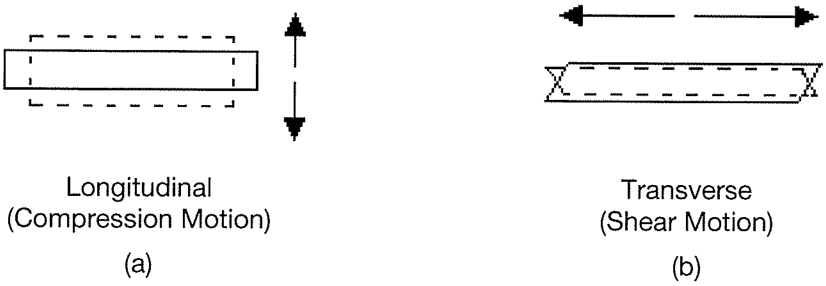


FIGURE 7-32 Elements.

high-temperature ultrasonic examinations, precautions are necessary so that the operational temperature does not approach the Curie temperature of the transducer. *Approximate* Curie temperatures of the more common element types are as noted in Table 7-2.

The primary advantage of polycrystalline ceramic transducers is their relative efficiency. With some of these materials, the efficiency can be as much as 60 to 70 times more efficient than their quartz equivalent.

Elements polarized as shown in Figure 7-32a will function with a "piston" type motion. The element "grows" taller and thinner, and as the voltage is removed from the element, it collapses and becomes "shorter and fatter." This motion continues until it has stopped ringing. This is analogous to striking a bell with a hammer just once. The bell rings and takes a while to stop ringing or oscillating. The transducer operates in much the same manner as the bell. A voltage from the pulser strikes it and it rings. This ringing has to be arrested or "damped" quickly. Superior resolution characteristics require that the transducer exhibit the minimum number of oscillations possible. If the oscillation is not damped, signals from reflectors that are relatively close together in a test piece will appear on the screen as one combined (reflector) signal instead of two separate signals. The ringing of the element has to be shortened in order to improve resolution of reflectors, whether they are close to the surface (near-surface resolution) or close together in time (spatial resolution). Refer to the example of the bell. If the bell is struck many times and in quick succession, it is difficult to establish the number of "strikes" on the bell. If a hand is placed on the bell while it is being struck, the vibrations are quickly damped after each strike. The number of times that the bell is struck may now be individually counted. This principle applies to the transducer. This quality is accomplished by placing "damping" or "backing" material onto the rear of the element, similar to placing a hand on the bell.

Transducer technology may vary between manufacturers, each having their own zealously guarded methods of damping transducers. The bond between the backing material and the element is of primary importance, as is the acoustic impedance match between the element and the backing material. Ideally, the transducer should have a short pulse length

TABLE 7-2 Approximate Curie Temperatures

Element type	Curie temperature, °C
Barium titenate	120
Lead zirconate titenate	190–350
Lead metaniobate	400
Quartz	575

and a high-energy output. These two features usually contradict each other (see Bandwidth). Return to the example of the bell. If there is a hand placed on the bell, it will not ring as loudly as when it is rung without the arresting hand. There is obviously a compromise between heavy damping and high-energy output. It boils down to a matter of selecting the right tool for the job to be done. Damping is accomplished by using a substance that is acoustically matched to the element material and that is also dense in structure. Usually, a tungsten and epoxy mixture is used. Another requirement of a damping material is that it attenuate the energy fast. It is extremely undesirable to have signals from energy bouncing around in the damping material. Designs of the backing material include the shaping of the backing and inclusion of scattered particles of reflective material that scatters the energy within the backing piece.

Regardless of the technique used, the transducer performance should match its useful purpose, that is, the introduction of ultrasonic energy into the part being examined. Applications that require the detection of reflectors that exist close together in the part being examined will require the use of a transducer that has a short pulse. It is preferable that the transducer is acoustically matched to its application. The transfer of energy from the transducer to the test piece or to the wedge material (in the case of angle beam units) has to be optimized (see Acoustic Impedance). The transducers used as "wedge drivers" should have a front "face," usually made from an epoxy, that has a good impedance match to the Plexiglas wedge to which it is attached. Transducers intended for use in direct contact applications such as conventional zero degree units, have front faces that are made from material that is acoustically close to the test piece, usually aluminum or steel. The material used for this application is generally aluminum oxide. Not only is the impedance match to the element and a steel or aluminum test piece reasonably good, but the material is also by nature extremely hard and therefore exceptionally wear resistant. It therefore goes without saying that the use of a wedge driver for a direct contact test is not recommended. Not only will the face wear very quickly, but from the acoustic standpoint the transfer of the energy will not be optimum.

The layer thickness of the facing material is extremely important. It should be equal to one-quarter wavelength in the facing material. This arrangement considerably enhances the emitted energy. See Figure 7-33, an example of single element transducer construction, and Figure 7-34 for examples of an angle beam unit. Note that the damping material is made at some angle so as to redirect the internal energy away from the element.

Piezocomposite Transducers

Primarily used in the medical field, the idea of piezocomposite transducers was considered as early as the mid-1970s. The technology necessary to manufacture this type of transducer was not readily available at that time and solutions to problems such as the facility for slicing the crystal accurately in a production mode were not possible at that time. Piezocomposite transducers function in a similar manner to regular ceramic transducers. The primary difference is that the piezocomposite ceramic is made up of small-sectioned pieces of ceramic material (PZT, PMN, etc.). See Figure 7-35.

Initially, the ceramic is sliced into squares. The small areas between the squares are filled with epoxy and the transducer is lapped to the required thickness, silvered, and polarized in a similar manner to the regular transducer elements. The difference to the user is in the performance. Because of the damping material (epoxy) around each square, the transducer exhibits superior bandwidth and therefore superior resolution. There is little or no need to apply a backing; therefore, the efficiency is greater than the conventional damped ceramic transducer. Because of the lack of backing, the height profile of these units can be reduced for accessibility to small areas. These transducers are particularly useful when testing grainy materials having increased signal-to-noise ratios.

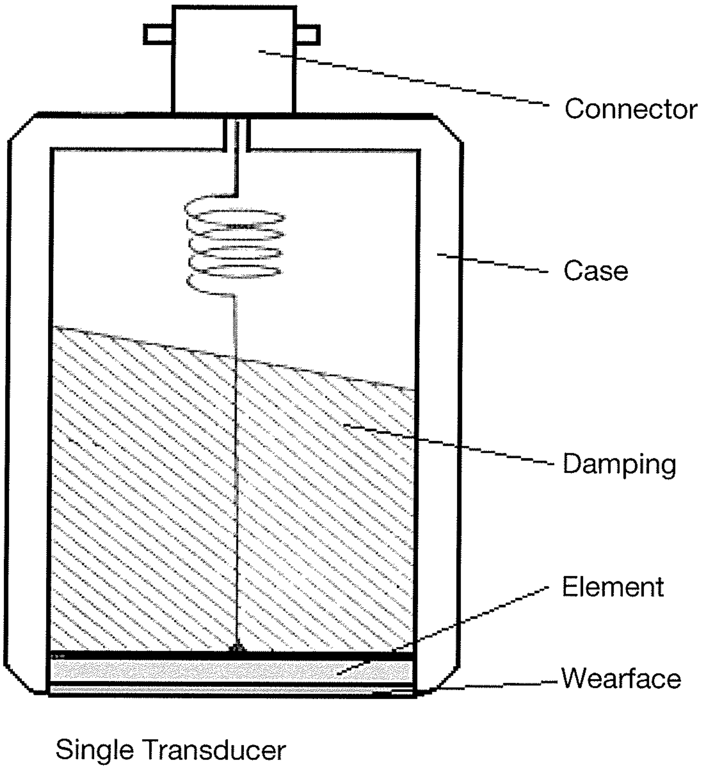


FIGURE 7-33 Single transducer.

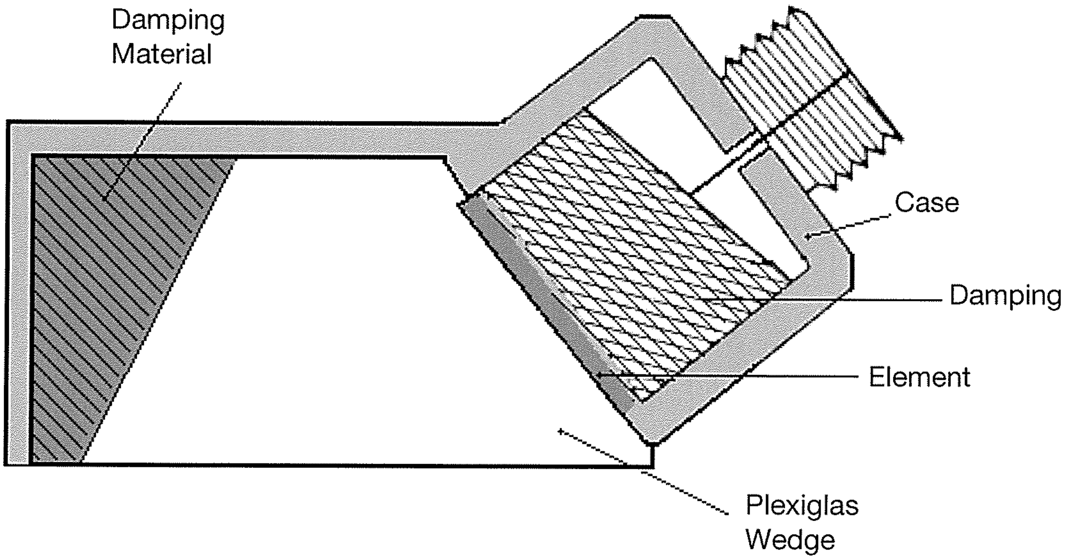


FIGURE 7-34 Angle beam transducer.

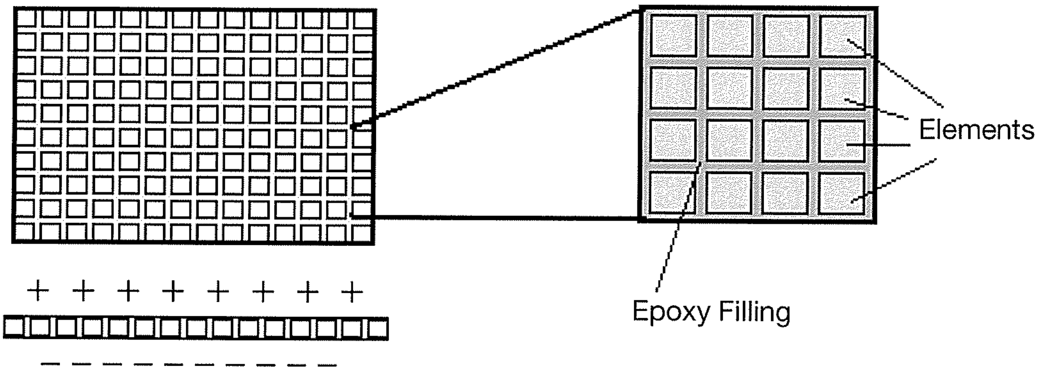


FIGURE 7-35 Piezo-composite element.

PVDF (Polyvinylidene Fluoride)

Ceramics are not the only materials that can produce the piezoelectric effect. Piezoelectric polymer sensors have been available in the nondestructive testing industry for some time. In the 1960s, it was discovered that whalebone exhibited a very weak piezoelectric effect. This inspired the search for other materials that could exhibit piezoelectric activity. Relatively high activity was found to exist in polarized polyvinylidene fluoride. The advantages of this material are:

1. PVDF has an acoustic impedance close to that of water, so that it allows efficient transfer of energy.
2. PVDF has a large frequency range and therefore a very broad bandwidth. Because of this, it exhibits very favorable spatial and near-surface resolution compared with conventional piezoelectric element material.
3. The PVDF material is flexible and can be shaped for beam focusing. It is therefore ideal for high-resolution immersion applications.

The disadvantages are:

1. PVDF is relatively low in power compared with conventional piezoelectric transducers and, in most cases, requires additional amplification.
2. It cannot be used in contact applications.

Noncontact Methods

EMAT (ElectroMagnetic Acoustic Transducer) (see Figure 7-36) technology is an alternative method of generating and receiving ultrasonic energy. These are transducers that are made up of coils that are placed in close proximity to the test piece. The coils produce a magnetic field that interacts with the metal, producing a deformation in the surface of the material. This deformation produces the wave of ultrasonic energy. The advantages of these units are:

1. There is no need for a couplant. An EMAT is a noncontact transducer.
2. They lend themselves to applications that normally have limitations, such as the examination of high-temperature components. Because this type of transducer depends on

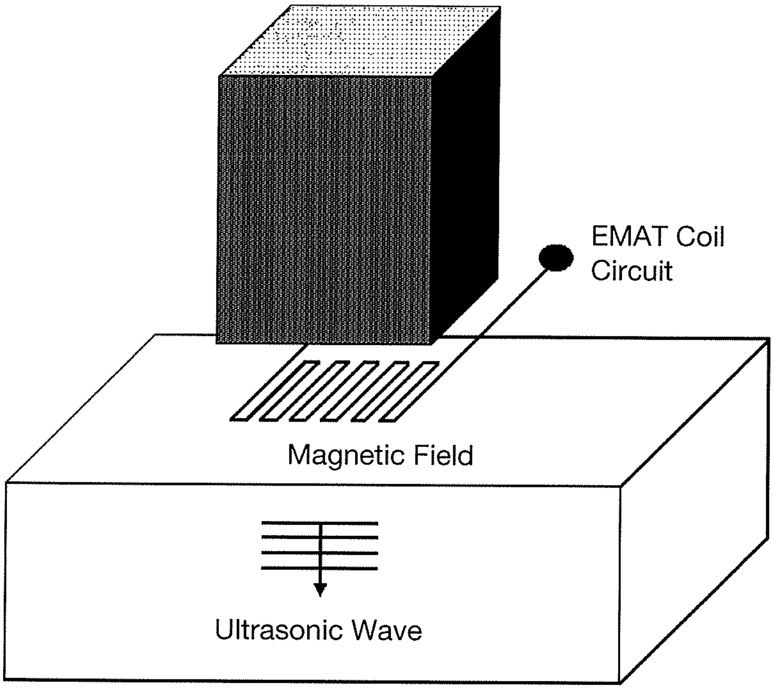


FIGURE 7-36 EMAT transducer.

the induction of a field, the transducer has to work in close proximity to the work surface. The strength of the magnetic field is reduced as the distance between the transducer and the component surface increases.

3. The gap between the transducer and the work face need not be composed of air. Examination of components that have been coated with some protective layer is possible. It is the front surface of the component material that actually generates the ultrasonic energy.
4. Focusing of the beam is also possible, as is steering the beam at various angles.
5. Horizontally polarized shear wave energy can be produced. The polarity is important in that horizontally polarized shear waves do not mode convert when striking surfaces that are parallel to the direction of polarization. This has certain advantages, particularly when examining austenitic welds and other materials with dendritic grain structure, e.g., certain cast stainless steels.

The disadvantages include:

1. Low efficiency compared with piezoelectric transducers.
2. Relatively large transducer size.
3. Producing ultrasonic energy in nonconductive material is only possible if a conductive layer is applied to the surface.

Laser-Generated Ultrasound

The use of laser technology for the generation of ultrasonic energy has been known since the latter part of the 1970s. Acoustic propagation is accomplished by briefly heating or "ablating" the surface of the test material. This brief heating of the surface causes the generation of thermal expansion on the surface of the material, which in turn results in the formation of a wave front that travels through the material. The technology generally employs two separate lasers for this application—one to ablate the surface and produce the wave, and a second (a laser interferometer) to detect the movement of the surface due to the disturbance from the reflected wave. The technology is commercially available and has been developed for (but not limited to) applications such as the inspection of composite materials in the aircraft industry. Reception of the energy is also possible with a conventional transducer coupled to the surface.

