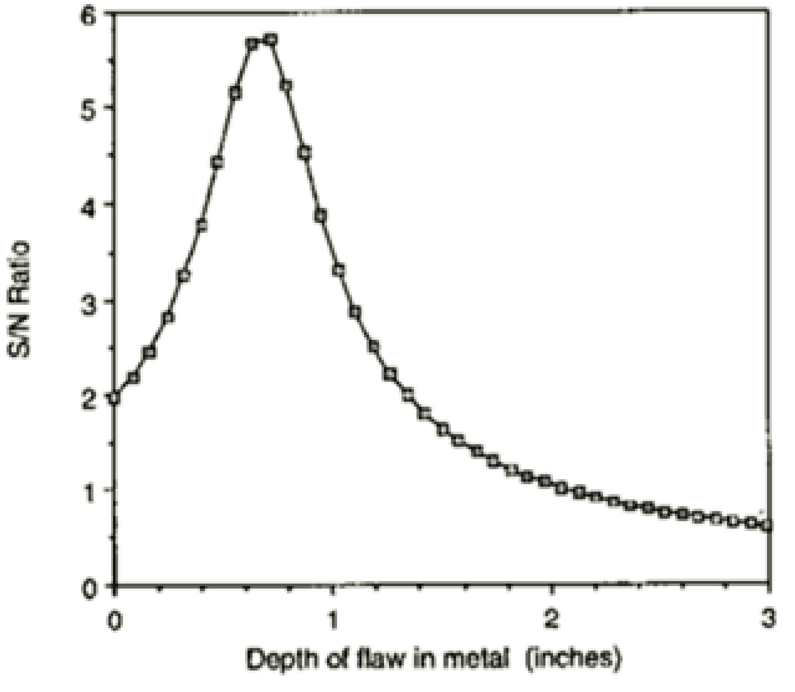
Nondestructive Evaluation Techniques > Ultrasonic Testing > Grain Noise Modeling

Grain Noise Modeling

Signal-to-Noise: The ratio of signal intensity to noise intensity.

In recent years, a number of theoretical models have been developed at Iowa State University to predict the electrical voltage signals seen during ultrasonic inspections of metal components. For example, the Thompson-Gray measurement model can predict the absolute voltage of the echo from a small defect, given information about the host metal (information such as density, sound speeds, surface curvature, etc.), the defect (size, shape, location, etc.), and the inspection system (water path, transducer characteristics, reference echo from a calibration block, etc.). If an additional metal property which characterizes the inherent noisiness of the metal microstructure is known, the independent scatterer model can be used to predict the absolute root-mean-squared (rms) level of the ultrasonic grain noise seen during an inspection. By combining the two models, **signal-to-noise** (S/N) ratios can be calculated.

Accurate model calculations often require intensive computer calculations. However, by making a number of approximations in the formalism, it is possible to obtain rapid first-order estimates of noise levels and S/N ratios. These calculations are for normal-incidence pulse-echo inspections through flat or curved surfaces, and the flaw may be a flat crack or a spherical inclusion. The figure below shows the results of one of the calculations.



Nondestructive Evaluation Techniques > Ultrasonic Testing > References and Standards

References and 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, in order 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***. ***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.

Nondestructive Evaluation Techniques > Ultrasonic Testing > Ultrasonic Inspection Formulas

Ultrasonic Inspection Formulas

- Wave Velocity
  - Longitudinal Wave Velocity
  - Shear Wave Velocity
- Wavelength
- Refraction (Snell's Law)
- Acoustic Impedance
- Reflection Coefficient

Wave Velocity

Longitudinal Wave Velocity:

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

Where:

V_L = Longitudinal Wave Velocity

E = Modulus of Elasticity

ρ = Density

ν = Poisson's Ratio

Shear Wave Velocity:

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

or

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

Where:

V_S= Shear Wave Velocity

E = Modulus of Elasticity

ρ = Density

ν = Poisson's Ratio

G = Shear Modulus

Wavelength

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

Where:

λ = Wavelength

V = Velocity

f = Frequency

Refraction (Snell's Law)

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{V_1}{V_2}$$

Where:

θ_1 = Angle of the Incident Wave

θ_2 = Angle of the Reflected Wave

V_1 = Velocity of Incident Wave

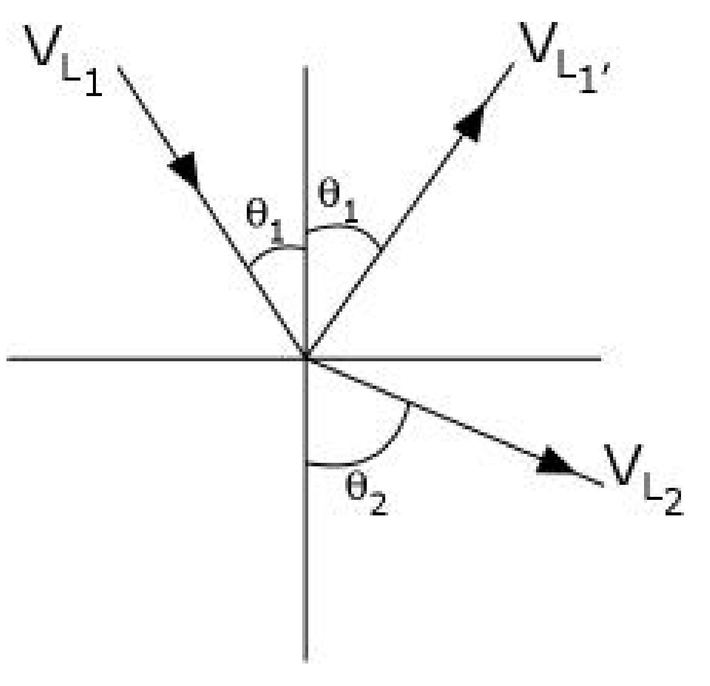
V_2 = Velocity of Reflected Wave

Snell's Law is used regularly when performing angle beam inspections. Snell's Law describes the relationship between the incident and refracted angles of a wave as it moves from one material into another material which has a different wave velocity. Refraction takes place at the interface due to the different velocities of the acoustic waves within the two materials. Snell's Law equates the ratio of material velocities V_1 and V_2 to the ratio of the sine's of incident (θ_1) and refracted (θ_2) angles. Snell's Law is usually presented in the form of one of the following equations.

$$\frac{\sin \theta_1}{V_1} = \frac{\sin \theta_2}{V_2}$$

or

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{V_1}{V_2}$$



The first equation states that the ratio of the sine of the incident angle and the wave velocity in material 1 is equal to the ratio of the sine of the refracted angle and the wave velocity in material 2. The second equation states that the ratios of the sine's of the two angles is equal to the ratio of the two velocities. It should be evident that the two equations are equivalent.

Example Calculations

Example 1

What is the incident angle that will produce a 70 degree refracted shear wave in steel using a Lucite wedge. First establish the values.

- θ_1 = the value to be determined
- θ_2 = 70°
- V_1 = 0.106 in/µs (sound velocity of a longitudinal wave in Lucite)
- V_2 = 0.128 in/µs (sound velocity of a shear wave in steel)

Plug the known values into the equation.

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{V_1}{V_2}$$

becomes

$$\frac{\sin\theta_1}{\sin(70)} = \frac{0.106\ \text{in}/\mu\text{s}}{0.128\ \text{in}/\mu\text{s}}$$

Simplify by dividing the right side of the equation and determine the sine of 70 with a calculator.

$$\frac{\sin\theta_1}{0.940} = 0.828$$

Multiply both sides of the equation by 0.940 to solve for $\sin\theta_1$.

$$\cancel{0.940} \times \frac{\sin\theta_1}{\cancel{0.940}} = 0.828 \times 0.940$$

$$\sin\theta_1 = 0.778$$

Finally, take the inverse sine of 0.778 to determine the angle whose sine equal 0.778.

$$\boxed{\theta_1 = 51.1^o}$$

Example 2

If the incident angle is 24 degrees when setting up an immersion inspection, what is the refracted shear wave angle in aluminum?

$$\frac{\sin\theta_1}{V_1} = \frac{\sin\theta_2}{V_2}$$

First establish the values.

- θ_1 = 24°
- θ_2 = the value to be determined
- V_1 = 0.148 cm/µs (sound velocity of a longitudinal wave in Lucite)
- V_2 = 0.313 cm/µs (sound velocity of a shear wave in steel)

Plug the known values into the equation.

$$\frac{\sin(24)}{0.148\ \mathrm{cm}/\mu\mathrm{s}} = \frac{\sin\theta_2}{0.313\ \mathrm{cm}/\mu\mathrm{s}}$$

Determine the sine of 24 degrees with a calculator. Sin(24) = 0.407. Plug in this value and cross multiply and divide.

$$\frac{(0.407)(0.313\ \mathrm{cm}/\mu\mathrm{s})}{0.148\ \mathrm{cm}/\mu\mathrm{s}} = \sin\theta_2$$

$$0.861 = \sin\theta_2$$

Finally, take the inverse sine of 0.861 to determine the angle whose sine equal 0.861.

$$\boxed{\theta_2 = 59.4^o}$$

Acoustic Impedance

$$Z = \rho V$$

Where:

Z = Acoustic Impedance

ρ = Density

V = Velocity

Learn more about acoustic impedance in the physics section.

Reflection

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

Where:

R = Energy Reflection Coefficient

Z_1 = Acoustic Impedance of Medium 1

Z_2 = Acoustic Impedance of Medium 2

Learn more about reflection and transmission of energy in the physics of waves section.

Near Field

$$N = \frac{D^2}{4\lambda}$$

or

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

Where:

N = Near Field

D = Transducer Diameter

λ = Wavelength

f = Frequency

V = Velocity

Near the ultrasonic transducer there are significant fluctuations in the sound intensity due to constructive and destructive interference of the multiple waves which originate from the transducer face. Because of acoustic variations within this field, called the near field, it can be extremely difficult to accurately evaluate flaws in materials when they are positioned within this area.

However, at some point the pressure waves combine to form a relatively uniform front. The area where the ultrasonic beam is more uniform and spreads out in a pattern originating from the center of the transducer is called the far field. Knowing where the far field starts is important since optimal detection occur when flaws are located at the start of far field since this is where the sound wave is well behaved and at its maximum strength. The transition point between the near field and the far field (sometimes referred to as the "natural focus" of an unfocused transducer) can be calculated if the frequency and diameter of the transducer and the speed of sound in the material are known.

Example Calculation

Calculate the end of the near field when using a 5 MHz, 0.375 inch diameter transducer to inspect a component made of brass. The sound velocity in brass is $0.1685\text{x}10^6$ inch/second

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

Note: Sometimes the radius of the transducer is used (like in the Java calculator). When the radius is used, the four in the denominator go away because the diameter squared divided by four is equal to the radius squared.