The advantages are:

1. When used with laser interferometry for reception, there is no need for couplant.
2. The laser can be located remote from the test surface (10 inches or more in certain instances).

Bandwidth

Transducer bandwidth can best be described in ultrasonic terms as the spectrum or range of frequencies that occur when pulsing the transducer. To make this more meaningful for comparison purposes, the bandwidth is measured within a given amplitude range. This is usually at either the –3 dB or –6 dB levels from maximum amplitude (see Figure 7-37).

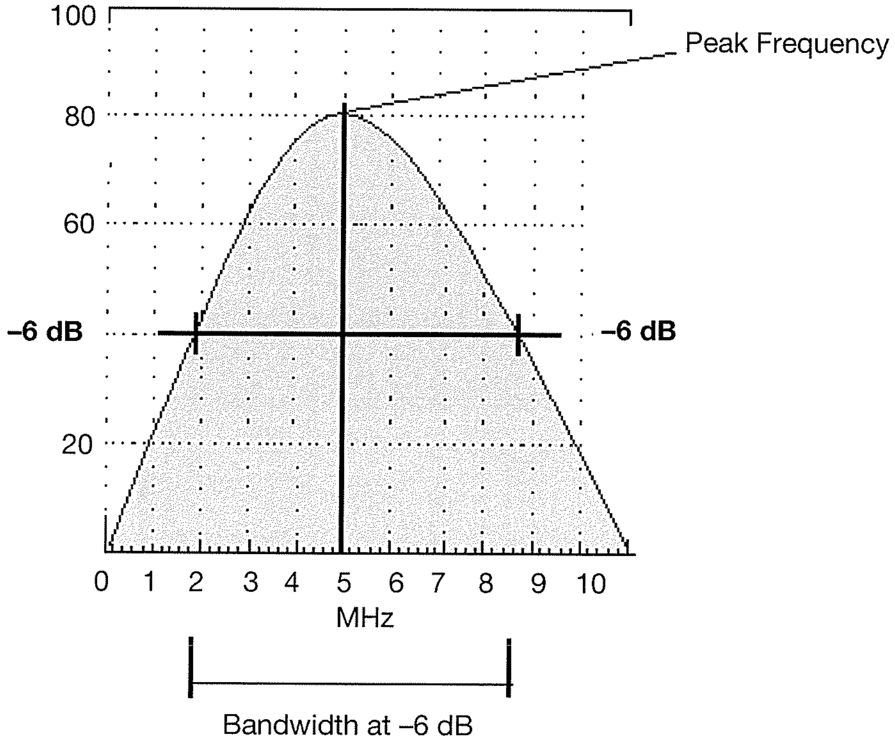


FIGURE 7-37 Spectrum.

This is a standard method of comparing the transducer's "quality factor" or "Q" that is varied by the mechanical damping placed on the element. The higher the Q, the greater the sensitivity. The lower the Q, the greater the resolution characteristics. A short-pulsed transducer provides a broader bandwidth but less energy, therefore a "low Q." See Figure 7-38.

Dual Transducers

Transducers that incorporate separate elements for transmission and reception of the ultrasonic energy are referred to as "dual" transducers. Designs vary, but a typical dual transducer construction is as shown in Figure 7-39. As can be seen, the elements are mounted on separate delay lines that are separated by an acoustically opaque (nontransmitting) material such as cork. The receiver element must not be able to receive energy directly from the transmitter element. In other words, they must not indulge in "cross-talk." The primary purpose of this type of transducer is to enhance the near-surface resolution capability of the ultrasonic system. The dual transducer can be designed to resolve reflectors that are very close to the scanning surface. To this end, they are designed with a certain "roof angle" or "squint angle." This produces energy in the test piece that is refracted in the direction of the receiver side of the transducer. It is obvious that the greater the roof angle, the better the resolution close to the scanning surface. It must be realized that the detection efficiency further out in the part will suffer. Again, it is a matter of selecting the correct transducer for the application. The dual transducer can be used in angle beam applications. In this case, the same advantages are present. The sound energy intersection area can be predetermined to enhance a specific area in the test piece or component under test. It is incorrect to refer to this type of transducer as a "focused" transducer, but the technique does limit the received reflected energy to the zone where the beam from the transmitter intersects the hypothetical area of the receiver beam. Note that there is no energy from the receiver; however, because the angle of incidence is equal to the angle of reflection, and because the receiver is "aimed" at the area of the transmitted beam, planar reflectors in the beam path will reflect

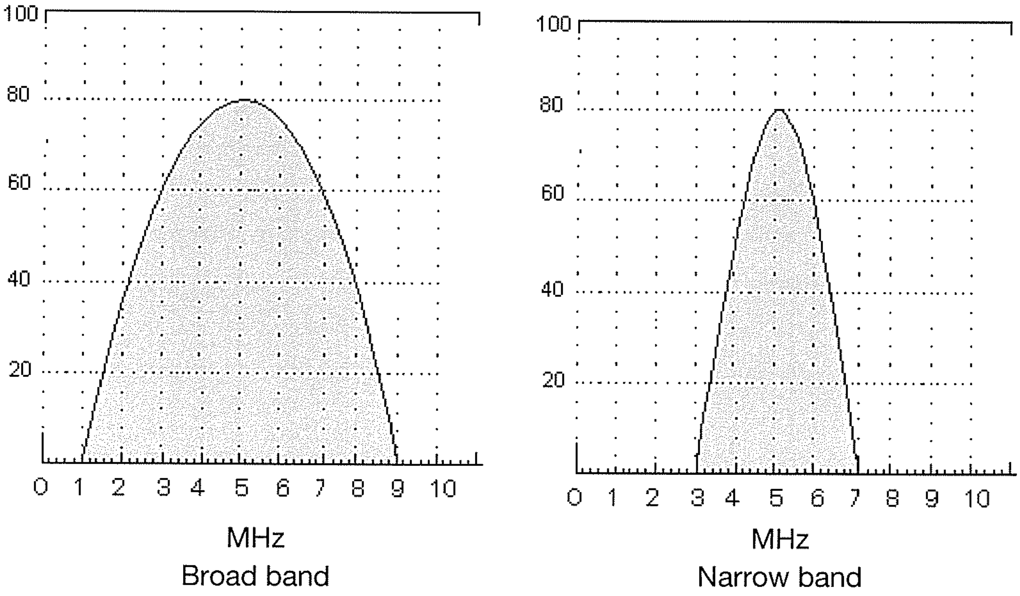


FIGURE 7-38 Bandwidth.

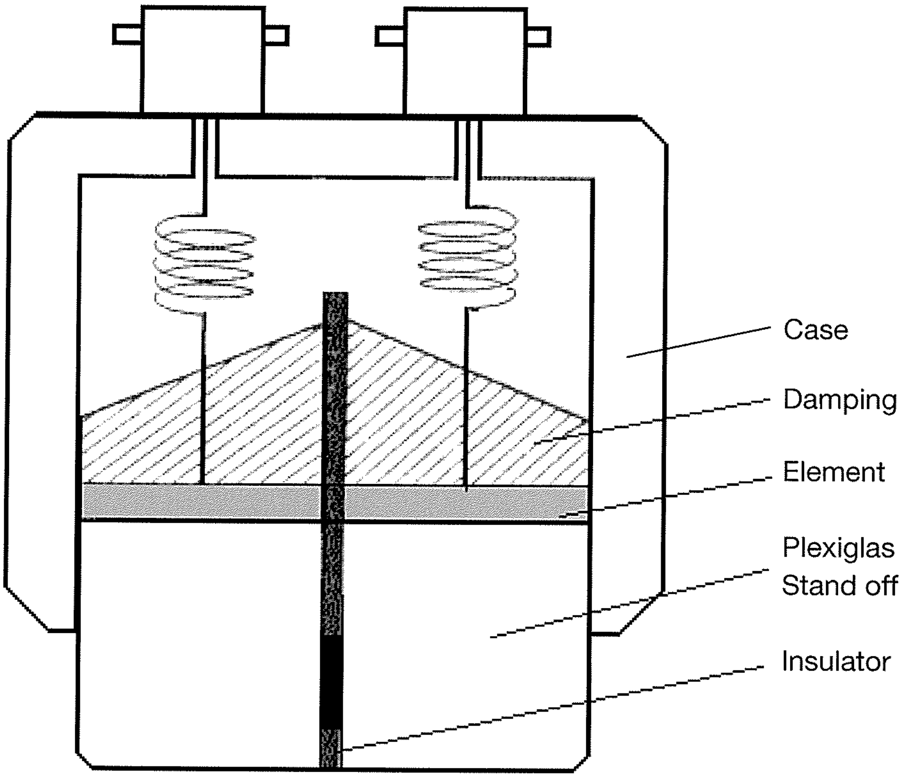


FIGURE 7-39 Dual transducer.

the energy towards the receiver. The energy that is detected by the receiver will be from the intersecting zone of the transmitter (see Figure 7-40).

Focused Transducers

The principles of optics apply to sonics. Focusing light is achieved with the use of lenses. Focusing sound energy is accomplished in a similar manner. Immersion testing, in particular, lends itself to the use of focused transducers (see Figure 7-41).

There are essentially three approaches that can be used to accomplish the task of focusing the beam:

1. Shaping the actual transducer element.
2. Attaching a concave lens to the transducer face.
3. Inserting a biconvex lens into the path of the sound energy, similar to focusing the light from the sun using a magnifying glass.

The sound energy can be focused so that it concentrates the energy at a particular depth or area within the test piece. This improves the detection of small reflectors at a predetermined depth. This is due to the small beam dimension at the focal point relative to the size of the reflector.

Contact angle beam transducer units that focus the energy have also been produced. This is accomplished by contouring the wedge under the transducer to a specific radius, dependent upon the desired focal length (see Figure 7-42). This radius is filled with a fluid having a velocity different from the wedge material, thus providing a lens to the ener-

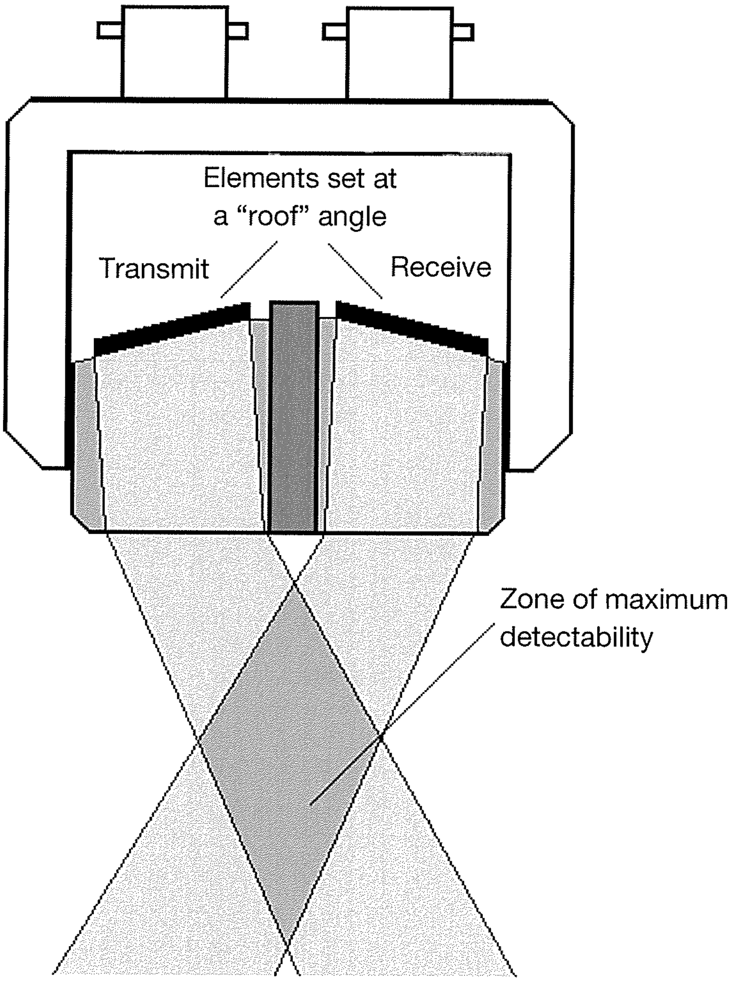


FIGURE 7-40 Angled dual transducer.

gy. This will produce a refracted (converging) beam in the wedge that refracts again to a focal point after entry into the test piece.

Phased Array Transducers

These transducers incorporate elements that are arranged in certain patterns for the purpose of dynamically focusing or steering the energy. Sequentially pulsing the elements, using a combination of elements in the array, and timing the pulses used to excite these elements, produces a beam focused at variable depths in the test material (see Figure 7-43). Multiple wave fronts are combined to form a beam of a particular shape. Element configurations can be circular or rectangular, depending on the desired beam shape and direction of energy propagation. Linear array units are more commonly used in the medical field for imaging than in the industrial sector.

Bubblers and Squirters

Immersion testing is not limited to placing the test material or component into a tank of water. An immersion test can be simulated by a device called a "bubbler" or a "squirter."

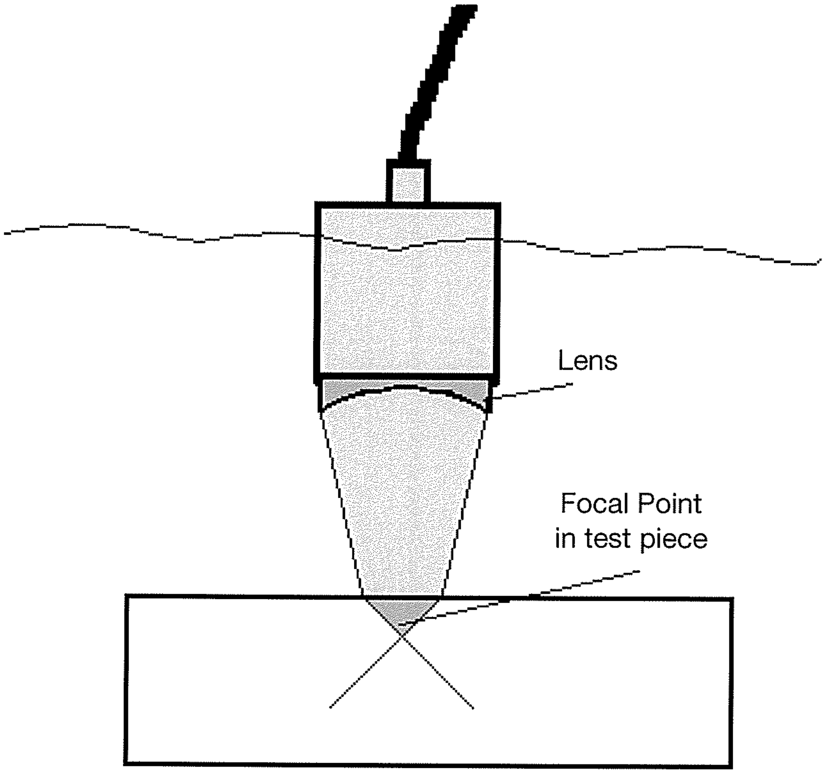


FIGURE 7-41 Focused transducer.