Substitute the values into the formula.

$$N = \frac{(0.375 \text{ in})^2 (5 \times 10^6 \text{ cycles/sec})}{4(0.1685 \times 10^6 \text{ in/sec})}$$

Complete the square and cancel terms where possible.

$$N = \frac{(0.375 \text{ in})^{\cancel{2}} (5 \cancel{\times 10^6} \text{ cycles}/ \cancel{\text{sec}})}{4(0.1685 \cancel{\times 10^6} \cancel{\text{in/sec}})}$$

Multiply.

$$N = \frac{0.703 \text{ in cycle}}{0.675}$$

Divide.

$$N = 1.04 \text{ inches}$$

The near field will extend into the material 1.04 inch from the transducer face. Within this near field area, it is hard to predict the signal amplitude from a reflector.

Learn more about radiated fields in the ultrasonic equipment section.

Beam Spread Half-Angle

$$\sin\theta = 1.2\frac{\lambda}{D}$$

or

$$\sin\theta = 1.2\frac{V}{Df}$$

Where:

λ = Wavelength

D = Transducer Diameter

V = Velocity

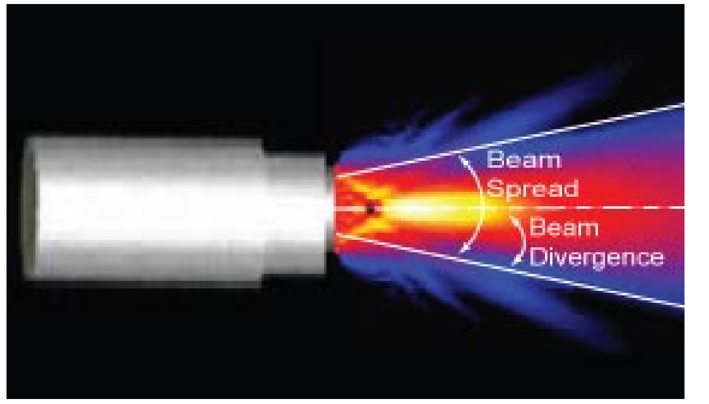
f = Frequency

A round transducers produces a cylindrical sound field in front of the transducer. However, the energy in the beam does not remain in a cylinder, but instead spread out as it propagates through the material. The phenomenon is usually referred to as beam spread.

Beam spread for a flat piston source transducer is a function of the transducer diameter (D), transducer frequency (f), and the sound velocity (V) in the liquid or solid medium through which the sound is traveling. The equation below can be used to calculate the beam divergence angle (1/2 beam spread angle). This angle represents a measure from the center of the acoustic axis to the point where the sound pressure has decreased by one half (-6 dB) to the side of the acoustic axis.

Example Calculation

Calculate the beam spread when using a 2.25 MHz, 0.375 inch diameter transducer to inspect a component made of brass. The sound velocity in brass is 0.1685x10^6 inch/second. First, substitute the values into the formula.



$$\sin\theta = 1.2\frac{0.1685 \times 10^6 \text{ in/sec}}{(0.375 \text{ in})(2.25 \times 10^6 \text{ cycles/sec})}$$

Cancel terms where possible.

$$\sin\theta = 1.2\frac{0.1685 \cancel{\times 10^6} \cancel{\text{in/sec}}}{(0.375 \cancel{\text{in}})(2.25 \cancel{\times 10^6} \text{ cycles/} \cancel{\text{sec}})}$$

Simplify.

$$\sin\theta = 1.2\frac{0.1685}{(0.375)(2.25)}$$

Multiply and divide.

$$\sin\theta = 0.2396$$

With a calculator find the inverse sin of 0.2396.

$$\theta = 13.86^o$$

The beam divergency is 13.86 degrees so beam spread, which is 2 times the beam divergency, will be approximately 27.7 degrees.

Learn more about beam spread in the ultrasonic equipment section.

Decibel (dB) Gain and Loss

$$\Delta I(dB) = 20\log\frac{P_2}{P_1}$$

Where:

ΔI(dB) = Difference in sound Intensity in Decibels

P_1 = Pressure Amplitude 1

P_2 = Pressure Amplitude 2

Calculation Examples

Example 1:

Two sound pressure measurements are made using an ultrasonic transducer. The output voltage from the transducer is 600 mV for the first measurement and 100 mV for the second measurement. Calculate the difference in the sound intensity, in dB, between the two measurements?

$$\Delta I(dB) = 20 \log \frac{V_2}{V_1}$$

Substitute in the voltage values:

$$\Delta I(dB) = 20 \log \frac{100 \text{ mV}}{600 \text{ mV}}$$

Divide to get a decimal value for the ratio:

$$\Delta I(dB) = 20 \log 0.1667$$

Take the log of 0.1667:

$$\Delta I(dB) = 20(-0.7782)$$

Multiply:

$$\Delta I(dB) = -15.56$$

The sound intensity changed by -15.56dB. In other words, the sound intensity decreased by 15.56 dB

Example 2:

If the intensity between two ultrasonic measurements increases by 6 dB, and the first measurement produces a transducer output voltage of 30 mV, what was the transducer output voltage for the second measurement?

$$\Delta I(dB) = 20 \log \frac{V_2}{V_1}$$

Substitute the know information in to the equation:

$$6 = 20 \log \frac{V_2}{30 \text{ mV}}$$

Divide both sides of the equation by 20

$$\frac{6}{20} = \frac{\cancel{20} \log \frac{V_2}{30 \text{ mV}}}{\cancel{20}}$$

Simplify:

$$.3 = \log \frac{V_2}{30 \text{ mV}}$$

Clear the log:

$$10^{0.3} = \frac{V_2}{30\ \mathrm{mV}}$$

Simplify:

$$\sim 2 = \frac{V_2}{30\ \mathrm{mV}}$$

Solve for P_2:

$$60\ \mathrm{mV} = V_2$$

The voltage output for P_2 is 60mV. Notice that a 6dB increase in sound intensity doubled the voltage output.

Example 3:

Consider the sound pressure difference between the threshold of human hearing, 0 dB, and the level of sound often produce at a rock concert, 120 dB. (Note: prolonged sound levels above 85 dB are considered harmful, while levels above 120 dB are unsafe.)

$$120\ \mathrm{dB} = 20 \log \frac{P_2}{P_1}$$

where: P_1 is the sound pressure of the reference level, and P_2 is the sound pressure experienced at the rock concert.

Divide both sides by 20:

$$6 = \log \frac{P_2}{P_1}$$

Clear the log:

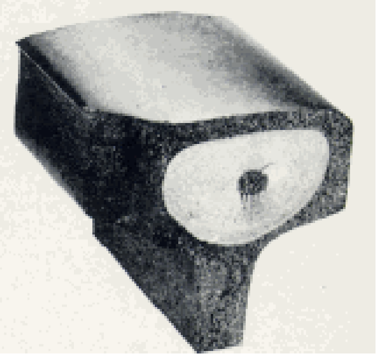
$$10^6 = \frac{P_2}{P_1}$$

So the sound pressure at a rock concert is 10^6 or one million times greater than that of the threshold of human hearing.

Learn more about the decibel in the physics of waves section.

Rail Inspection

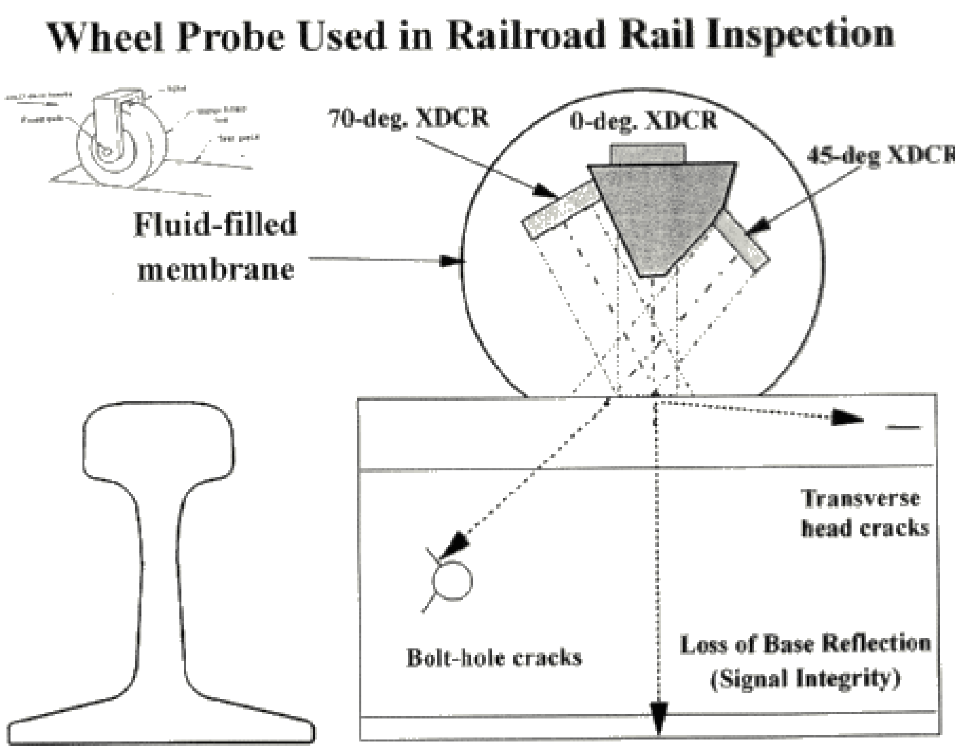
One of the major problems that railroads have faced since the earliest days is the prevention of service failures in track. As is the case with all modes of high-speed travel, failures of an essential component can have serious consequences. The North American railroads have been inspecting their most costly infrastructure asset, the rail, since the late 1920's. With increased traffic at higher speed, and with heavier axle loads in the 1990's, rail inspection is more important today than it has ever been. Although the focus of the inspection seems like a fairly well-defined piece of steel, the testing variables present are significant and make the inspection process challenging.



Rail inspections were initially performed solely by visual means. Of course, visual inspections will only detect external defects and sometimes the subtle signs of large internal problems. The need for a better inspection method became a high priority because of a derailment at Manchester, NY in 1911, in which 29 people were killed and 60 were seriously injured. In the U.S. Bureau of Safety's (now the National Transportation Safety Board) investigation of the accident, a broken rail was determined to be the cause of the derailment. The bureau established that the rail failure was caused by a defect that was entirely internal and probably could not have been detected by visual means. The defect was called a transverse fissure (example shown on the left). The railroads began investigating the prevalence of this defect and found transverse fissures were widespread.