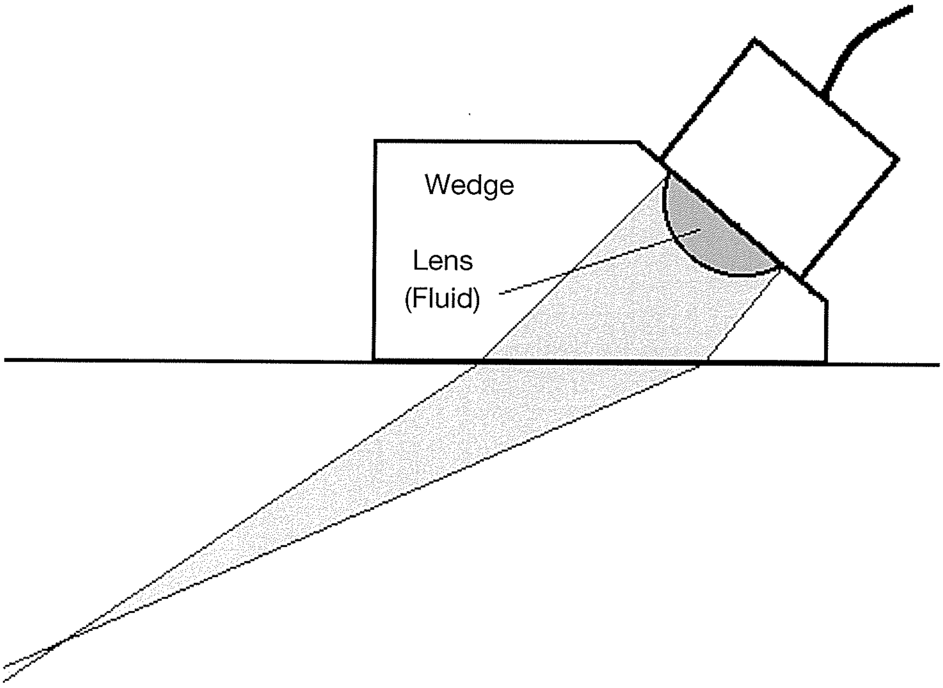


FIGURE 7-42 Focused wedge.

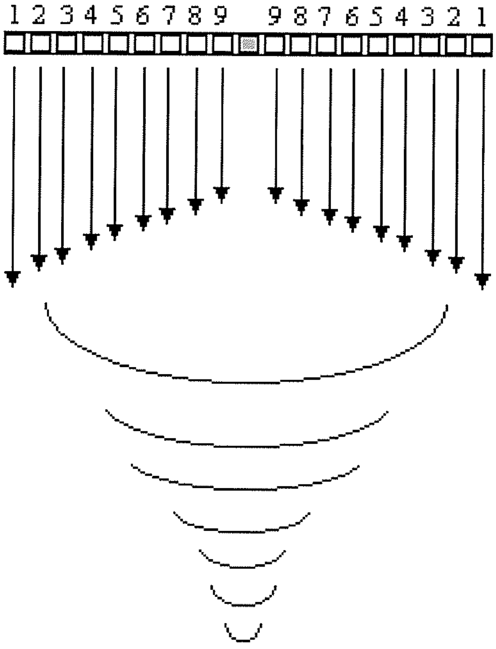


FIGURE 7-43 Phased array.

A bubbler is a device wherein the transducer is located within a housing that includes a fluid reservoir. The fluid is continuously pumped into the housing. The transducer is placed slightly above the level of the holder. When the unit is placed on the test surface, or more often, the test surface is placed over the unit, the housing fills with fluid and provides a film of couplant to the front of the transducer (see Figure 7-44).

A squirter (see Figure 7-45) comprises a holder with a nozzle. The transducer is located inside of this device and the smooth jet of water that exits the nozzle carries the sound energy to the surface of the test component. This device is generally incorporated into automated test systems such as those for production line inspection of pipe, or inspection of aircraft components where immersion of the component is impractical. Through-transmission techniques are best suited for the squirter. In the pulse-echo mode, extraneous signals may appear at the surface of the test component due to the water striking the surface of the test part. The size of the ultrasonic beam can be controlled by varying the size of the nozzle orifice. (Note that the example in Figure 7-45 does not have a smooth water jet.)

Wheel Transducers

Immersion testing is found in many forms. The wheel transducer is another variation. Transducer(s) are located in a holder(s) within a sealed wheel that has been filled with fluid. The fluid can be water, thin oil, or other suitable materials. The transducers can be placed at strategic angles within the wheel so as to provide the desired refracted test angles. This device is very useful for examination of moving components where surface couplant is to be limited. They are commonly used in the railroad industry to test carriage wheels and railroad track on the fly. The wheels usually require a fine spray of water to couple the tire to the test component. There are special wheel transducers that do not need couplant on the tire surface (dry coupled). The wheel tire material can be made so that it is virtually invisible to the ultrasound by matching the tire characteristics to the fluid in the wheel.

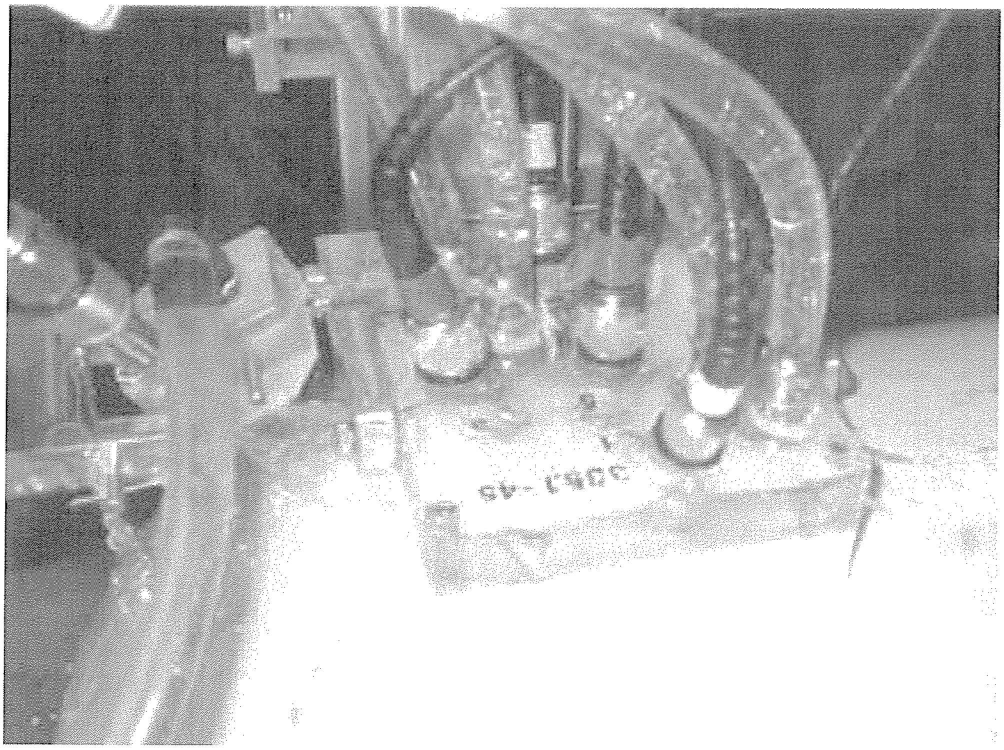


FIGURE 7-44 Bubbler. (Courtesy of Matec Instruments.)

Transducer Problems

As mentioned previously, the ultrasonic test begins with the transducer. It is therefore of utmost importance that the transducer is performing as required. Problems with the transducer need to be identified prior to any test. It is advisable to document the performance of each transducer when purchased so that its performance can be monitored during its lifetime. Items such as pulse width, amplitude, and angle (if appropriate) should be quantified. Photographs of the spectrum and wave-form should be acquired. These parameters should be checked on a regular basis and the performance verified. It is advisable to verify the parameters on the same system each time it is used. Variables such as pulsers, receivers, and cables, can exhibit anomalies that may be erroneously attributed to the transducer alone. Possibilities of changes in performance include, but are not limited to:

1. Pulse length. This can increase for the following reasons:
   a) The backing or damping material becomes detached from the transducer.
   b) The wear face becomes detached from the transducer.
   c) The element or wear-face is cracked.
   d) The tuning coil is detached.
2. Low sensitivity. This can occur for a number of reasons such as, but not limited to:
   a) Deterioration of or damage to the transducer element material.
   b) Detachment of the transducer face.
   c) Detachment of the tuning coil.
3. Beam skew (apparent) due to partial detachment of the transducer face.

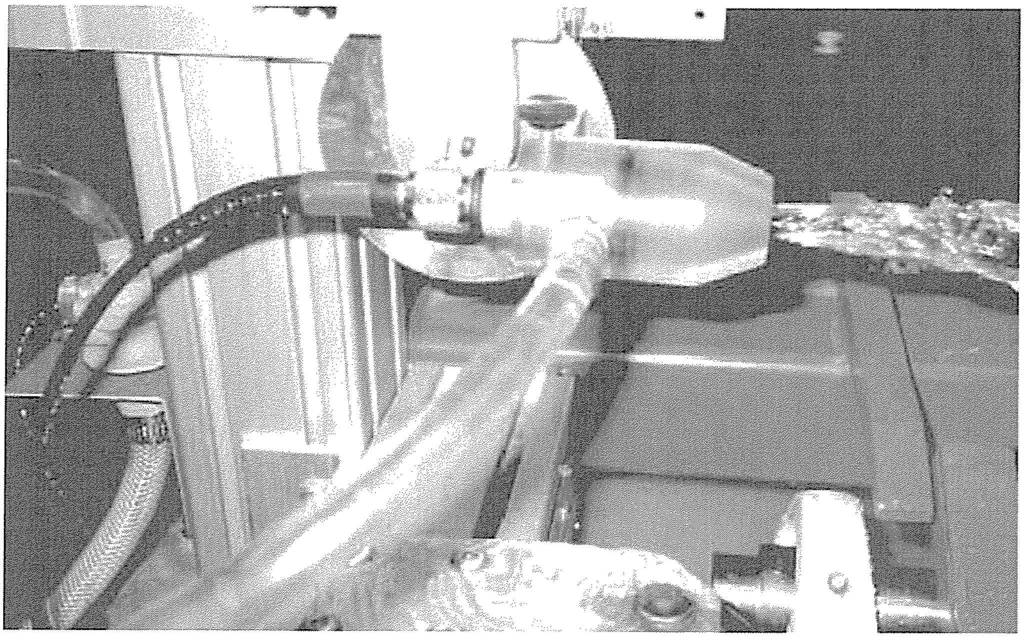


FIGURE 7-45 Squirter. (Courtesy of Matec Instruments.)

4. Faulty connections. Damaged or loose wires in the transducer housing.
5. In the case of angle beam transducers, wearing down of the Plexiglas wedge may cause the refracted angle to change.

In conclusion, the transducer is a precision component in the ultrasonic system. Treated with due care, it will provide many years of service.

IV. TECHNIQUES

The ways in which sound waves propagate through materials and are attenuated, reflected, or transmitted dictate the different ultrasonic methods or techniques used to detect the many types of discontinuities that can exist in materials. These techniques fall into two main categories, one called "pulse-echo," and the other called "through-transmission." Any of the techniques that may be used requires *calibration* of the ultrasonic system so that the time base can have some meaning in terms of material thickness. This is also true for through-transmission techniques where depth information is not available, since the practitioner needs to be sure that an adequate time base is available to show the transmitted energy.

Calibration Techniques

The process of calibration needs to be just as disciplined as the inspection technique. In fact, the whole inspection relies on the calibration process. Some of the following calibration techniques are concerned with measuring and documenting the characteristics of the transducer and flaw detector.

Transducer Characteristics

Compression Wave Transducers

Resolution. The ultrasonic pulse consists of a few cycles of sound energy at the test frequency. Therefore, the pulse occupies some space in time, or distance, within the material. The amount of space occupied is called the "pulse width." Physically, it is the number of cycles in the pulse multiplied by the wavelength of that frequency in the test material, or, mathematically:

$$W = n \times \lambda$$

Where
n = The number of cycles in the pulse
λ = Wavelength

Pulse width is important because while one pulse is being processed, another closely following pulse cannot be properly processed. This means that two reflectors that only have a small separation in depth will only show as a single, messy signal on the trace. Because the two signals overlap, the time difference between them cannot be measured. The ability of an ultrasonic system to discriminate between two reflectors that are close together is called "resolution."

Resolution for a given transducer can be determined in one of several ways:

1. By calculation of the pulse width and expressing that in terms of distance occupied in the test material. For example, the wavelength of a 5 MHz compression wave in steel is 0.047″ (1.192 mm). If the transducer in question has two-and-a-half cycles in the pulse, then the pulse width for the transducer is 0.047″ × 2.5, which comes to 0.117″ (2.98 mm). Signals from surfaces closer together than this will begin to merge.
2. By measuring the pulse width on the calibrated trace. If the timebase has been calibrated for the test material, any signal positioned clear of any other can be used to measure pulse width. Figure 7-46 shows a trace calibrated to 25 mm full scale. The signal in the middle of the trace starts at 11 mm and ends at 14 mm. The pulse width is 14 – 11 = 3 mm.
3. By checking the resolution on a suitable calibration block. Such a block is the IIW V1 block, described in the "Calibration Blocks" section. The transducer is placed as shown in Figure 7-47, opposite the machined slot.

If the transducer is capable of resolving the distances, three distinct signals should be shown on the trace (see Figure 7-48). The block has been designed so that the distance between the first and second reflecting surfaces is 1 μsec at steel velocity. For the round trip, the time difference between the first and second signals is 2 μsec. A disadvantage of the resolution check that can be performed on the IIW V1 block is that it is confined to straight beam transducers. An alternative approach is illustrated in Figure 7-49, which shows a pair of holes drilled on a common axis from opposite sides of the block. The two holes are of different diameters and meet in the center of the block. A sound beam, at any angle, aimed at the region where the two holes meet, will reflect from both holes. If the two echoes are resolved on the trace, the transducer can be said to have sufficient resolution for that spacing. If the holes are 0.5″ (12 mm) and 0.25″ (6 mm) in diameter, respectively, the time difference between the two is equivalent to 0.125″ (3 mm). The advantage of this approach is that it is applicable to both straight beam and angle beam transducers.

Dead Zone—Initial Pulse (Main Bang). When using single crystal transducers, the initial pulse and ringing of the crystal are connected to the receiver circuit and displayed

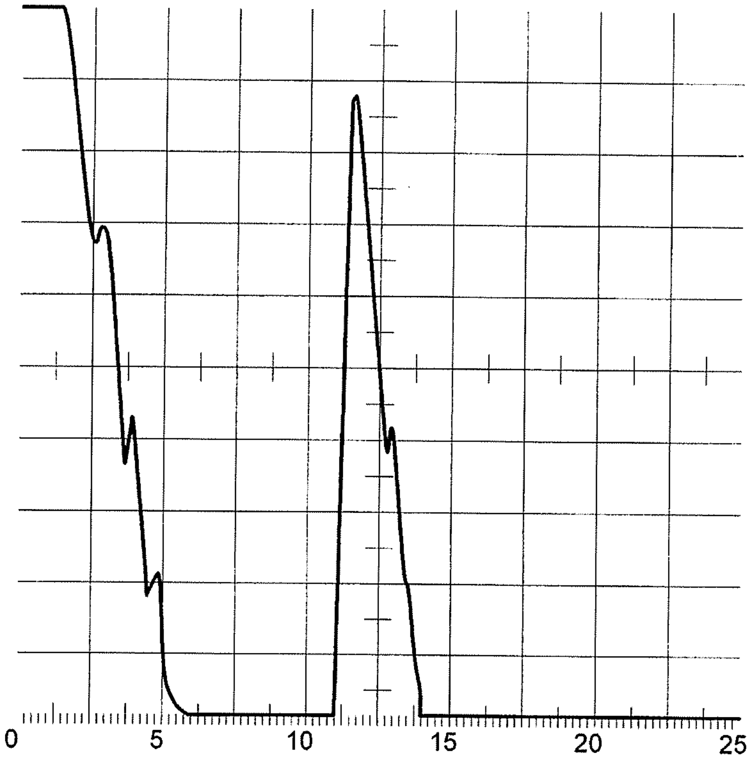


FIGURE 7-46 A-scan 3.

on the timebase. This signal occupies the early part of the trace, and indicates the "dead zone" in the material. While the crystal is transmitting, the trace cannot display received signals clearly in this region. For this reason, it is usual to use dual crystal transducers for components less than 0.5″ (12.5 mm) in thickness. The dead zone can be measured on a calibrated time base by noting the point at which the initial pulse dies away. It should be remembered that the initial pulse, and hence the dead zone, will increase as the gain is increased. So it is necessary to measure the dead zone at the working gain for the inspection.