One of the methods used to inspect rail is ultrasonic inspection. Both normal- and angle-beam techniques are used, as are both pulse-echo and pitch-catch techniques. The different transducer arrangements offer different inspection capabilities. Manual contact testing is done to evaluate small sections of rail but the ultrasonic inspection has been automated to allow inspection of large amounts of rail.

Fluid filled wheels or sleds are often used to couple the transducers to the rail. Sperry Rail Services, which is one of the companies that perform rail inspection, uses Roller Search Units (RSU's) comprising a combination of different transducer angles to achieve the best inspection possible. A schematic of an RSU is shown below.

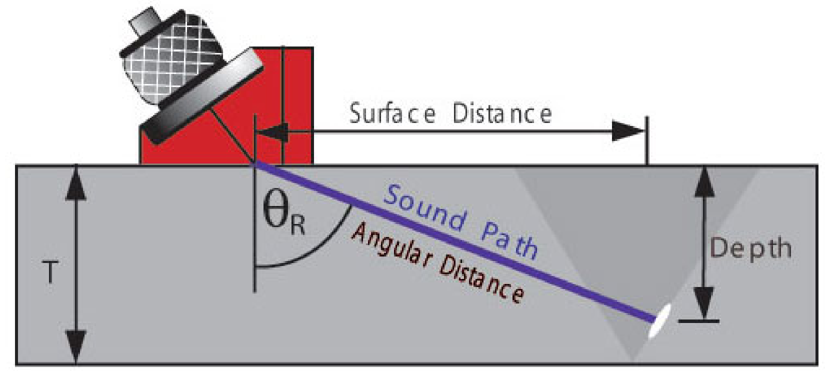


Weldments (Welded Joints)

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.

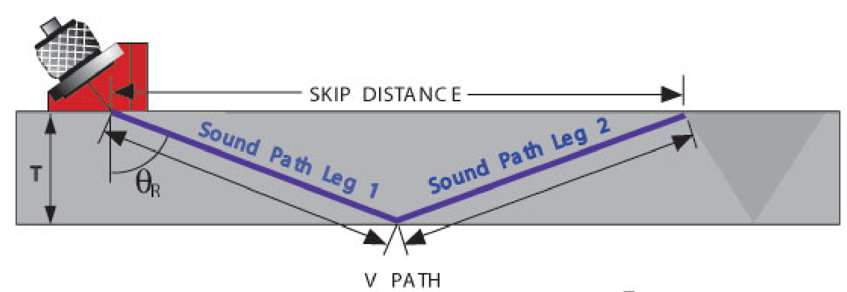
With the exception of single gas pores all the defects listed are usually well detectable by ultrasonics. Most applications are on low-alloy construction quality steels, however, welds in aluminum can also be tested. Ultrasonic flaw detection has long been the preferred method for nondestructive testing 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 because an angle beam transducer may not be able to provide a return signal from a laminar flaw.



θ_R = Angle of Refraction
T = Material Thickness
Surface Distance = $\sin\theta_R$ x Sound Path
Depth (1st Leg) = $\cos\theta_R$ x Sound Path

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.



θ_R = Refracted Angle
T = Material Thickness
Skip Distance = 2T x $\tan\theta_R$

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

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

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.

Electromagnetic Acoustic Transducers (EMATs)

Transducer: A device for converting a nonelectrical signal, such as sound, light, heat, etc., into an electrical signal, or vice versa.

Eddy Currents: A current induced in a conductor situated in a changing magnetic field or moving in a fixed one.

As discussed on the previous page, one of the essential features of ultrasonic measurements is mechanical coupling between the transducer 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 sample by placing both objects 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.

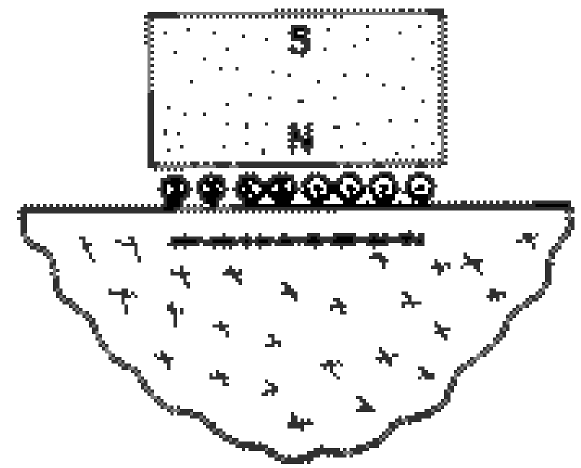
Electromagnetic-acoustic transducers (EMAT) acts through totally different physical principles and do not need couplant. When a wire is placed near the surface of an electrically conducting object and is driven by a current at the desired ultrasonic frequency, **eddy currents** will be induced in a near surface region of the object. If a static magnetic field is also present, these eddy currents will experience Lorentz forces of the form

F=J\times B

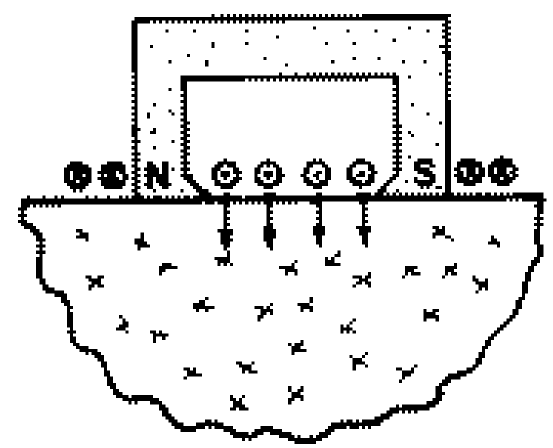
F is the body force per unit volume, **J** is the induced dynamic current density, and **B** is the static magnetic induction.

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, using EMATs can eliminate errors associated with couplant variation, particularly in contact measurements.

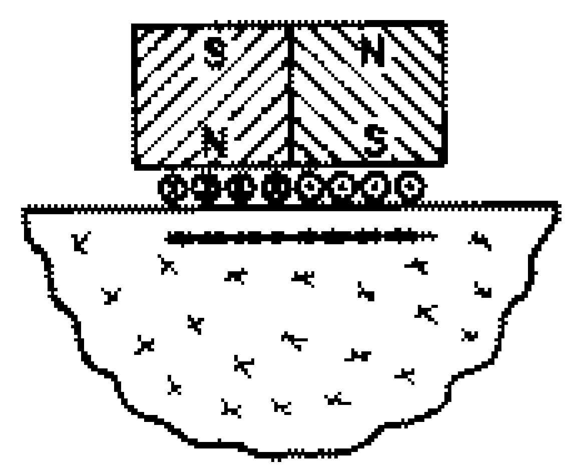
A number of practical EMAT configurations are shown below. In each, the biasing magnet structure, the coil, and the forces on the surface of the solid are shown in an exploded view. The first three configurations will excite beams propagating normal to the surface of the half-space and produce beams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



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

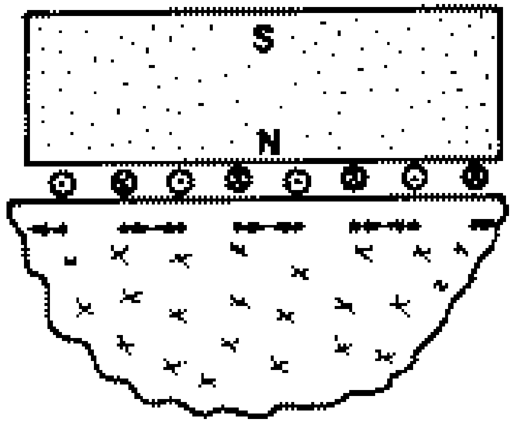


Cross-sectional view of a tangential field EMAT for exciting polarized longitudinal waves propagating normal to the surface.

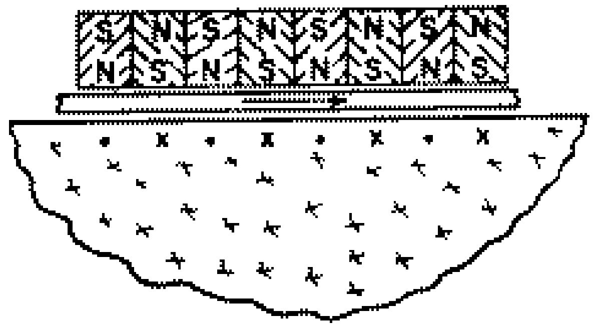


Cross-sectional view of a normal field EMAT for exciting plane polarized shear

waves propagating normal to the surface.



Cross-sectional view of a meander coil EMAT for exciting obliquely propagating L or SV waves, Rayleigh waves, or guided modes (such as Lamb waves) in plates.



Cross-sectional view of a periodic permanent magnet EMAT for exciting grazing or obliquely propagating horizontally polarized (SH) waves or guided SH modes in plates.

Practical EMAT designs are relatively narrowband 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, which may also be generated by pulsed electromagnets.

The EMAT offers many advantages based on its couplant-free operation. These advantages include 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 highly consistent measurements.

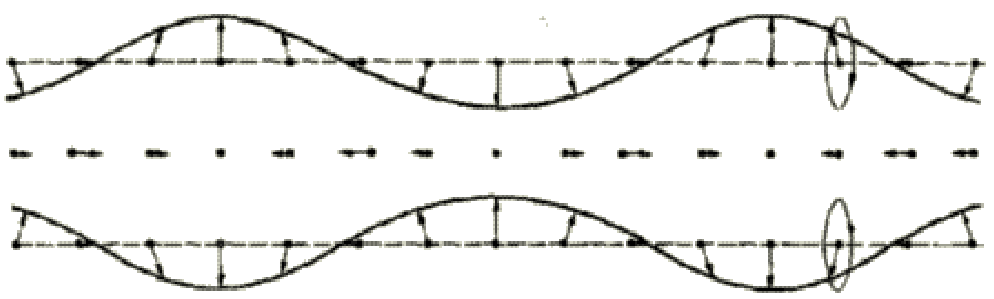
These advantages are tempered by low efficiencies, and careful electronic design is essential to applications.

More information about the use of EMATs can be found at the following links.

[Lamb Wave Generation With EMATs]
[Shear Wave Generation With EMATs]
[Velocity Measurements With EMATs]
[Texture Measurement I With EMATs]
[Texture Measurement II With EMATs]
[Stress Measurement With EMATs]
[Composite inspection With EMATs]

Lamb Wave Generation with EMATs

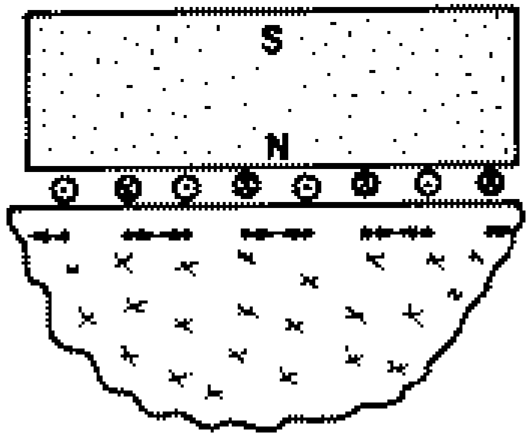
Lamb waves are similar to longitudinal waves, with compression and rarefaction, but they are bounded by the sheet or plate surface causing a wave-guide effect.



Electromagnetic-acoustic transducers (EMAT) designed to generate Lamb waves 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

$$F = J \times B$$

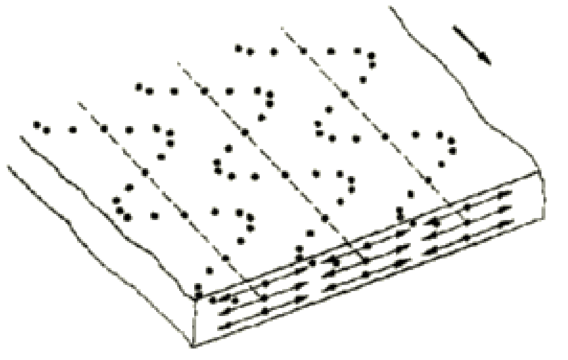
F is the body force per unit volume, **J** is the induced dynamic current density, and *B* is the static magnetic induction.



Pictured above is a cross-sectional view of a meander coil EMAT for exciting Lamb waves in plates.

Shear Wave Generation with EMATs

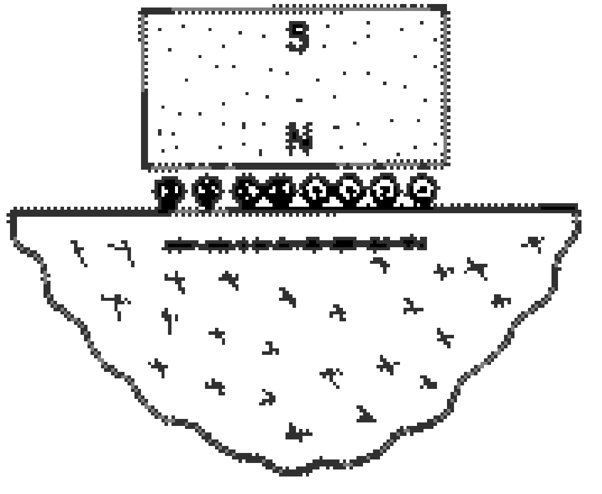
Shear waves have an inherent polarization direction depending on how they are generated. Pictured below are horizontally polarized shear waves propagating along the length of a plate.



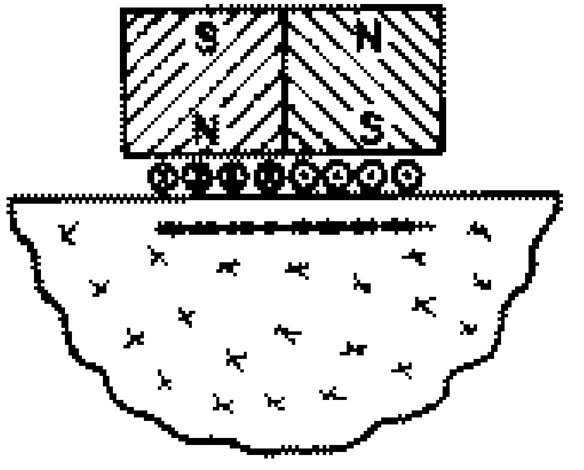
Electromagnetic-acoustic transducers (EMAT) designed to generate shear waves actually vibrate the atoms within the material being investigated. When a wire is placed near to the surface of an electrically conducting object and is driven by a current at the desired ultrasonic frequency, eddy currents 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

$$F=J\times B$$

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



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



Cross-sectional view of a normal field EMAT for exciting plane polarized shear waves propagating normal to the surface.

Velocity Measurements with EMATs

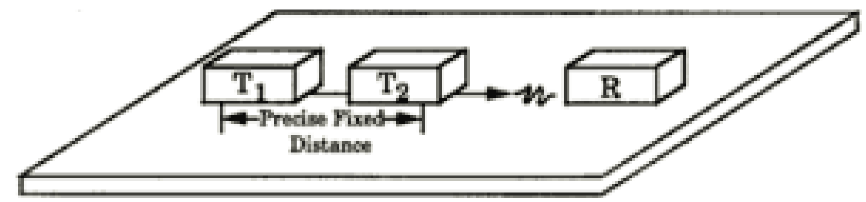
Electromagnetic-acoustic transducers (EMAT) generate ultrasound in the material being investigated. When a wire or coil is placed near the surface of an electrically conducting object and is driven by a current at the desired ultrasonic frequency, eddy currents will be induced in a near surface region. If a static magnetic field is also present, these currents will experience Lorentz forces of the form

$$F=J\times B$$

F is the 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 transducers 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, the use of EMATs can eliminate errors associated with couplant variation, particularly in contact measurements.

Differential velocity is measured using a T1-T2---R fixed array of EMAT transducers at 0°, 45°, 90° or 0°, 90° relative rotational directions depending on device configuration.



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

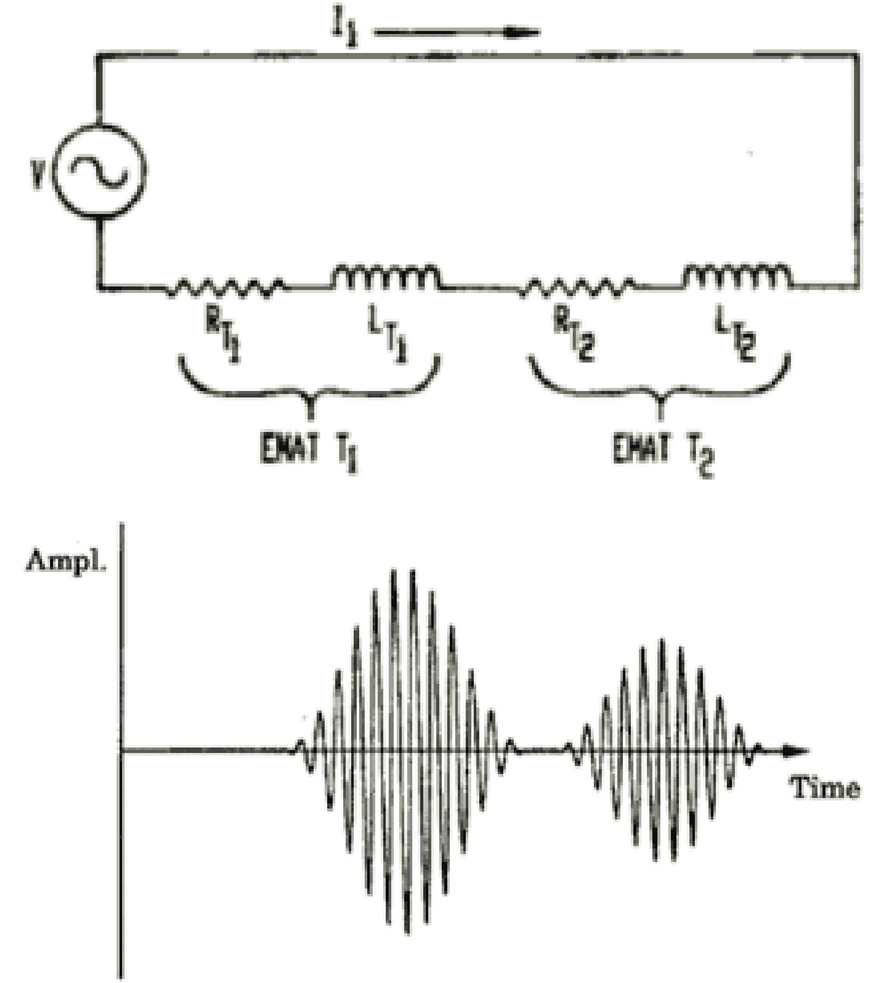
EMAT Driver Frequency: 450-600 kHz (nominal)
Sampling Period: 100 ns
Time Measurement Accuracy:

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

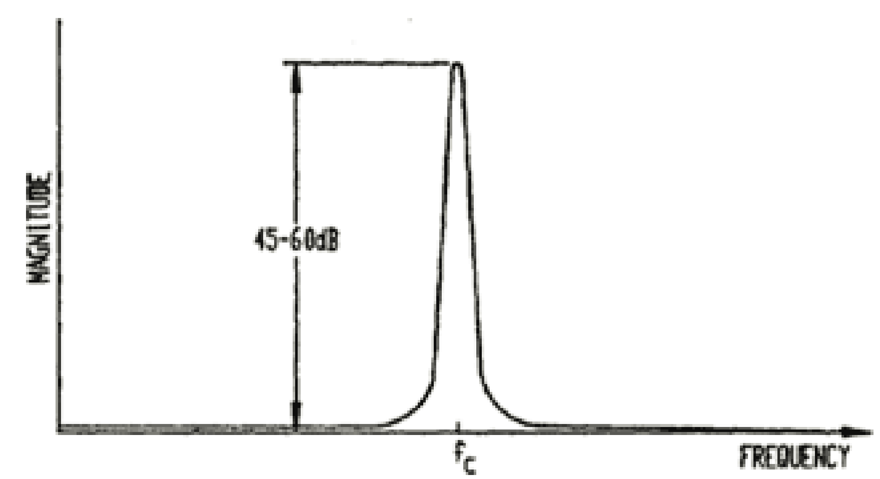
W440 < 3.72E-5
W420 < 1.47E-4
W400 < 2.38E-4

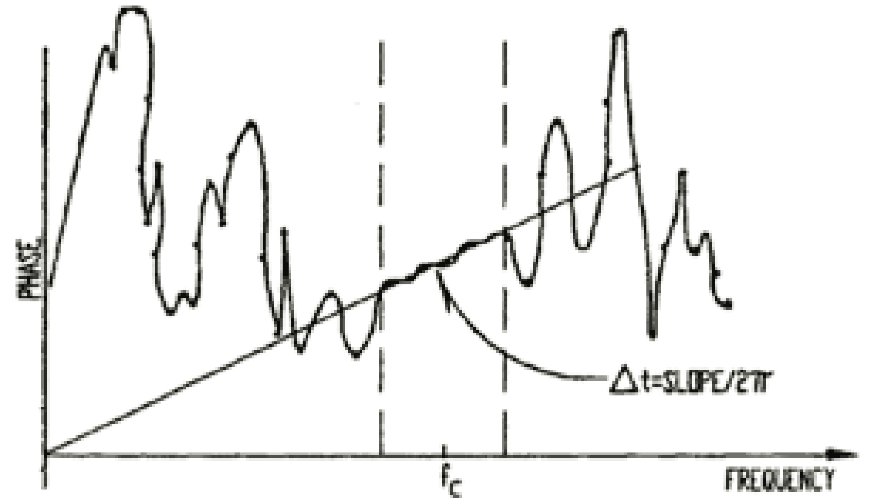
Time Measurement Technique:

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.