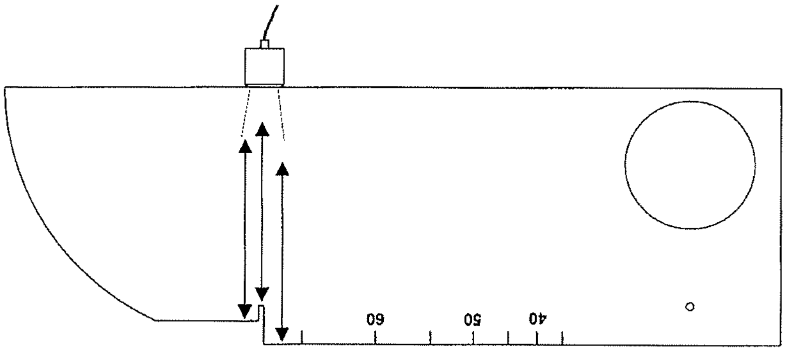


FIGURE 7-47 Resolution on IIW block.

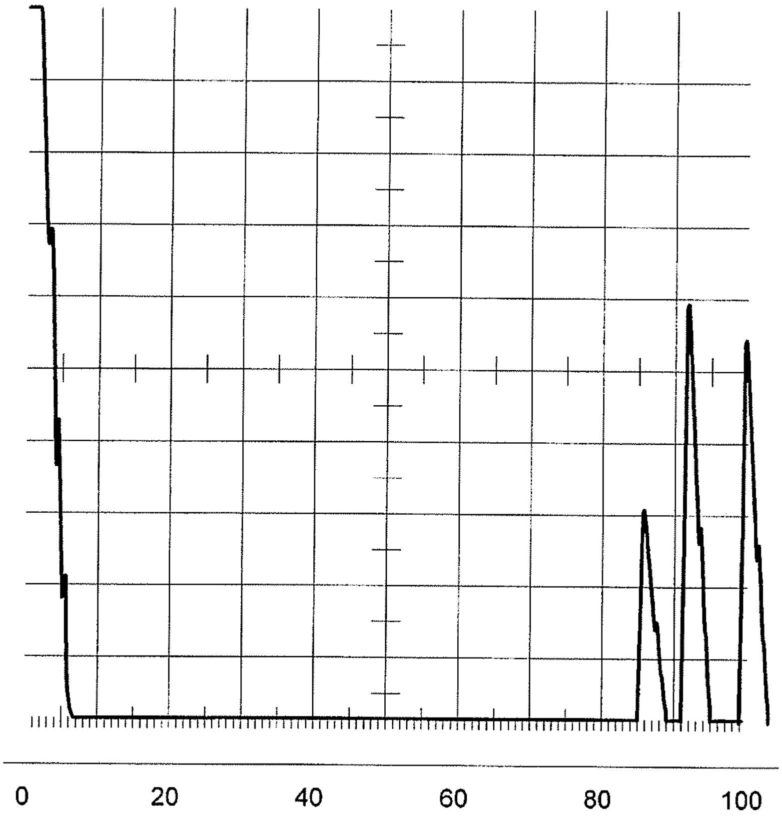


FIGURE 7-48 A-scan resolution.

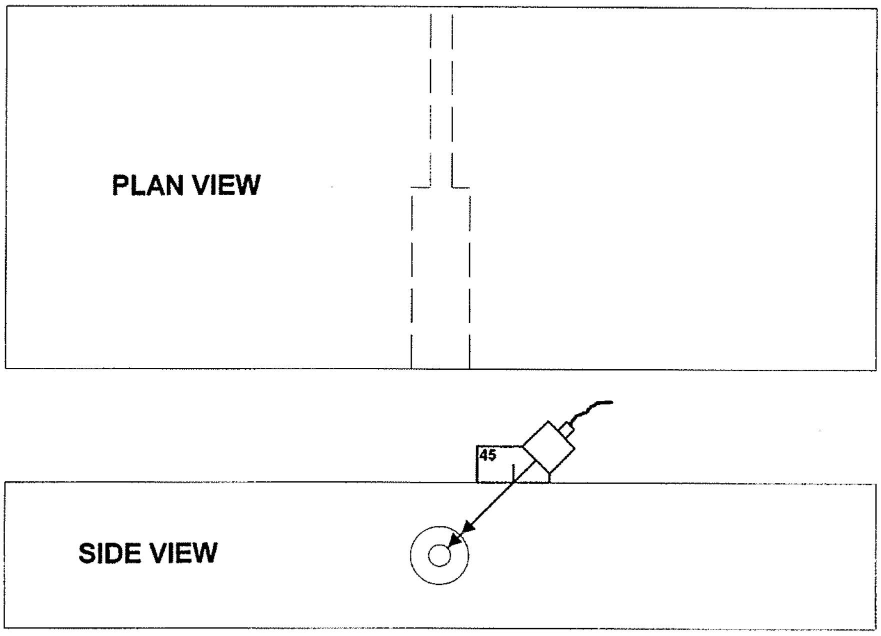


FIGURE 7-49 Angle beam resolution.

Angle Beam Shear Wave Transducers

Probe Index (Exit Point). With angle beam transducers for contact scanning, the crystal is mounted on a Plexiglas incidence wedge in order to generate the desired refracted angle in the component. The center of the sound beam emerges from the wedge at a position called the "probe index" or "beam exit point." This position is engraved on the side of the transducer wedge and is the position from which horizontal distance (HD) is measured. With use, the wedge may become worn and the actual exit point can move. The new probe index must be measured and marked if accuracy is to be preserved.

The IIW V1 block allows several angle beam calibration checks to be carried out. One of these checks is to determine the true probe index. Figure 7-50 shows a 45° shear wave angle beam transducer positioned on the IIW—V1 block so that the beam center is aimed at the 100 mm radius. The intersection of the narrow slot with the scanning surface marks the center of the 100 mm radius. As the transducer is moved forward or back past the slot, the echo from the 100 mm radius will be seen to rise and fall. When it reaches maximum amplitude, the beam center is aligned with the radius center, and is perpendicular to the tangent to the radius. The slot marking the center of the radius is now aligned with the true probe index. If this differs from the marked index, a new probe index must be marked on the wedge or the discrepancy measured and recorded so that allowance can be made during subsequent operations.

Beam Angle. The beam angle of an angle beam transducer can be measured on the V1 block once the true probe index has been established. The large Plexiglas-filled hole in the V1 block provides the target for beam angle measurement. From the center of this hole, angles have been projected to the edges of the block and the intersection engraved with the angle every five degrees from 35° to 70°.

When an angle beam transducer is scanned toward the hole, as shown in Figure 7-51, the signal maximizes when the beam is aiming straight at the center of the hole. As this occurs, the probe index is aligned with the true beam angle mark on the edge of the block. The actual beam angle should be checked against the nominal angle; any variation must be noted and the actual angle should be used when conducting discontinuity plotting and sizing techniques.

Beam Spread Diagram. Some discontinuity sizing techniques make use of beam spread diagrams to identify the edges of a discontinuity. For this, a practical beam spread diagram must be drawn for the probe being used. To obtain an accurate beam spread diagram, the following information is required:

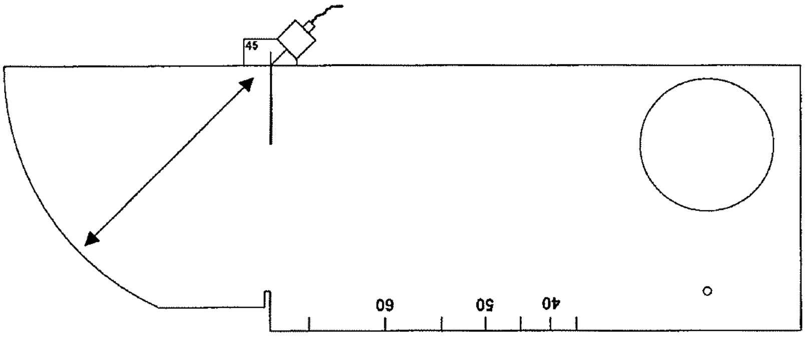


FIGURE 7-50 Angle beam on IIW block.

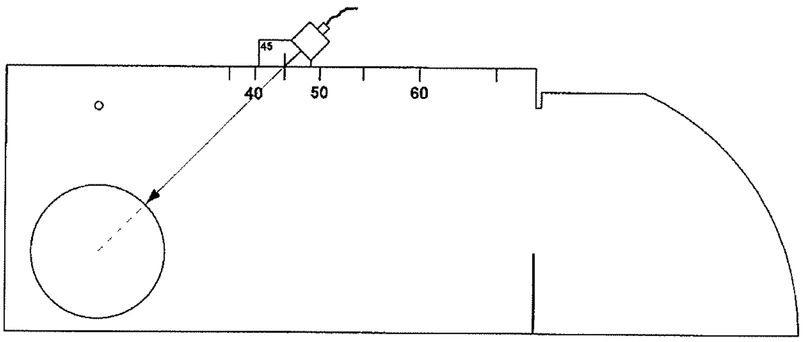


FIGURE 7-51 Angle Beam on IIW block 2.

1. Beam angle of the probe in question
2. The beam limits to be used (–6 dB or –20 dB)
3. The exact probe index (exit point) for the probe in question

Beam angle and probe index are defined in Calibration Techniques above. The choice of 20 dB drop, or 6 dB drop will be dictated by the relevant inspection code or standard. Once the above information has been obtained, the next step is to prepare the plotting aid shown in Figure 7-52.

The card shown in Figure 7-52 has a horizontal scale representing the horizontal distance along the scanning surface from the probe index to a reference mark (the center line of a weld, for instance). The vertical scale represents the thickness of the component. From the intersection of these two scales, the beam path scale is drawn in at the measured beam angle for the probe (not the nominal angle marked on the probe).

The next step is to measure the beam spread at various depths so that a beam spread diagram can be constructed. This is done using a beam calibration block such as the IOW block (see Calibration Blocks). These blocks contain a series of side drilled holes 1/16″ (1.5 mm) diameter and at various depths below the surfaces of the block. On the card shown in Figure 7-53, lines are drawn parallel to the horizontal scale at the depths of the holes that are to be used for the beam spread diagram. It is only necessary to plot the beam spread to the maximum range that will be used on the time base. In specimen thick-

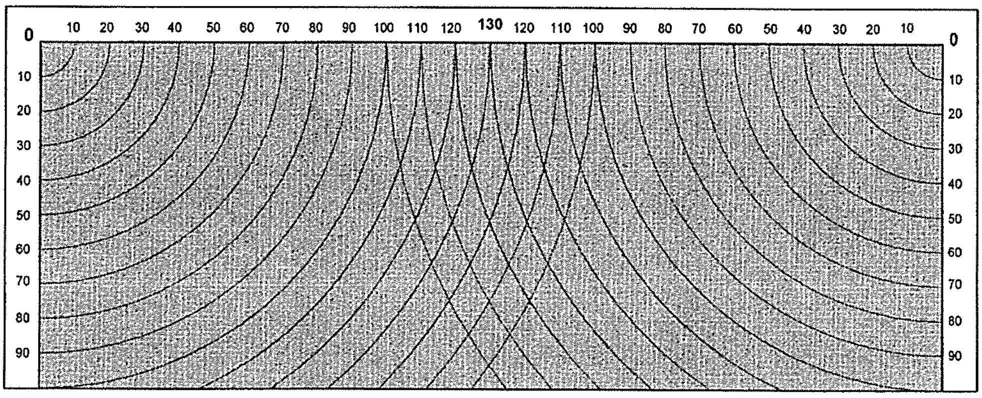


FIGURE 7-52 Plot card.

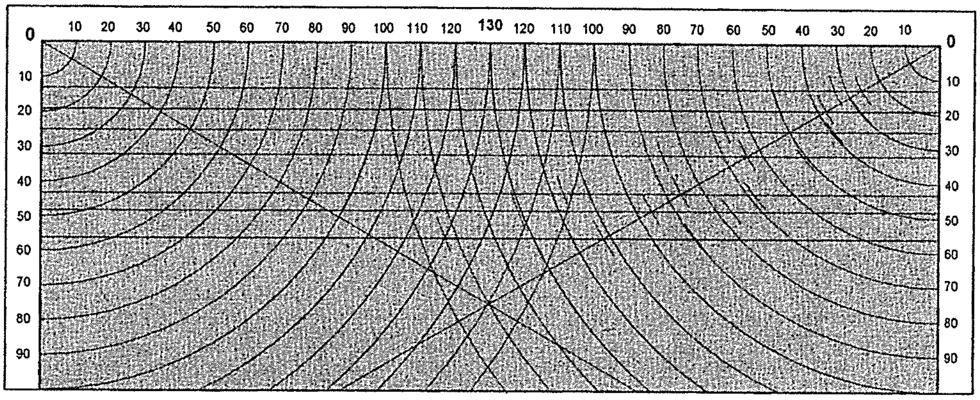


FIGURE 7-53 Plot card.

ness terms, this should be at least twice specimen thickness if discontinuities at full skip distance are to be plotted.

If, for example, the component being tested is 25 mm thick, then parallel lines would be drawn at IOW block hole depths of 13, 19, 25, 32, 43, 48, and 56 mm, as shown in the diagram. Each of the holes would then be scanned from the appropriate surface. The echo from the hole is maximized by moving the probe along the scanning surface, as shown in Figure 7-54. When the signal reaches its maximum amplitude, the beam center is pointing at the center of the hole. The signal height is then adjusted to a convenient value, usually 80% of full screen.

The gain setting in dB is noted and the gain reduced by the appropriate intensity drop (–6 dB or –20 dB). The new signal height is noted and marked on the screen with a wax pencil before returning the signal to the original (80%) height. The beam path length is

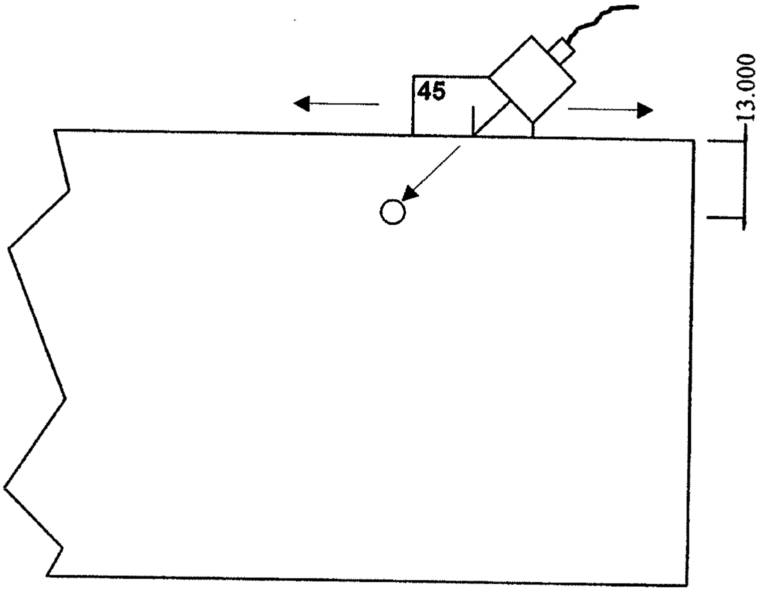


FIGURE 7-54 Depth hole.

taken from the time base and recorded in a table for that depth of hole and beam center position.

The transducer is then scanned forward until the signal amplitude has decreased to the wax pencil line (i.e., by the required intensity drop). The time base range is again noted and recorded as the beam *back-edge* position.

The last step is to move the transducer back to locate the maximum amplitude and then scan back until the signal again reaches the wax pencil line. Note this time base range and record it as the beam *front-edge* position.