Received Waveforms from T_1 and T_2





Slope of the phase is determined by a 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).

Directed ultrasonic velocity measurements predict formability by taking advantage of the effects of directional anisotropy that exists in the worked sheet (induced by the rolling process). One consequence of directionality is a change in mechanical properties with direction. For example, the yield strength and ductility may change with the orientation at which a laboratory tensile specimen is cut from a sheet. Generally, minimum and maximum values of these quantities occur at 0 degrees, in the vicinity of 45 degrees and at 90 degrees with respect to the rolling direction (see Figure 1). Any formation of **ears** in drawing operations (two fold and four fold) will also generally take place along these axes.

When forming sheet metal, practical consequences of directionality include such phenomena as excess wrinkling, puckering, ear-formation, local thinning, or actual rupture. At best, these can cause individual pieces to be scrapped. A more serious consequence is the down time required to correct the manufacturing process.

Ears: The tendency for a material being plastically deformed (pressed into product) to have uneven edges due to material texture, often called "ears".

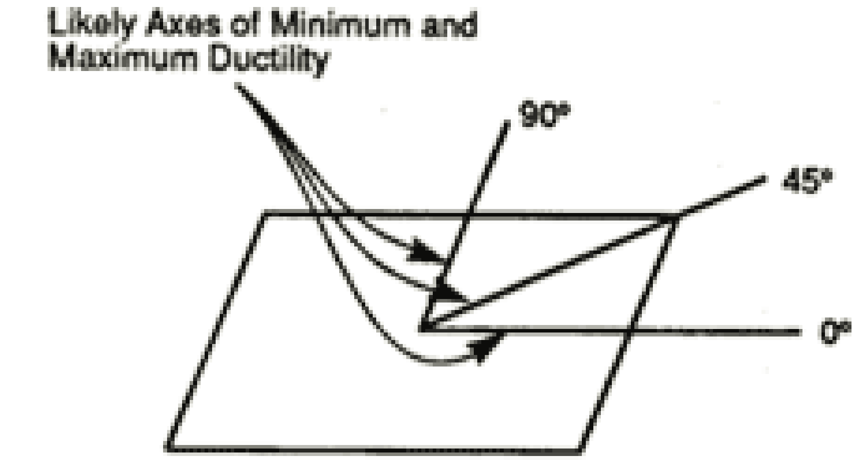


Figure 1
Directionality in Properties of a Rolled Sheet

A number of specialized laboratory mechanical tests have been developed to identify the severity of directionality. Included are measurements of plastic strain ratios in tensile tests, limiting drawing ratio measurements, cupping tests, etc. Of particular interest here is the plastic strain ratio, defined as

$$r=e_{w}/e_{t}$$

Where $\mathbf{e_w}$ is the strain ratio in the width direction and $\mathbf{e_t}$ is the strain in the thickness direction of a tensile coupon loaded in the plastic regime. The plastic strain ratio determines the relative tendency of deformation to occur in the plane of the sheet ($\mathbf{e_w}$) as opposed to through the thickness ($\mathbf{e_t}$). In general, **r** will vary with the angle at which the tensile coupon is cut with respect to the rolling direction of the sheet.

Directions with large values of **r** will generally correspond to directions of ear formation when a cup is deep drawn, as sketched in Figure 2. The "RD" indicates the rolling direction, with respect to which the angles that are measured. The upper set of curves shows the variation of **r** with angle. The lower sketches represent the resulting cup contour.

Two commonly used figures of merit are the average plastic strain ratio or normal anisotropy, defined as

$$r = \frac{r(0^\circ)+2r(45^\circ)+r(90^\circ)}{4}$$

and the planar anisotropy, defined as

$$\delta-r = \frac{r(0^\circ)+2r(45^\circ)+r(90^\circ)}{2}$$

Formability of a drawing quality sheet depends largely on two factors: drawability (capability to be drawn from the flange area of the blank into the die cavity) and stretchability (capability to be stretched under biaxial tension to the contours of the punch). Drawability is related primarily to plastic anisotropy, and the average plastic strain ratio, **r**, is a common measure of its value. This is schematically illustrated in Figure 2. The planar anisotropy, Ar, is thought to be a measure of the tendency to form ears. As will be discussed shortly, directionality is sensed in ultrasonic velocity measurements by taking advantage of another one of its consequences, the dependence of elastic properties on direction. These are determined nondestructively from the elastic wave speeds.

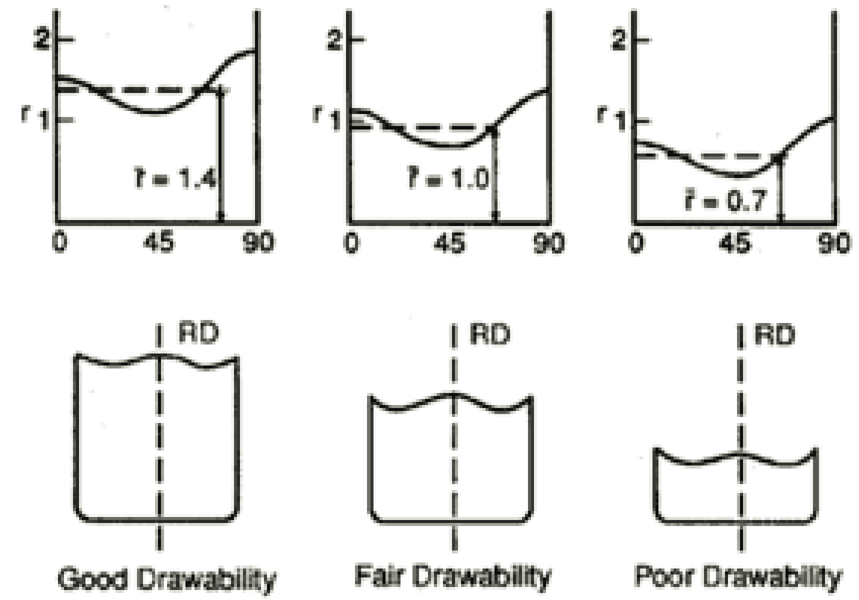


Figure 2
Relationship of Plastic Strain Ratio to Drawability

Figure 3 illustrates the causes for the existence of directionality (anisotropy) in the processed sheet. There are two kinds of anisotropy: one is caused by the alignment of the nonmetallic inclusions existing in the ingot (called mechanical fibering or fiber texture) and the other is due to the alignment of the grains or crystals, and is called preferred orientation or crystallographic texture. The effects of preferred orientation have more profound implications in deep drawing operations, and it is this property that is sensed by ultrasonic measurements.

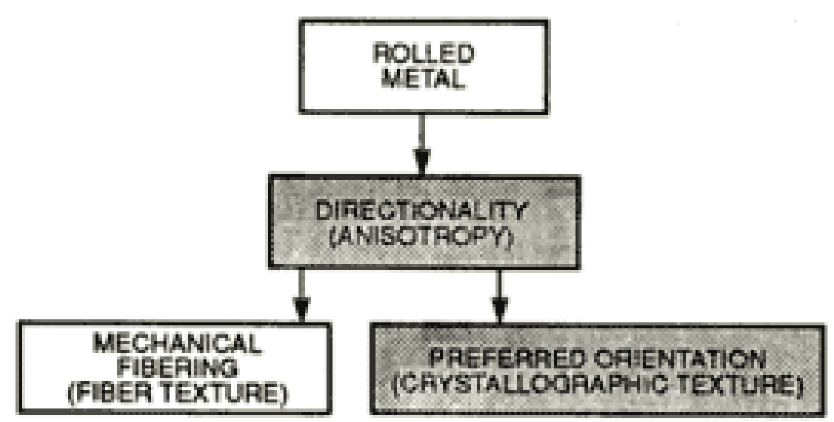


Figure 3
Causes of Directionality

Figure 4 demonstrates how the preferred orientation is developed through the effects of the rolling operations on the grains of the unprocessed sheet. In response to the force imposed in working the metal, extensive plastic deformation must take place. At a microscopic level, this may be thought of as a result of dislocation motion along planes of low resistance. Two interrelated phenomena result: an elongation of the grains that could be observed visibly, and a change in the crystallographic orientation of the grains. The latter is believed to be the primary cause of directionality of properties associated with deep drawing. It can be sensed by X-ray diffraction or by ultrasonic wave speed measurements.

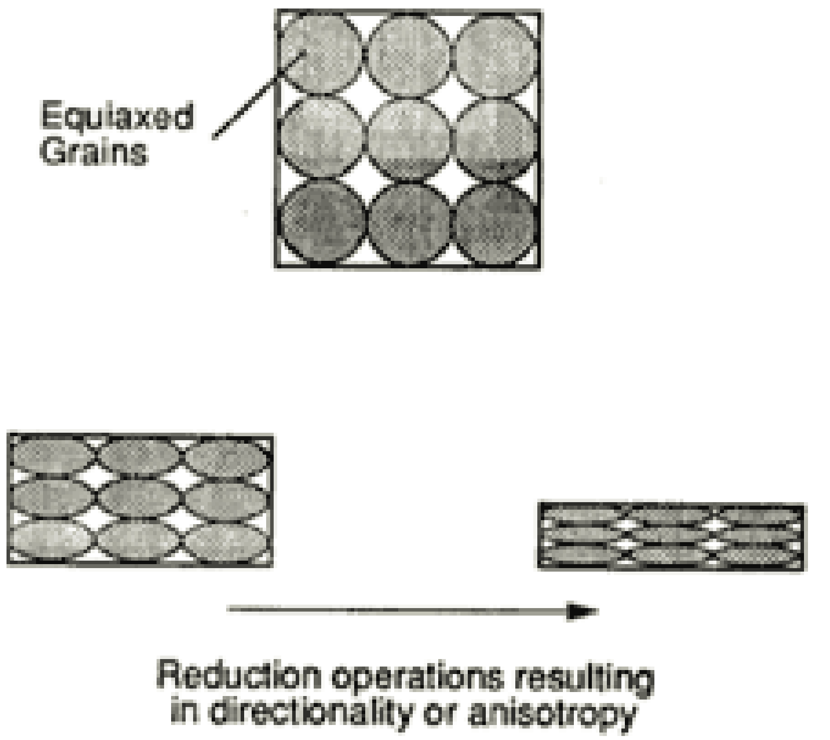


Figure 4
Microstructural Modification by Rolling

As an example of the effects of texture on the drawing capability of the sheets, one can qualitatively consider the impact of idealized textures in low carbon steel sheets. The bcc structure of the steel is strongest when measured along its cube diagonal or [111] direction, less strong along its edge diagonal [110] and weakest along its face diagonal [100], as defined in Figure 5. It is known that when the material assumes the cube-on-corner texture (in which the crystals line up with the strongest direction, [111]) normal to the sheet, the most favorable normal anisotropy is obtained. On the other hand, an unfavorable normal anisotropy is associated with the cube-on-face texture, Figure 6.