The three recorded time base ranges are then transferred to the plotting card by drawing arcs centered on the card zero. The arcs cut the parallel line for the hole depth in question and the beam center arc also cuts the beam path scale. These arcs are shown in Figure 7-53. The above steps are repeated for each of the seven holes to be used in the beam spread diagram. Once all the arcs have been plotted, the edges of the beam can be drawn as shown in Figure 7-55 and the beam spread diagram is complete.

System Checks and Calibrations

The techniques discussed so far have concentrated on the transducer, but in the overall preparation for an inspection, the combination of transducer and instrument must be addressed. Many of the checks rely on the practitioner being certain of the position of a signal with respect to the transducer or scan surface, which, in turn, relies on time base calibration.

Time Base Calibration—Compression Waves

Time base calibration is concerned with establishing a known depth scale across the trace for the material to be inspected. This requires a calibration block made of the same material as the intended work piece. The IIW V1 block is a calibration block for steel. It has reflecting surfaces that allow direct calibration of the time base for 25, 50, 100, and 200 mm. By using multiples of those values, other timebase ranges can be established (see Calibration Blocks).

The objective for the time base calibration is that "zero" on the trace represents the scanning surface and "full scale" represents a known depth or thickness. Between zero and full scale, the graticule should represent a linear change of depth. There is a major problem facing the practitioner, because the point on the trace that represents entry of the

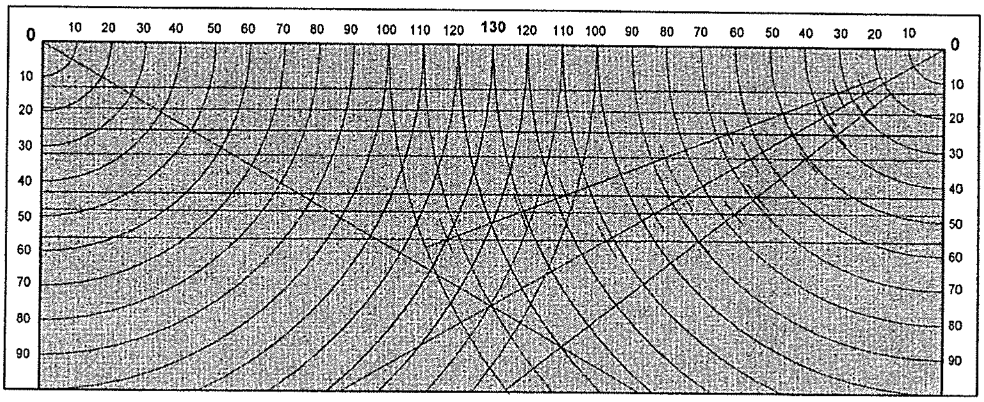


FIGURE 7-55 Plot card.

beam into the surface is not obvious. In the case of a single crystal transducer, sound starts as the applied pulse voltage is released. The start point is therefore somewhere in the "initial pulse," where the signal is saturated.

Of course, the calibration block is of known thickness, so all that needs to be done is to identify the first echo from that thickness on the block and position it at "full scale," right? Wrong! The zero has to be correct too, or the time base will be a little too long or too short. Somehow, there has to be a pattern display with two signals that are exactly a known distance apart, and whose start points can be identified.

When looking at a multiple echo pattern as sound bounces up and down inside the material, the one certain fact is that between one back wall reflection and the next, the sound has traveled through the specimen thickness. So, for instance, the space from the beginning of the first back reflection to the beginning of the second (first multiple of the back reflection) is directly related to the wall thickness. Figure 7-56 shows a single crystal

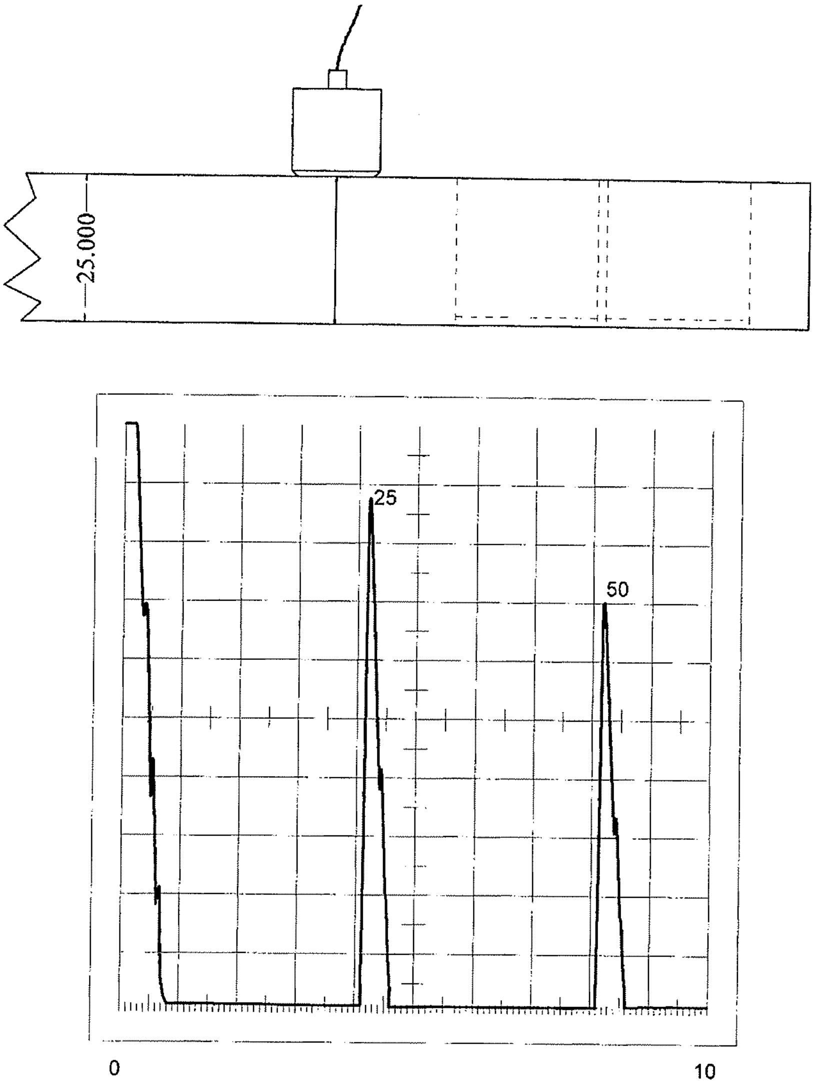


FIGURE 7-56 Repeat signals.

transducer positioned on the V1 block for the 25 mm range. To the left of the trace (time base) is the initial pulse and to the right are the back reflection and first multiple signals. The two signals are spaced apart by one round trip in the block.

To exploit this known distance, the left-hand edge of the first back reflection is moved using the "delay" control until it coincides with "zero" on the graticule. Then, using the "depth" or "range" control, the left-hand edge of the first multiple back-reflection signal is moved to coincide with "10" on the graticule. The position of the first back-reflection signal is checked and adjusted, using the "delay" control if necessary, and the first multiple signal checked and adjusted using the "depth" control. These adjustments are made until the left-hand edges of the two signals are correctly aligned with the graticule, as shown in Figure 7-57.

At this stage, the time base is calibrated for a range of 25 mm, but zero is 25 mm, and ten is 50 mm (i.e., the back reflection and first multiple echoes). The requirement was that zero means scanning surface (0 mm). However, all is not lost! Lock the depth control, then use delay to place the first back reflection echo at 10, and the job is done! Zero is now 0 mm and 10 is 25 mm.

The above technique, using delay and depth (range) controls to adjust the back reflection and first multiple echoes to fit the graticule, can be used for any of the direct ranges on the V1 block. Because there is a delay due to the Plexiglas column, and because the

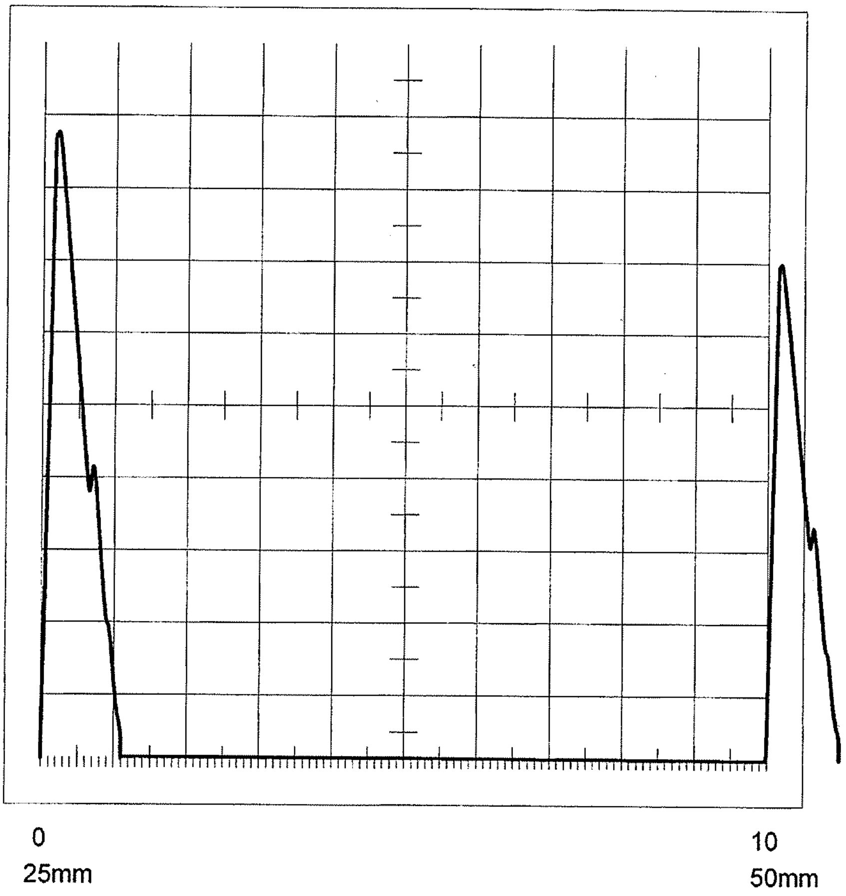


FIGURE 7-57 Signal from 50 mm.

transmitter is separated from the receiver, there is no way in which the beam entry point can be identified with a dual crystal transducer. The only way to calibrate is to use the above procedure.

Time Base Calibration—Shear Wave Transducers

Calibration of the timebase for a known time base range is also necessary in most angle beam inspections. This calibration can be carried out on the V1 block for 100 mm beam path range, and on the DIN 54 122 (*V*2) block for 25 mm and 50 mm. The procedure is similar to the one described above (see Figures 7-58 and 7-59).

The narrow slot that marks the center of the 100 mm radius also serves another purpose. It makes a corner reflector at the scanning surface to enable the first return echo to reflect back to the radius to give a multiple echo pattern. The calibration of the time base can therefore be set from the first back echo to the second. This is achieved by using the delay control to bring the first back echo to zero on the time base. The range control is then used to position the second back echo to 10 on the time base. The time base now represents 100 mm of the material, but is set from 100–200 mm. To correct this setting to read 0–100 mm, the delay control is used by adjusting the control until the first back echo is at 10.

Calibration of Amplifier (Test Sensitivity)

Just as it was necessary to calibrate the time base in order to correctly position reflectors, so it is necessary to calibrate the amplifier to a known amount of gain. This is necessary to make sure that enough gain is used to detect critical discontinuities, that the gain is not so high that spurious indications appear, and to ensure repeatability between inspections.

The simplest form of setting gain is to choose a known target in a calibration block, and use the gain to set the amplitude of the echo from the target to a predetermined height. The target could be the back wall, a side-drilled hole, a flat-bottomed hole (FBH) in the calibration block, or even a keyway or oilway in the component itself. The

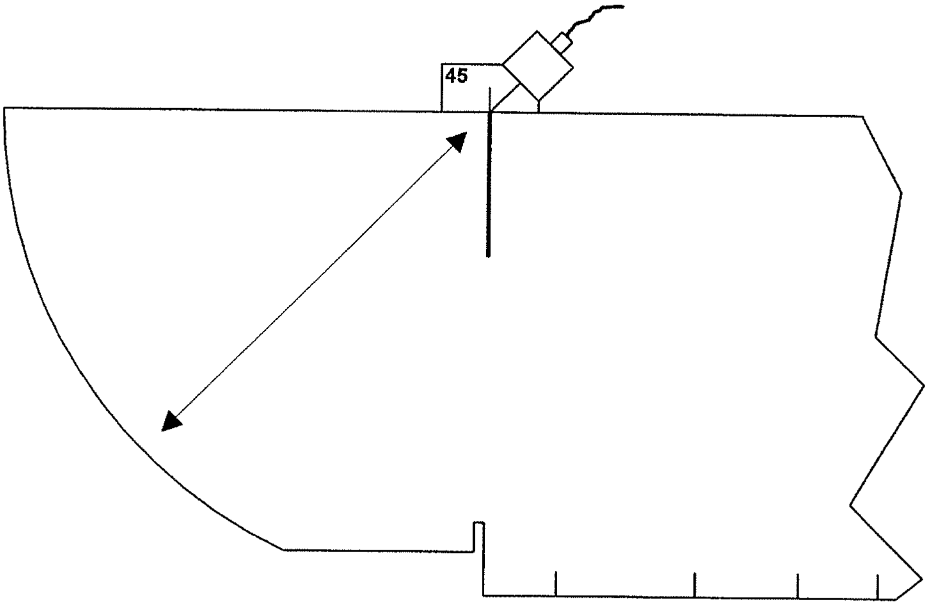


FIGURE 7-58 IIW radius.

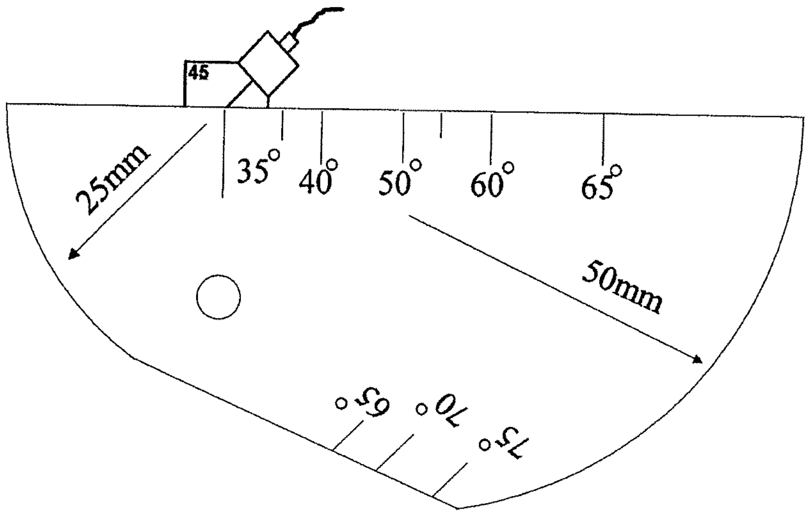


FIGURE 7-59 V2 block.

main objective is that the actual target used is documented so that anyone can repeat the test.

Distance and Area Amplitude Blocks

Since the amplitude of an echo can be a function of the area and depth of the reflector, targets of known area and depth can be used to set test sensitivity. There are calibration blocks that are designed to perform this function. Essentially, flat-bottomed holes are used as targets. They range in size from 1/64″ (0.4 mm) to 8/64″ (3.2 mm) diameter in 1/64″ steps. Sets of blocks in those sizes are available in a range of scanning depths.

Sensitivity is set by selecting an appropriate FBH size and scanning depth in a block of the same material as the component to be tested. The transducer is placed on the block and scanned to obtain the maximum echo amplitude from the FBH. The gain is adjusted to bring this echo to a predetermined height. This is known as "reference sensitivity" or "reference gain." Reporting levels are generally compared to this signal amplitude.

Gain as a Function of Beam Path Distance

In the Section II, it was shown that the intensity of sound energy decreases with distance along the beam due to attenuation. This means that simple signal amplitude references, like those just described, do not apply the same sensitivity across the entire time base. There are however, techniques to overcome this problem.

Distance Amplitude Correction (DAC)

Imagine listening to the radio while sitting close to the speaker. If the distance from the speaker to the ear increases, the volume will decrease relative to the distance from the speaker to the ear. This is because the sound is being attenuated in the air. If it were necessary to hear the sound at the same level, regardless of the distance from the ear to the speaker, a remote volume control could be used and the volume (amplitude) could be gradually increased relative to the distance from the source. This would enable the sound from the speaker to be heard at the same level when near the speaker or far away (this is distance amplitude correction). By electronically maintaining the same signal amplitude to the ear as the distance from the speaker is increased or decreased, the volume to the ear has remained the same.

As in the above scenario, when the distance between the transducer and a reflector increases, the amount of energy reaching and returning from the reflector to the transducer decreases. This principle is made apparent by observing the amplitude of the reflected signal from a given size reflector placed at different distances from the transducer. The apparent amount of signal reduction will be dependent on, but not limited to, such factors as material attenuation, transducer frequency, and transducer size.

Ultrasonic systems can include circuitry that electronically increases the gain according to the distance of the reflector, taking into consideration the amount of attenuation in the test material and the other factors mentioned above. This is also known as "swept gain." It is effectively a controlled increase in gain along the time base (sweep). For example, a signal from a ¼″ diameter flat reflector placed at a depth of one inch with its signal amplitude set at 80% can now electronically appear at the same amplitude on the time base if the reflector was at perhaps two, four, five, ten, or more inches, away from the transducer. This type of presentation is necessary when factors such as attenuation affect gating conditions in automated test systems. The variable of material attenuation is reduced or eliminated in this way.

A curve can also be plotted to graphically express the reduction in sound energy as it moves through the test material. This is known as a "DAC" curve see Figure 7-60. Certain specifications require that a DAC curve be generated for a specific examination. This is sometimes needed to determine an acceptance or rejection level based on the amount of energy that is returned to the transducer by a reflector (see note below). In this instance, a DAC curve is generated by observing and noting the amplitudes of signals from known sized reflectors, e.g., flat bottomed holes or side drilled holes at various depths in the test piece. The signal amplitudes are plotted on the screen as the reflectors are interrogated at the varying distances (depths) from the transducer. A line is drawn to connect the signal amplitude points along the time base.

Note. There are many variables to be considered when determining the size of a reflec-

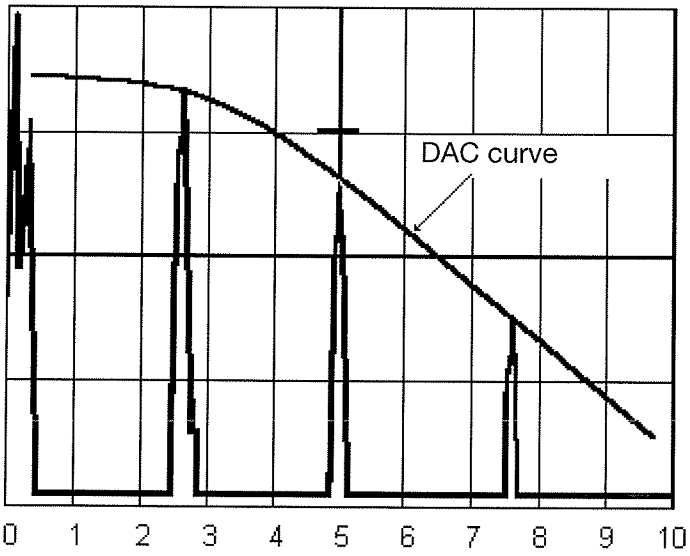


FIGURE 7-60 DAC curve.

tor. Estimating or measuring reflector size based solely on amplitude is not a very practical or accurate method.

Reasonable size comparisons using flat bottomed holes drilled perpendicular to the scanning surface can be made under controlled conditions. In terms of quantifying the amount of energy that returns to the transducer from a reflector, a number of variables need to be considered, e.g., the size, shape, and orientation of this reflector.

Transfer Corrections

When reference amplitudes are established using calibration or reference blocks, there may be differences between the calibration block and the component that affect the sensitivity. These may be due to differences in surface condition, material thickness, or attenuation. The differences can be compensated for; this process is known as "transfer correction" (transferring from calibration block to component). The following example is for angle beam transducers, but the same process also applies to straight beam transducers.

Transfer Correction Technique. The transducers are placed on the calibration block and the received signal from one full skip distance is maximized. The signal amplitude is set at 80% FSH (full screen height). The beam path length along the timebase is noted.

The transducer is moved to locate the echo from the second full skip. With a wax pencil, the signal amplitude and the beam path length at its time base location are noted.

By dividing the dB difference by the beam path length, the energy losses can be calculated in dB per unit distance (inches or mm). This value should be noted.

The transducers are then placed on the part and the above procedure is repeated.

The calculation is performed as above and the dB difference per unit distance is noted.

The difference is subtracted in order to determine the amount of change that needs to be made to the reference sensitivity for the examination of the part.

By performing the above procedure, compensation for attenuation, differences in curvature, surface condition, and beam spread losses will be taken into account.

Distance, Gain, Size (DGS) Technique

The DGS system was developed by Krautkramer in Germany as a method of standardizing inspection and to provide assistance with acceptance and rejection decisions. The principles are based on the known beam characteristics of each transducer. The way in which specific reflectors will respond to the beam can be predicted. DGS plots curves for two types of reflectors. The first is a total beam reflector, effectively back wall reflectors (i.e., bigger than the beam) at increasing depths. This forms one boundary of the DGS diagram. Inside the back wall curve is the second type—a series of curves for reflectors that are smaller than the beam. These reflectors are FBH targets; each curve represents one diameter of FBH at increasing depths (see Figure 7-61).

Curves are calculated and produced for each transducer type and are available in data sheet form and as transparent accessories to clip in front of the screen. The calibration procedure uses the echo from a full back wall as the setting up target. This is adjusted using the gain control to a specific height on the CRT (40% FSH, for example). The next step is to refer to the "size" curve for the FBH diameter specified. Read down the "distance" line to the distance equivalent to the component thickness and note the dB difference between the "back wall" curve and the "size" curve at that distance. Go back to the flaw detector and increase the gain by that dB difference. At the new gain setting, the reference FBH reflector at the back wall depth, would give a 40% FSH signal. At any other depth, the signal from the reference FBH would follow the size curve for the depth concerned.

In angle beam shear wave applications, there is not likely to be a back wall echo. Instead, the echo from the 100 mm radius on the IIW V1 block is used. Because this is not the back wall echo from the component, a transfer correction has to be made. This entails

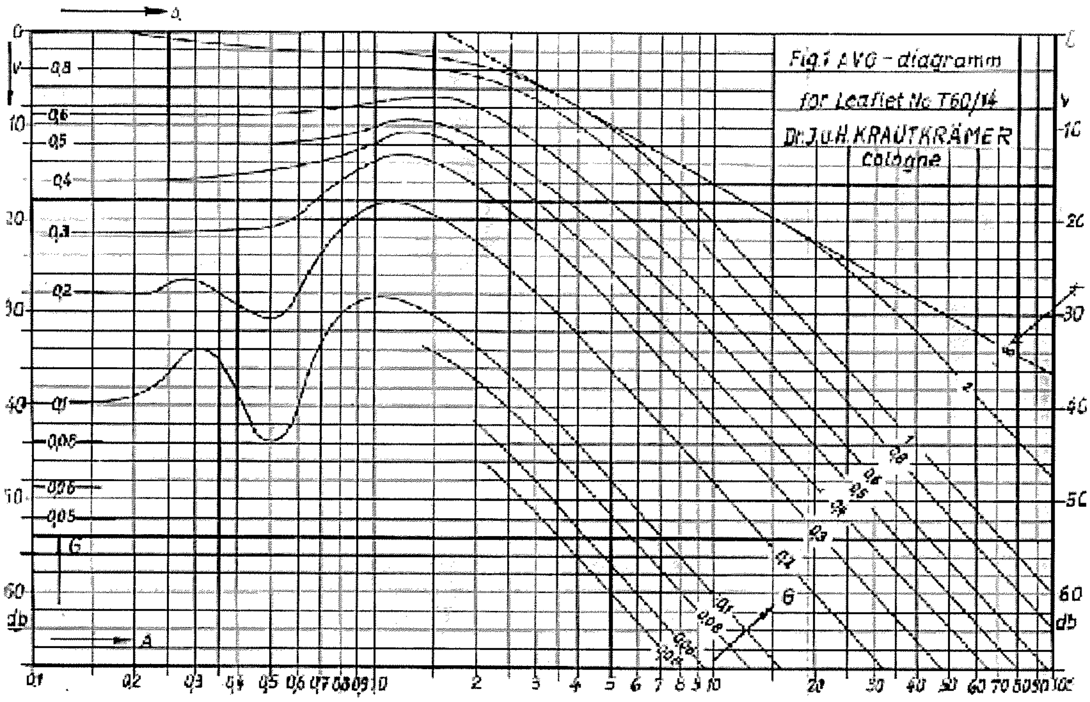


FIGURE 7-61 DGS diagram. (Courtesy of Krautkramer Branson.)

measuring the sound intensity through the V1 block and through the component, expressing that as a dB difference, and adding that difference to the reference echo as well as adding the size difference.

The greatest attribute of the DGS system is probably the fact that it allows the determination of what would be the smallest discontinuity that could be detected with that transducer at that depth. Since a FBH reflector is a near-perfect reflector, any real discontinuity would give a weaker response. Therefore, a lot of time can be saved by *not* looking for a discontinuity that can't be found.

System Checks

Various checks and calibrations are available for testing the entire system, i.e., transducer, cable, and flaw detector. The simplest is the check for overall system gain, using the large Plexiglas insert in the V1 block. The transducer is placed on the Plexiglas and the gain increased until 2 mm of noise (grass) appears or full gain is reached. The number of back wall echoes that appear on the screen is taken as a measure of the system gain for that transducer, frequency, and flaw detector.

Other checks need to be carried out from time to time to ensure that the performance of the system has not deteriorated. These include linearity of the amplifier (vertical linearity) and linearity of the time base (horizontal linearity).

Vertical Linearity. It has been established that signal amplitude has some meaning and that signal amplitudes are comparable in a measurable denomination (dB). In order to compare amplitude data, it is necessary that the measuring device, or comparator, be "linear"; in this case, that the measured signal amplitude is accurate within a given tolerance. Knowing this, there is confirmation that the measured signal amplitudes displayed on the screen are meaningful for the intended purpose. This provides information for the comparison of reflectors.

The procedure for verification of vertical linearity is one that demonstrates the instrument's ability to maintain an amplitude ratio between two signals, throughout the instrument's "linear range," while varying the gain. This practice is referred to as "screen height linearity verification." The basic procedure is as follows:

1. Two signals from either one or two reflectors are established at 80% FSH and at 40% FSH.
2. The gain is reduced until the 80% signal is positioned at 70% FSH. At this point, the lower signal should have an amplitude of 35%.
3. This procedure is repeated in steps that reduce the higher signal amplitude by 10%. The lower signal amplitude (if the display is linear) should remain at 50% of the higher signal amplitude throughout the vertical range. The specification to which this evaluation is being conducted may include acceptance criteria.

Note. There are several standards that provide the methodology for conducting these checks.

Amplitude Control Linearity. Verification that that the gain control is linear with respect to the signals noted on the screen is also an essential requirement. This procedure is known as "amplitude control linearity verification" and is as follows:

1. A signal from a reflector is set at an amplitude of 80% FSH. The gain is reduced by –6 dB on the control. The signal should now have an amplitude of 40% FSH.
2. If the signal amplitude is set to 10% FSH and 20 dB of gain is inserted, the amplitude should become 100% FSH.
3. Other values throughout the range of interest are selected and verified.

To summarize: screen height linearity checks are conducted to verify that the display is linear throughout its useable vertical range. Amplitude control linearity checks verify that the gain control on the instrument is in fact adjusting the signal amplitude by the selected number of dB.

Horizontal Linearity. Horizontal linearity is a measure of the instrument's ability to display time (distance) in a linear fashion across the screen. This means that in any given material, repeat signals from parallel surfaces will be represented on the screen as equidistant signals along the time base. For example, a ruler is calibrated to measure in inches or millimeters. If the ruler is not divided into some known denomination, it cannot be used as a measuring device. The same principle applies to the ultrasonic instrument. It is necessary to know that if the horizontal position of the signal on the screen indicates that a reflector is, for example, indicating 6 inches of steel thickness under the transducer, this measured distance is actually 6 inches.

With ultrasonic instruments, the ability to calibrate the circuitry (sweep) to display either inches, millimeters, or even microseconds is possible. The instrument screen displays a combination of the speed of sound in the test material and the distance that the sound has traveled. To do this, a "calibration standard" is necessary. This is referred to as "horizontal linearity." The instrument is calibrated and verified by using a standard having a known thickness. With the transducer placed on this standard, the instrument's controls (sweep and delay) are set to display signals in multiples of this thickness, which coincide with selected equal increments on the screen. If the signals can be aligned with these equally spaced increments, the instrument can be considered to have achieved horizontal linearity.

Inspection Techniques

Pulse-Echo Techniques

Contact Scanning Using Compression Waves. Compression wave pulse-echo techniques usually employ, either a single or dual crystal transducer directing ultrasonic energy perpendicular or near perpendicular to the scanning surface. These techniques are often known as "straight beam testing" techniques. There are some special techniques using compression waves at steeper angles used, for instance, in detecting cracks in ferrous materials under stainless steel cladding and for time of flight diffraction (TOFD) testing, but these will be covered separately.

In the standard compression wave techniques, reflections from the back wall and discontinuities are used to assess the suitability of a component for service. In order to obtain a reflection, it is necessary for the reflector to be orientated so that part of its surface is parallel to the scanning surface, in other words, normal to the beam. Laminar discontinuities and volumetric discontinuities like gas pores and nonmetallic inclusions are all suitably orientated. Discontinuities that are angled to the scanning surface may either not reflect at all or may reflect the sound away from the transducer.