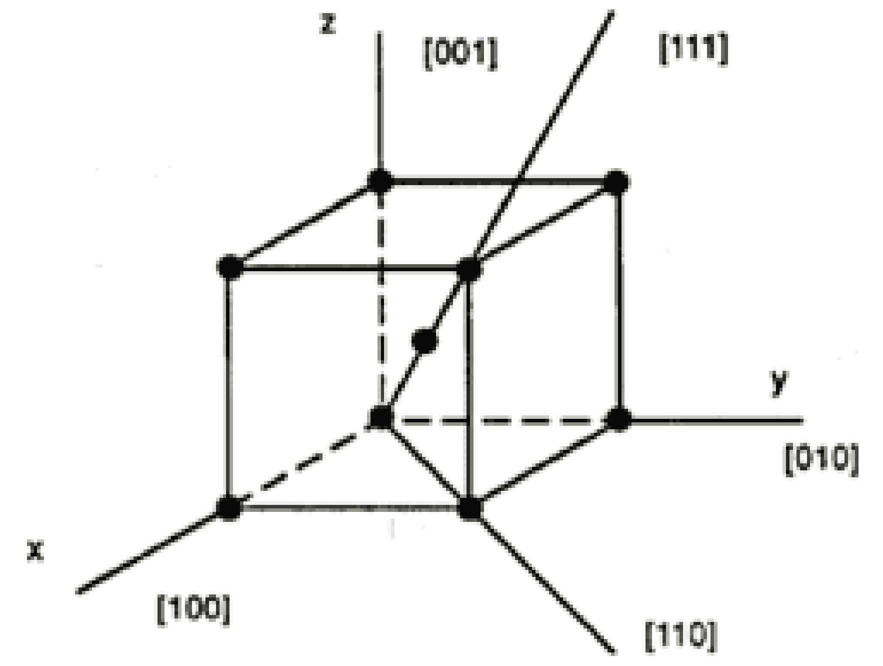


Figure 5
Important Crystallographic Directions in BCC Metals

Signal processing includes the estimation of normal anisotropy from ultrasonic determinations of the strengths of such texture components. It is obviously desirable to monitor texture as early as possible in the rolling process to better control the amount of annealing and cold work necessary for a proper drawability.

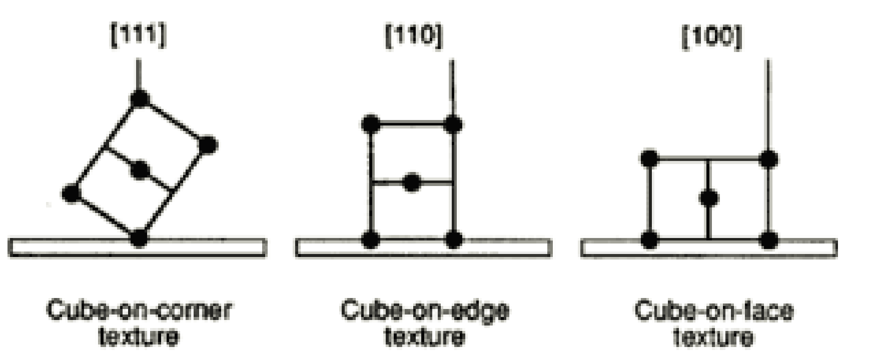


Figure 6
Extreme Texture Components

In practice, the crystallites in commercial metal sheets do not only exhibit these few ideal orientations. Instead, they have a continuum of orientations which is best described by the crystallite orientation distribution function (CODF), giving the probability that a grain will have a particular orientation. There will be peaks in the CODF near ideal orientations, but the maxima are not necessarily sharp.

The conventional metallurgical technique for obtaining the grain orientations has been the measurement of pole figures using X-ray diffraction. A pole figure can only give an incomplete assessment of the orientations in a two dimensional form. However, computer programs have been developed to generate a complete description of the orientations (i.e. the CODF) based on the analysis of multiple pole figures.

Although a complete description, the complexity of the CODF, which is a function of the Euler angles describing possible crystallite orientation, renders its direct use awkward for many purposes. An alternate approach is to represent the CODF as a superposition of simple, known functions, much as a waveform might be represented as a sum of sine and cosine functions in a Fourier series. Formally, one writes

$$W(\xi,\Psi,\phi)=\sum^{\infty}_{l=0}\sum^{l}_{m=-l}\sum^{l}_{n=-l}w_{lmn}z_{lmn}\xi e^{-im\Psi}e^{-in\phi}$$

where ??, ?? are Euler angles describing the crystallite orientation with respect to the plate, 4=cos(O), z_{lmn} are generalized Legendre function, and the w_{lmn} are constants, known as orientation distribution coefficients (ODC's). Thus, the ODC's are analogous to the constants in a Fourier series. Given an experimental determination of the CODF, the ODC's can be determined using well-known mathematical manipulations. Alternatively, knowledge of the ODC's fully specifies the CODF. Hence, these two contain equivalent information that fully specifies the texture. The ODC's may be thought of as measures of the severity of the directional properties of the sheet. Figure 7 summarizes the procedure employed in determining the ODC's from X-ray pole figures.

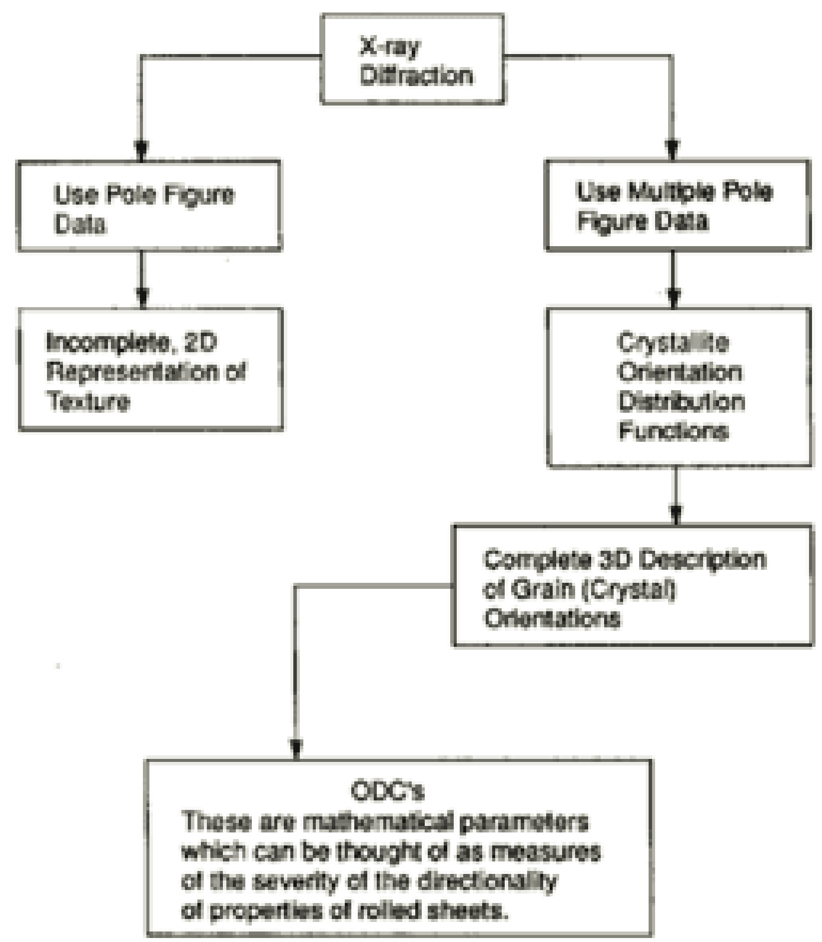


Figure 7
X-Ray Determination of Orientation Distribution Coefficients

Measurement techniques use the angular variation of the ultrasonic waves in the sheet to detect texture and directionality. The effects of texture on velocity of an ultrasonic wave is to slow it down in one direction and make it faster in another (Figure 8). Ultrasonic velocity measurements take advantage of this effect, thus determining the formability and texture parameters such as the r's and W's.

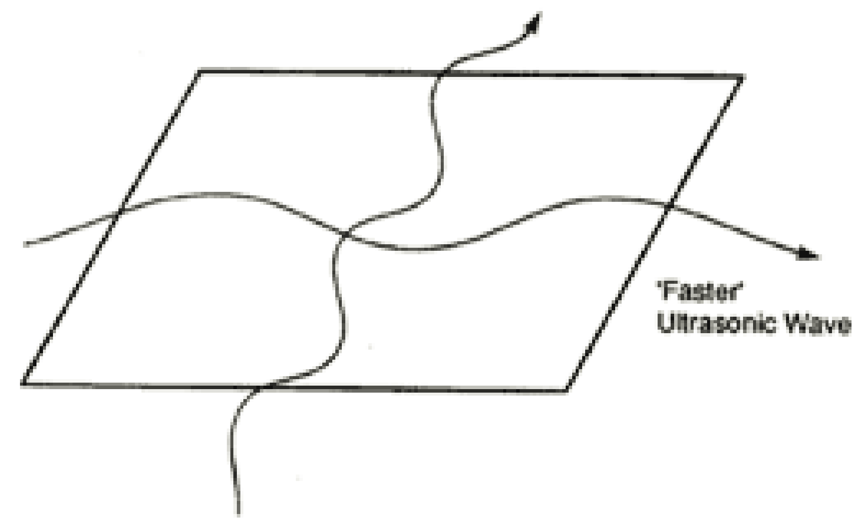


Figure 8
Effects of Texture on Wave Speed

Texture Measurement with EMATs II

When using techniques sensitive to the anisotropic elastic properties of the sheet, one cannot recover the full set of ODC's. For fundamental reasons, the fact that elastic stiffness is described by a fourth rank tensor implies that W_{lmn} can only determine when one is less than or equal to four. For cubic metals, the independent members of this set are the ODC's, W400, W420, and W440. The technique is designed to quantitatively measure these ODC's. Comparison to independent X-ray and **neutron** diffraction measurements have shown a high degree of accuracy, as illustrated in Figure 9 (Thompson, Smith, Lee and Johnson, Met. Trans. 20A 1989).