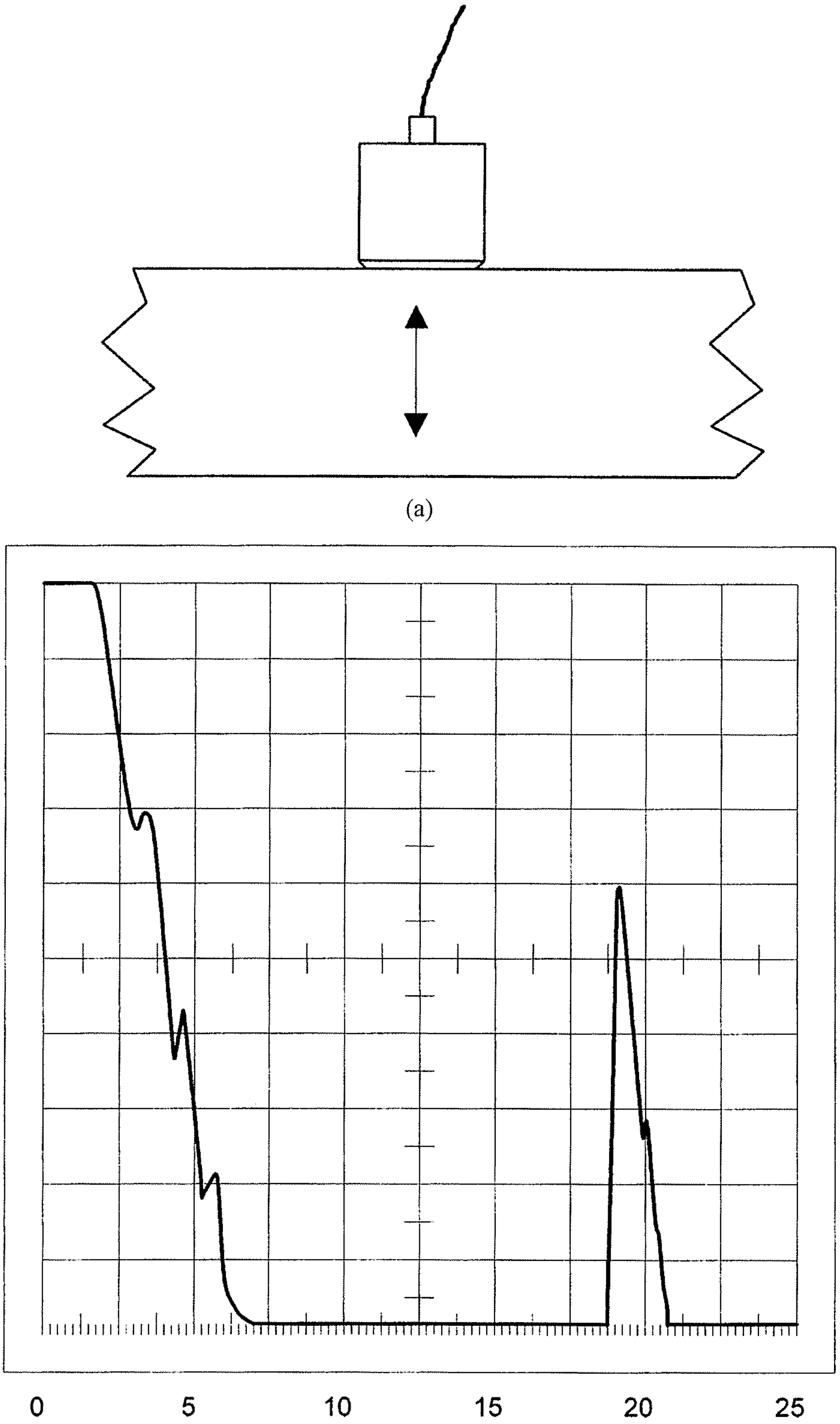
Figure 7-62a shows a single crystal compression wave transducer set up for thickness measurement of a metal part, and Figure 7-62b shows the corresponding ultrasonic A-scan trace in which the time base has been calibrated for 25 mm full scale.

The initial pulse appears at zero on the left of the trace and the back reflection signal appears three-quarters along the time base, indicating a sample thickness of 18.75 mm. Thickness gauging is one of the simplest examples of compression wave testing. Notice that the initial pulse occupies almost a quarter of the time base so that 6 mm of metal path are obscured. This obstructed area is known as the "dead zone."

Figure 7-63a shows a dual element transducer set up for thickness measurement on a sample that is 4 mm thick. Figure 7-63b shows the trace for this sample with the time base again calibrated for 25 mm. Notice that the selection of "dual" operation of the flaw detector isolates the transmitter from the receiver circuit, so there is no initial pulse and, therefore, no dead zone. The first back reflection signal (also called "back wall echo" or "BWE") shows at 4 mm on the time base. Notice also that multiples of the BWE appear at 8, 12, 16, 20, and 24 mm on the time base.

One way in which the reading accuracy can be improved is to take a reading from a multiple and divide the result by the number of passes corresponding to that multiple. Take, for example, the reading at 24 mm (which is the sixth signal). Divide 24 by 6 and the answer is 4 mm. However, suppose the actual thickness was 4.15 mm. It would be difficult to read that accurately on the first back reflection signal, but the sixth signal would have been judged at 24.9. This number divided by 6 equals 4.15 mm. In practice, this sort of accuracy could only be expected on samples with very smooth scanning and back wall surfaces. For thickness measurement in the field on corroded surfaces, errors of up to ±0.5 mm are typical. Figure 7-63c illustrates an actual thickness gage being used to read the thickness of a plate that is corroded.

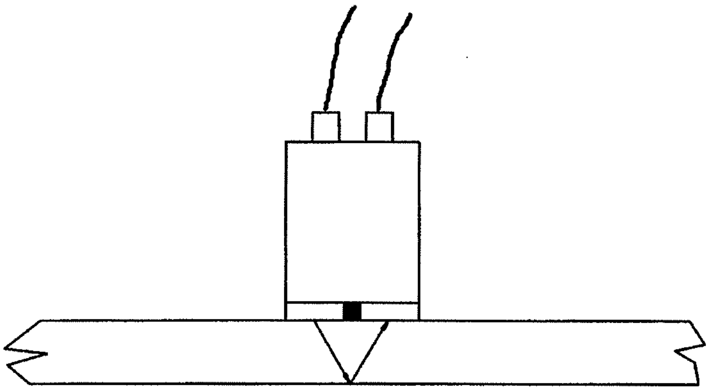
Figure 7-64a shows a single element transducer set up to detect laminations in steel plate 20 mm thick. The lamination is smaller than the beam. Notice in Figure 7-64b that the position of the lamination echo occurs on the screen at 11 mm below the scanning surface and the back reflection echo indicates a 20 mm thickness. The back reflection echo is reduced in amplitude because part of the beam is reflected by the lamination. If the lamination had been bigger than the beam, there would be no back reflection echo. If, on the other hand, the lamination had been smaller, the signal from the lamination would have been smaller in amplitude and the back reflection echo bigger. It might have been necessary to increase the equipment gain to see the lamination at all. In the extreme case, the



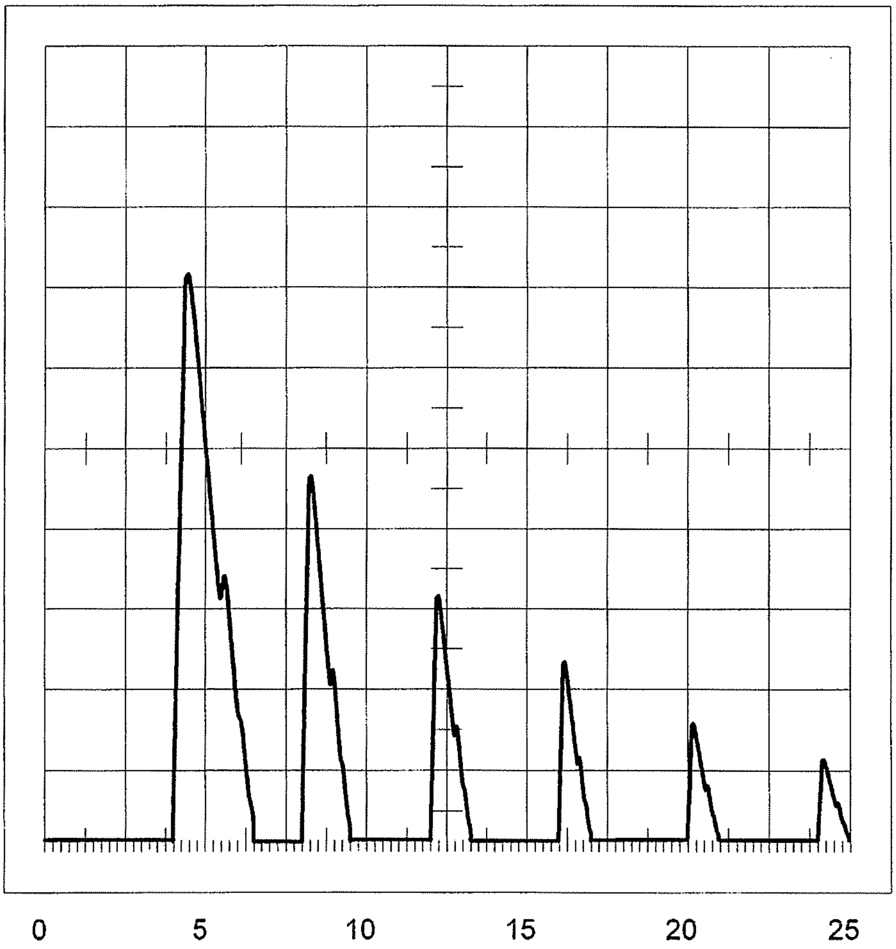
(a)

(b)

FIGURE 7-62 Thickness measurement.



(a)



(b)

FIGURE 7-63 (a) and (b) Thickness measurement.

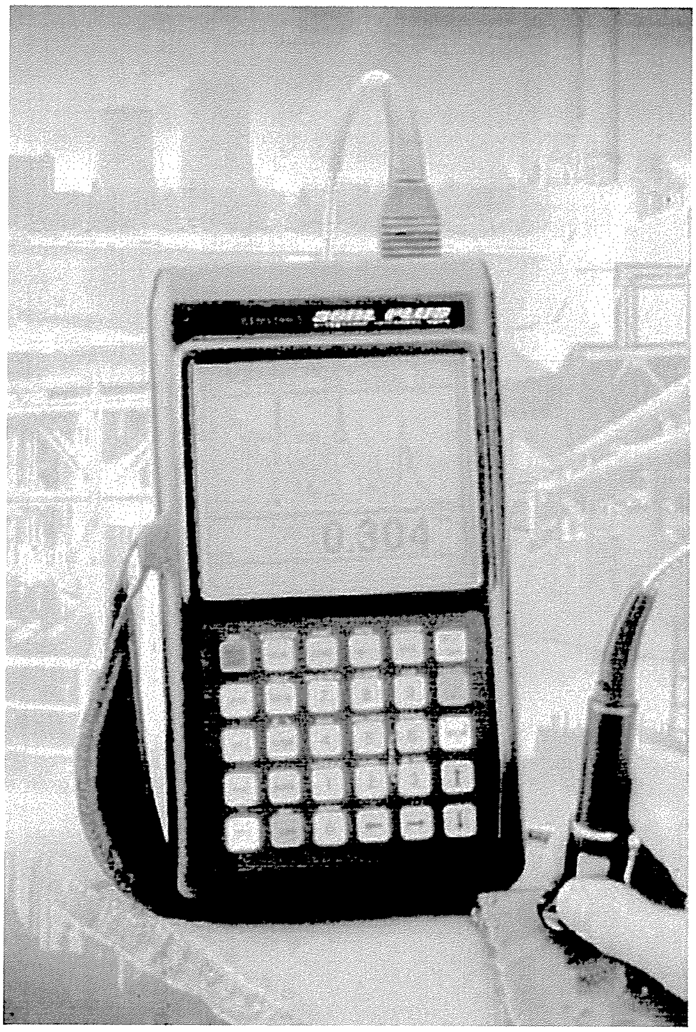
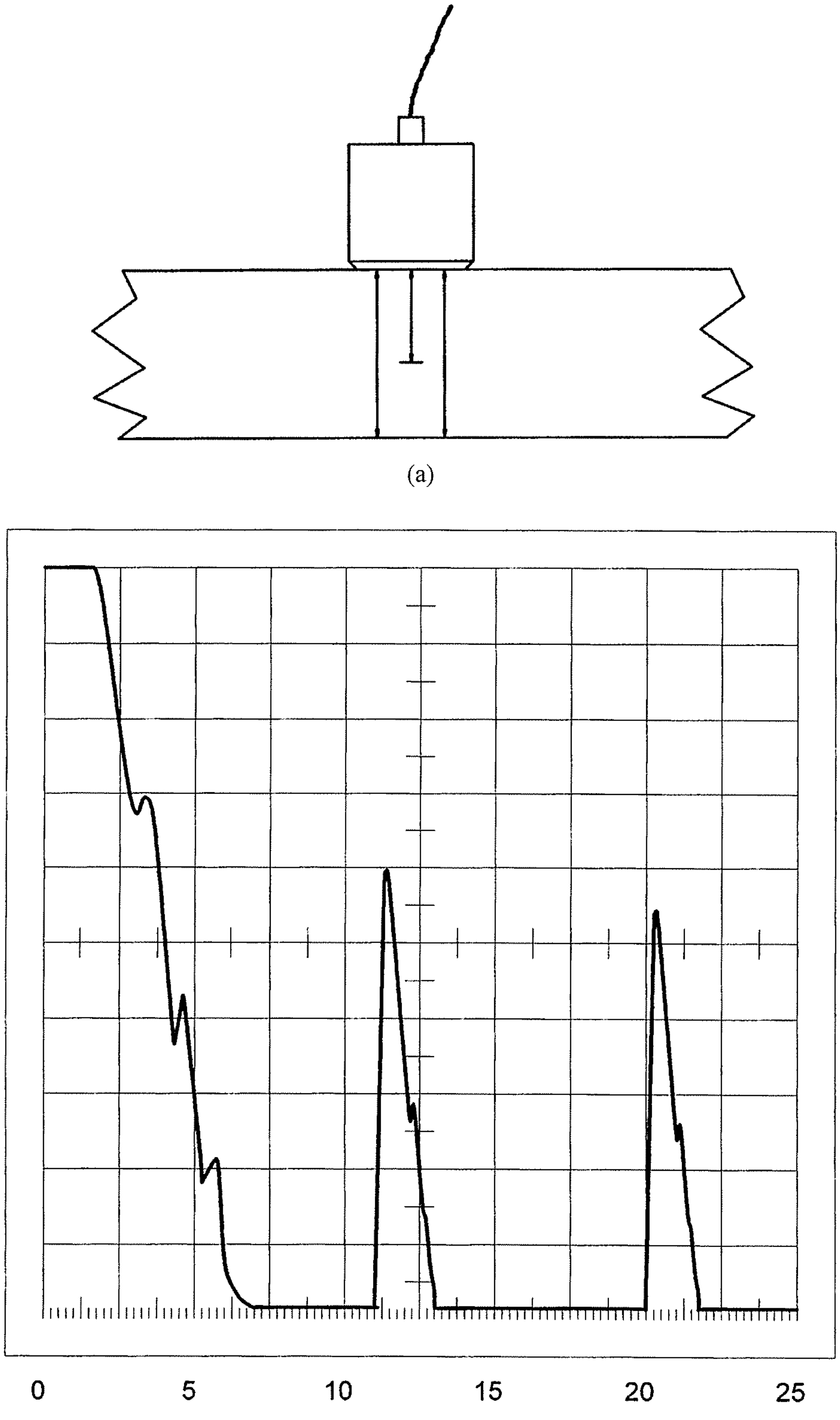


FIGURE 7-63 (c) Thickness gauge on corroded plate.

lamination might be so small that it could not be detected at the test frequency or gain used. Therefore, the detection of suitably orientated discontinuities is dependent on the size of the discontinuity, the test frequency, and the gain used. Higher frequencies can detect smaller reflectors due to their shorter wavelength.

It must be remembered that attenuation of the ultrasonic beam also has an effect on detection. As the energy penetrates deeper into the material, it weakens. Eventually, the beam is too weak to allow small echoes to get back to the receiver. The higher the test frequency, the greater the attenuation and the less penetration that can be achieved. The material and its grain structure also affect attenuation. The practitioner must balance the conflicting requirements of discontinuity size to be detected, material properties, and ultrasonic beam properties in the choice of transducer and test frequency.

Figures 7-65a and b show two discontinuities unfavorably oriented to the sound beam. The inclined discontinuity in Figure 7-65a is reflecting the energy away from the transducer, but also obscuring the back wall. The result would be no signals visible on the display, but there would be a reduction in the back reflection. In Figure 7-65b, the vertical



(a)

(b)

FIGURE 7-64 Perpendicular reflector.