Neutron: A neutral hadron that is stable in the atomic nucleus but decays into a proton, an electron, and an antineutrino with a mean life of 12 minutes outside the nucleus.

Azimuthal: A system used in analytical geometry to locate a point P , with reference to two or three axes.

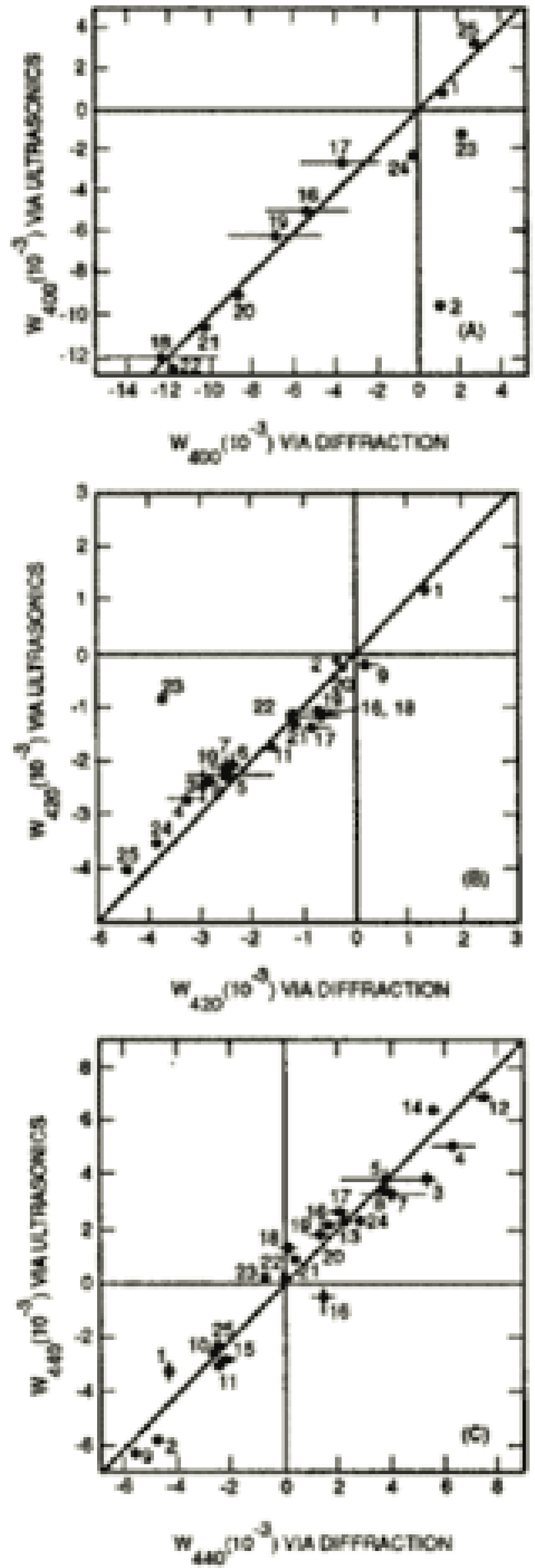

W400(10-3) VIA ULTRASONICS
W400(10-3) VIA DIFFRACTION
(A)
W420(10-3) VIA ULTRASONICS
W420(10-3) VIA DIFFRACTION
(B)
W440(10-3) VIA ULTRASONICS
W440(10-3) VIA DIFFRACTION
(C)

Figure 9
Comparison of Ultrasonic and X-Ray or Neutron Diffraction Determinations of ODC's

Despite their small number, the ODC's accessible by ultrasonic measurement play a major role in formability theory because of a strong correlation that exists between anisotropic elastic and plastic properties. As noted by Davies, Goodwill, and Kallend (Met. Trans. 3, 1627-1631, 1972), "the coefficient, W400, sets the overall value of average strain ratio J, W420 controls the tendency to form two ears during deep drawing while W440 controls the tendency to form four ears."

Figure 10 plots the polar Z(O) and azimuthal Re(e-lv) variations of these terms. W420 and W440 determine the weights of CODF components having twofold and fourfold variations, respectively, in the plane of the sheet. Theory, as shown in the **azimuthal** plots, provide information on planar anisotropy and correlate with a corresponding degree of earing. However, W400 controls the weight of a CODF component which is independent of orientation in the plane of the plate but varies with polar angle with respect to the plate normal. Hence, it is a measure of normal anisotropy.

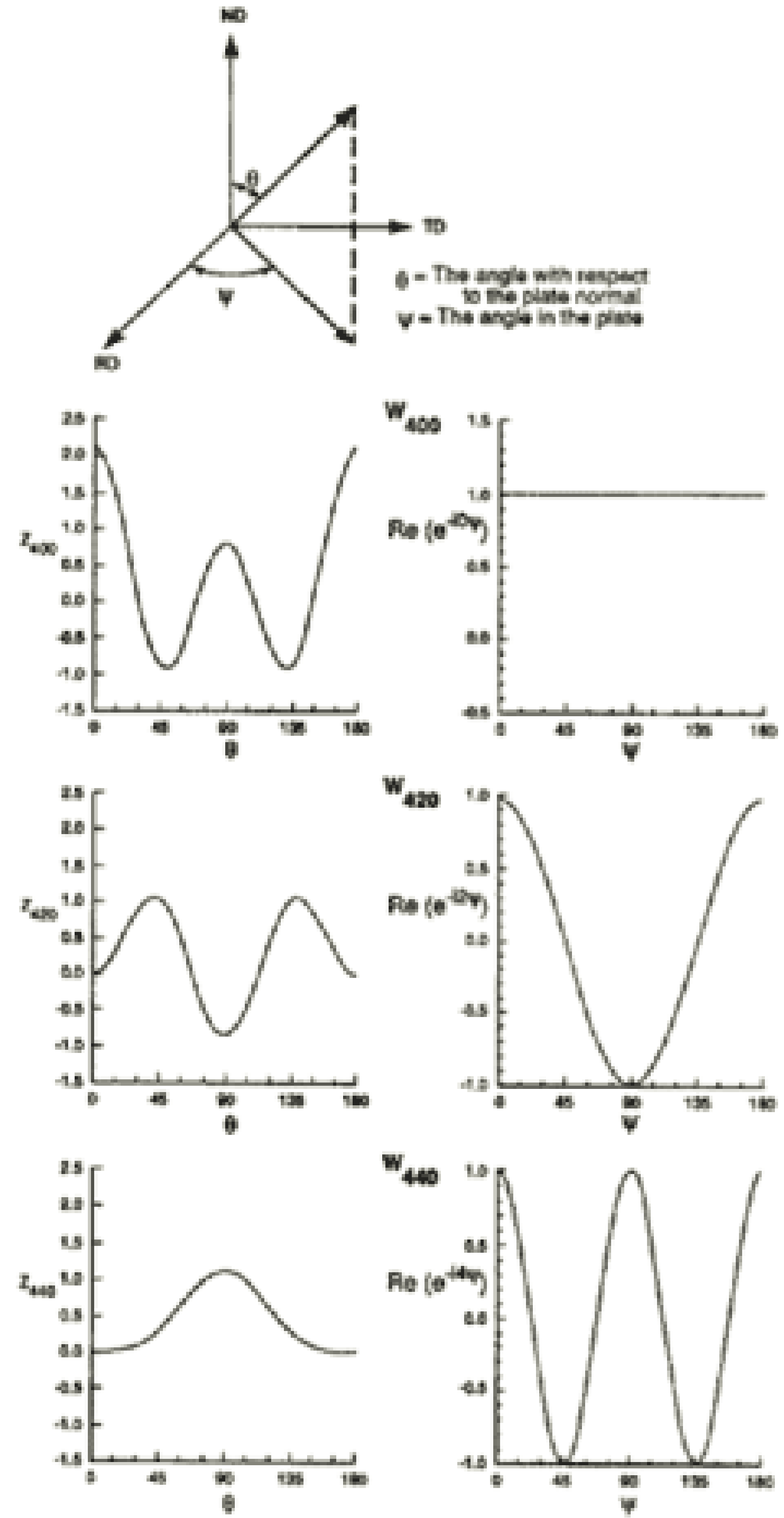


Figure 10
Polar and azimuthal variation of CODF components governed by the ODC's W_{400}, W_{420} and W_{440}

The following applet may be used to calculate ODC's W400, W420, and W400 from Lamb wave velocities propagating at 0°, 45° and 90° with respect to the rolling direction. First choose the material. This assigns the correct elastic constants c_{11}, c_{12}, c_{44}, and density for the cubic material being investigated. Next enter the "measured" Lamb wave velocities.

These correlations between elastic and plastic anisotropy have received extensive experimental study in the steel sheet industry. Experimental results (Stickles and Mould, Met. Trans. 1, 1303-1312, 1970; Mould and Johnson, Sheet Metal Ind. 50, 328-348, 1973) have demonstrated the correlation of the average Young's modulus

$$\bar{E} = \frac{[E(0) + 2E(45) + E(90)]}{4}$$

and its anisotropy

$$\Delta E = \frac{[E(0) - 2E(45) + E(90)]}{2}$$

with the corresponding plastic anisotropy parameters, r-bar and delta-r as defined in earlier equations. Here E(theta) is defined as Young's modulus of a coupon cut at an angle theta with respect to rolling direction. These successful laboratory studies led to a commercial instrument presently used extensively in the steel industry (Modul-r®, Tinious Olsen, Willow Grove, Pa).

These ultrasonic techniques rest on the same physical principles. However, instead of requiring samples be cut from the sheet, anisotropic elasticity information is inferred from ultrasonic wave speed measurements. From this data, one can directly infer ODC's, as has already been illustrated in Figure 9. Alternatively, one can estimate the anisotropic value of Young's modulus, and hence E-bar and delta-E. This allows existing, well-known correlations to be used to predict r-bar and delta-r for a steel sheet. Finally, one can use the tool to gather raw data that will lead to other correlations between ultrasonic measurements and formability parameters.

In summary, there is a quantitative correlation between the directionality of properties of a rolled metal sheet, such as the plastic strain ratio or elastic modulus, and the underlying texture. Figure 11 is an attempt to visualize this correlation. Just as the elastic and plastic properties of a sheet metal vary with direction (demonstrated by variation in Young's modulus, E, and plastic strain ratio, r), the distribution of grain orientations have their own angular variation.

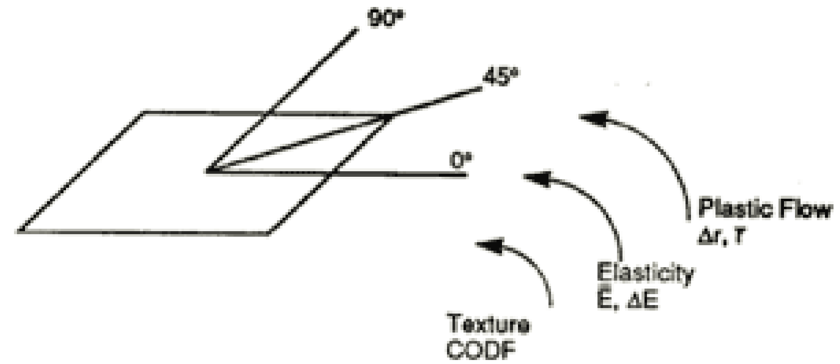


Figure 11
Correlation between angular variations of various physical properties

Ultrasonics can characterize texture nondestructively and rapidly. Unlike the conventional X-ray techniques which have limited surface penetration, velocity measurements can assess the bulk texture using ultrasonic waves, Figure 12. This characterization capability, tempered with more quantitative analysis of the relation between texture and drawability, can be of great advantage to the enhancement of forming operations.

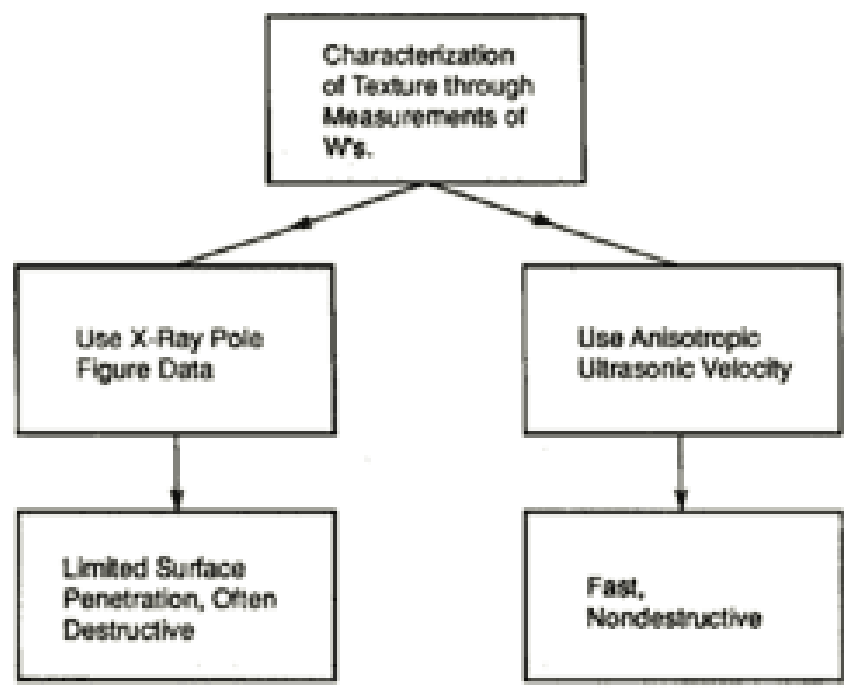


Figure 12
Texture characterization

Figure 13 is a flow chart demonstrating the ultrasonic measurement technique as compared with tensile tests and Modul-r. The velocities of the ultrasonic waves are measured along the axes of expected maximum and minimum ductility (0, 45, and 90 degrees with respect to the rolling direction). Once corrected for effects of dispersion and coating, they are used to calculate the average Young's moduli in these directions. Calculated moduli will then be used to find the normal and planar anisotropy. This is done by using existing correlations. It can also be used as a tool to develop data necessary to define new correlations in related applications.

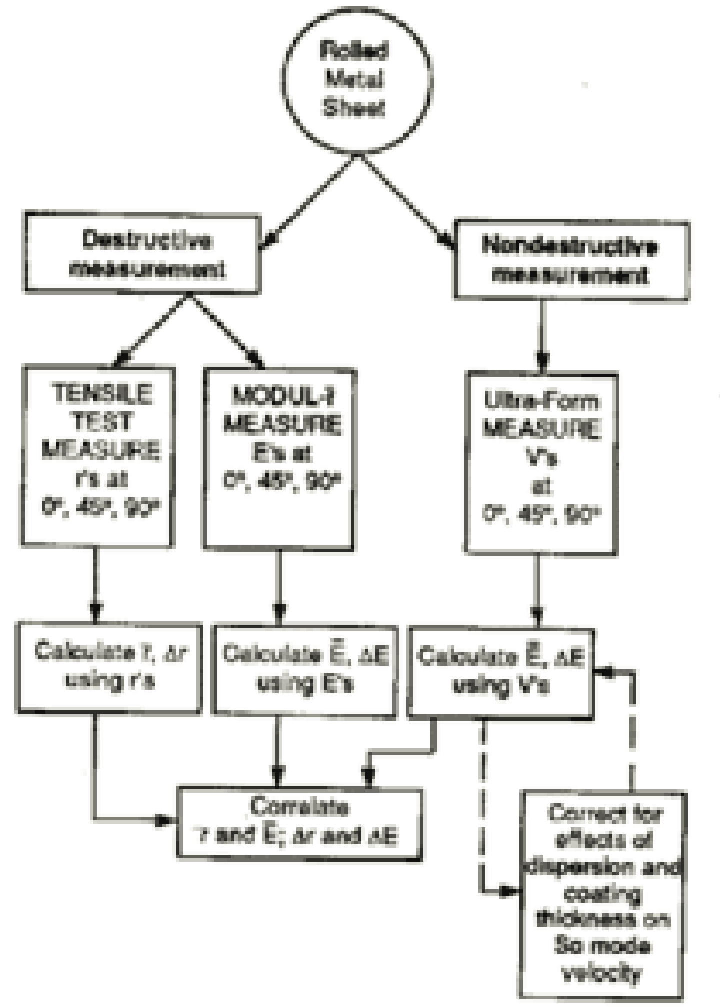


Figure 13
Comparison of techniques for estimation of plastic strain ratio

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Ultrasonic Measurement of Stress

For sheet and plate specimens experiencing applied or residual **stress**, the principal stresses s_a and s_b may be inferred from orthogonal velocity measurements. The following equation relates ultrasonic velocities to the principal stresses experienced in sheets or plates.

Stress: The force per unit area on a body that tends to cause it to deform.

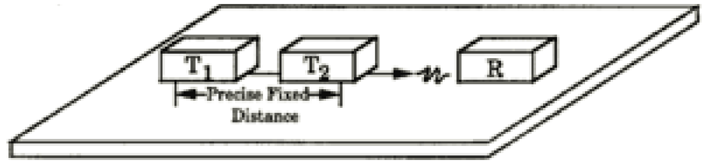
2pV_{avg}\cdot [V(\phi^{\circ})-V(\phi^{\circ}+90^{\circ})]=s_a-s_b

V_{avg} is the average shear velocity. It is understood that velocity difference [V(\phi^{\circ})-V(\phi^{\circ}+90^{\circ})] will be maximized when the ultrasonic propagation directions are aligned with principal stress axes. The magnitude of this difference, along with the density and mean velocity can be used to predict the principal stress difference.

It is particularly noteworthy that no acoustoelastic constants or other nonlinear properties of the material are needed for a stress prediction, which distinguishes this approach from other ultrasonic stress measurement techniques. The nonlinear material characteristics have been suppressed by the process of taking the velocity difference.

Measurement Technique

Differential velocity is measured using a T_1-T_2-R fixed array of EMAT transducers at 0° and 90° relative rotational directions depending on device configuration.

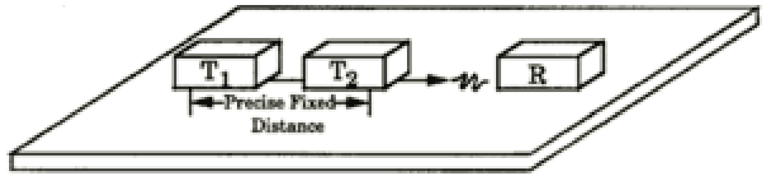


EMAT Driver Frequency: 450-600 kHz (nomioverview_stress.gifnal)
Sampling Period: 100 ns
Time Measurement Accuracy:

- Resolution: 0.05 Ns
- Accuracy required for less than 2 KSI Stress Measurements: Variance 2.47 Ns

Composite Inspection with EMATs

An electromagnetic acoustic transducer (EMAT) requires no couplant and can be noncontact in the generation and reception of ultrasound. Measurements using EMAT probes can therefore be done with a high degree of reproducibility. In an NDE project EMATs have been applied to a number of composites, including poorly conducting graphite/epoxy composites and nonconducting glass/epoxy and ceramic matrix composites. In order to generate sound waves via the Lorentz force mechanism, the surface of the composite must be conducting. An aluminum tape (0.003" aluminum foil with adhesive layer) is applied to the composite surface to achieve this. Ultrasound is generated in the aluminum foil and the adhesive bond between the metal and the composite allows the propagation of sound waves into the bulk of the composite.



EMATs on aluminum foil which in turn is bonded to composite material

Two types of EMAT probes are used: shear horizontal (SH) wave probes originally designed to study rolled plates in a stress and texture project in CNDE and, more recently, EMATs that generate normal incidence shear waves. Using the SH wave probes, the mechanical **anisotropy** of composite laminates were investigated in a configuration somewhat akin to the "acousto-ultrasonic" technique. Directivity of the received EMAT signals 'Showed excellent correlation with fiber' directions in the laminate. The SH wave probes, although not intended for generating bulk waves, had a sufficient fringing field to be used in a transmission measurement through a full inch of graphite epoxy laminate. EMAT-generated plate modes were also used in the detection of skin-core separation in a honeycomb sandwich structure (a rudder skin).

Anisotropy: Having properties, as conductivity, speed of transmission of light, etc., that vary according to the direction in which they are measured.

A large rise in amplitude (signal to noise ratio of 4-5) was detected over the defect, as expected from damping considerations. Some polymer composites contained a metallized layer in the form of foil or mesh (for EMI and lightning protection purposes). These composites did not require the help of the aluminum tape in using EMATs. In a graphite epoxy panel with 0/90 lay-up of graphite fiber, also containing a copper mesh, azimuthal scans using a pair of EMATs showed the combined effects of the fiber tows at 0° and 90° and the direction of the copper wires at ±35°. In addition, it has been found that EMATs can also be applied directly to a graphite epoxy panel that contains a top ply of nickel-plated graphite fibers.