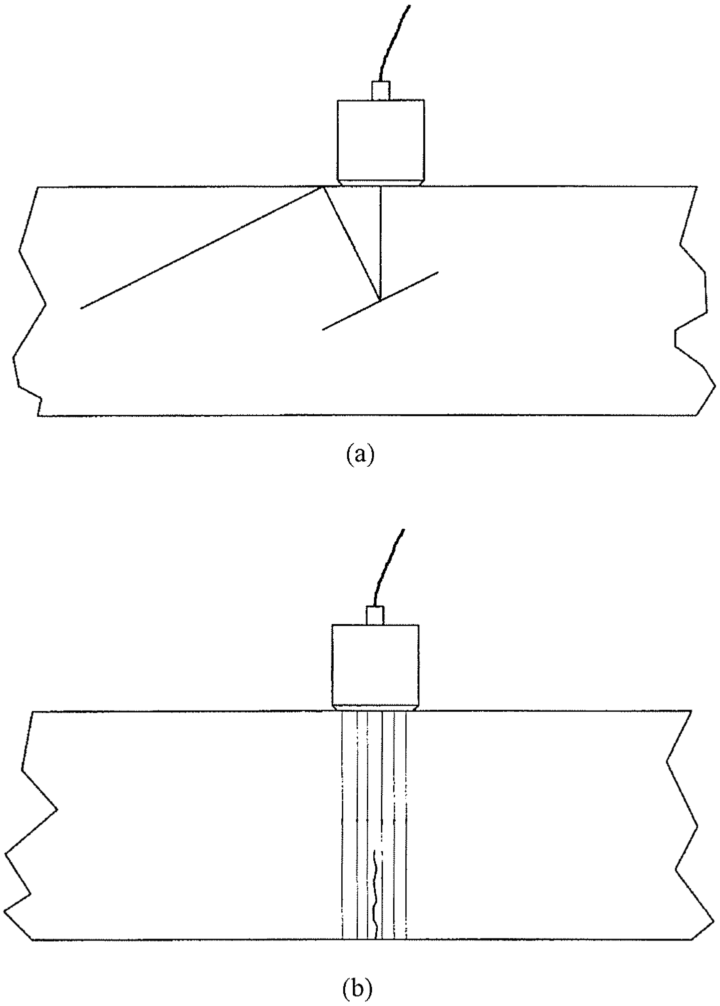


FIGURE 7-65 Adverse reflectors.

crack allows the sound to pass on either side without reflecting but would give a normal back wall echo. The possible orientation of the discontinuity must also be considered in devising a test procedure.

Finally, a test technique for the detection of laminations in thin plate is illustrated in Figures 7-66a, b, and c. The technique is called the "multiple echo" technique for reasons that are obvious from Figures 7-66b and c. The timebase has been calibrated for 50 mm for a sample 3 mm thick. With the transducer in position 1 (sound material), the multiple echo pattern stretches to 30 mm (14 signals) as shown in Figure 7-66b. With the transducer in position 2, over the lamination, the multiple echo pattern only stretches to 15 mm, as can be noted in Figure 7-66c. This is because the echoes are closer together; so close, in fact, that they interfere with each other, leaving no clear time base in between echoes.

Contact Scanning Using Angle Beam Shear Waves. If the possible orientation of any discontinuity is considered to be unfavorable to a beam perpendicular to the scanning surface, it will be necessary to tilt the beam to an appropriate angle to ensure that the beam strikes the discontinuity as near perpendicular as possible. For small angles (up to about

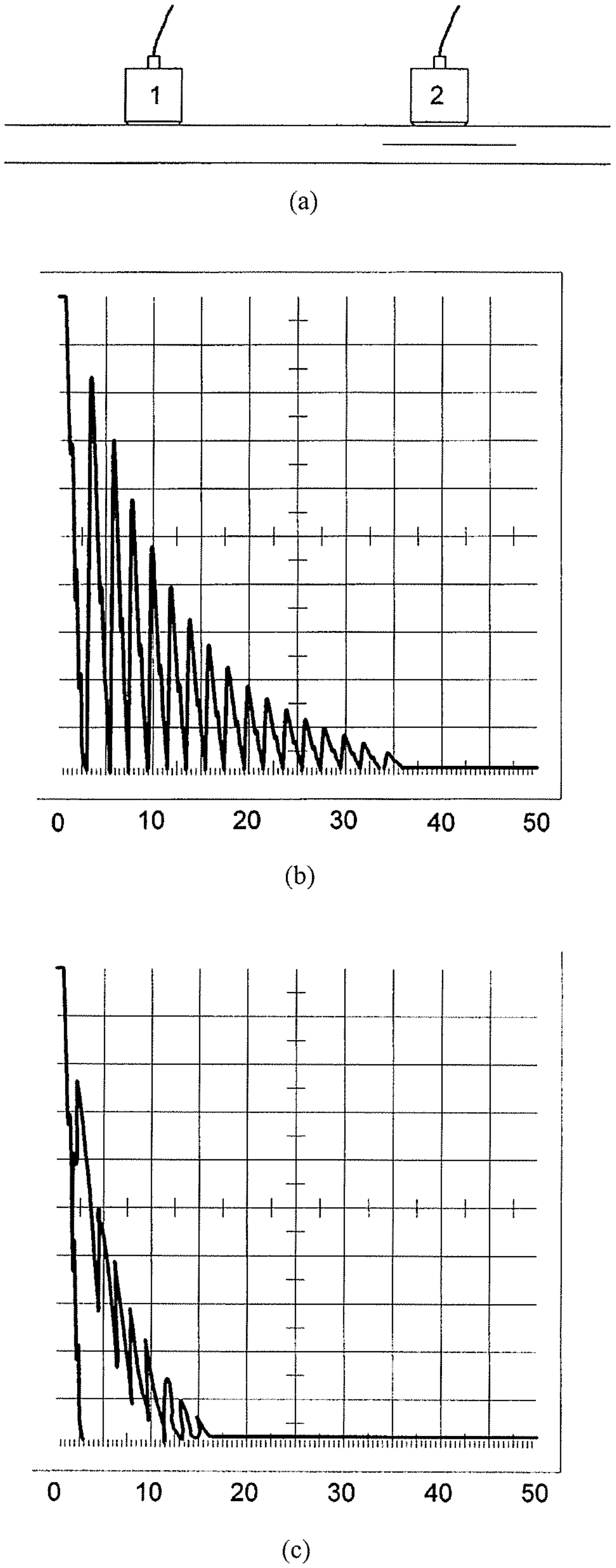


FIGURE 7-66 Lamination detection.

10° in the test material), compression waves may be used. However, for larger angles, mode conversion to shear wave energy makes the use of compression waves alone impossible. It therefore becomes necessary to increase the incident angle beyond the first critical angle, leaving only a shear wave in the part.

The lowest practical angle for testing with a shear wave alone is about 35° refracted shear wave angle. This does not mean that testing at angles between 10° and 35° is impossible. However, if an angle in this range needs to be used, the practitioner must consider carefully the geometry of the part. The next decision is whether to use the compression wave or the simultaneous shear wave, depending on what happens to the unwanted mode. Regular off the shelf transducers are either straight beam compression wave or shear wave angle transducers of 35° to 70°.

The common or "preferred" angles available in ultrasonics for shear wave testing are 45°, 60°, and 70°, although other angles can be made to order. The angles marked on a shear wave transducer are for steel, unless followed by an identifying letter for other materials. For instance, "45°Al" would denote a 45° shear wave angle transducer for aluminum.

Half Skip and Full Skip Techniques

The simplest angle beam test is one that looks only for vertical surface-breaking discontinuities originating at the scanning surface or back wall. Figure 7-67a shows a 45° shear wave transducer positioned on a 20 mm thick plate. The beam reflects at the bottom and then top surfaces at an angle equal to the angle of incidence of the shear wave beam, 45° in this case. Note that with no discontinuity present, no echo energy returns to the transducer.

Figure 7-67b shows the transducer aimed at a slot breaking the bottom surface. This slot will produce an echo arriving back at the transducer at a fixed time that is twice the beam path distance A–B divided by the shear wave velocity. The trace is shown at Figure 7-67c; the time base is calibrated for 100 mm return trip time, and the beam path distance is shown as 28 mm.

In Figure 7-67d, the distance A–B along the scanning surface is called the "half skip" distance and for a 45° probe this is equal to the specimen thickness. Position C is called the half skip position. Any discontinuity breaking the bottom surface of this part will produce a signal at 28 mm.

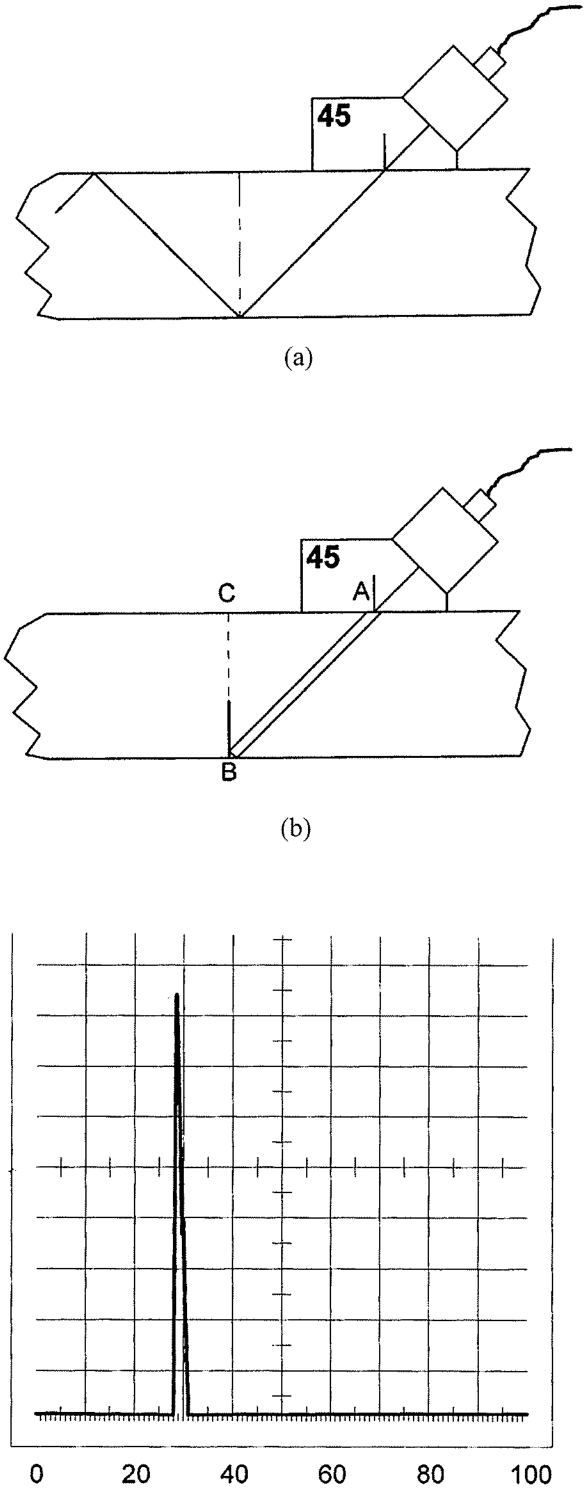
Figure 7-67d shows the transducer positioned to reflect from a top surface-breaking slot. The distance A–D is called the "full skip" distance and a full skip signal would appear at 56 mm on the time base, as shown in Figure 7-67e. If the transducer is scanned along a 20 mm plate containing top and bottom surface-breaking discontinuities, only three signal patterns are possible:

1. No signal representing sound material
2. A signal at 28 mm representing a bottom corner reflector
3. A signal at 56 mm representing a top corner reflector

For the practitioner, interpretation of results is relatively simple since there are only two screen locations on which to concentrate. The technique is commonly used to detect fatigue cracks during the in-service inspection of critical components.

Beam Path Distance Techniques

Of course, not all discontinuities occur at the top or bottom surfaces. In welds or castings, for example, planar and volumetric discontinuities may occur anywhere within the volume of the part. In order to detect, correctly assess, and position such discontinuities, it is necessary to determine the distance along the beam path at which the reflection occurs. This distance together with the known beam direction and angle allows the position of the discontinuity to be plotted.

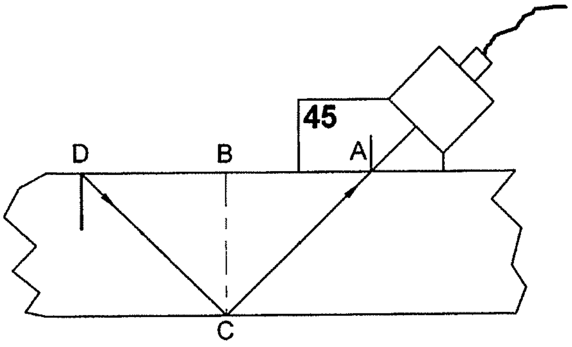


(a)

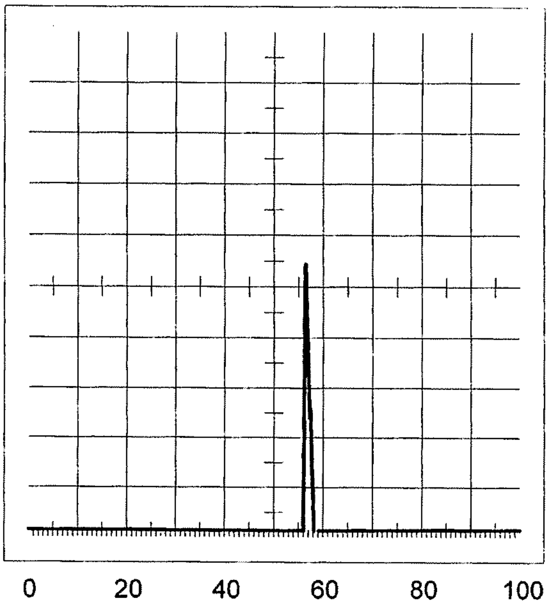
(b)

(c)

FIGURE 7-67 Discontinuity detection.



(d)



(e)

FIGURE 7-67 *Continued.*

Volumetric discontinuities, such as gas pores or slag inclusions in welds, are not very sensitive to beam angle. Approached from almost any direction, there is likely to be a facet of the discontinuity that will reflect back to the transducer. On the other hand, planar discontinuities, such as lack of side wall fusion in welds and angular cracks, are very sensitive to beam angle. The practitioner must be aware of the types of discontinuities that might occur during fabrication and service in a part to be inspected.

To be able to measure beam path distance, the time base must be calibrated for the shear wave velocity in the material to be inspected. This process of calibration requires suitable calibration blocks. Such calibration blocks should be capable of being used for a variety of beam angles. An example of a calibration block (IIW) is shown in Figure 7-68.

Figures 7-69a–f illustrate how this technique can be used to locate a region of lack of

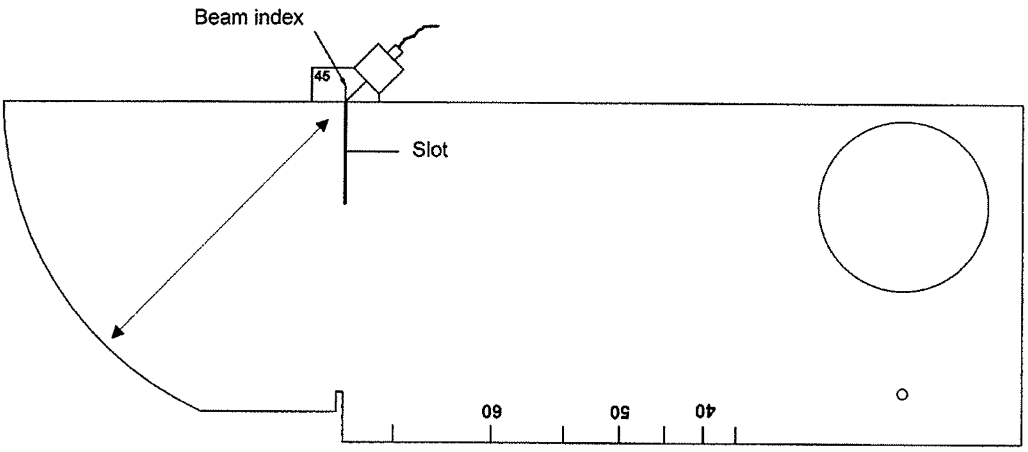


FIGURE 7-68 Beam index.

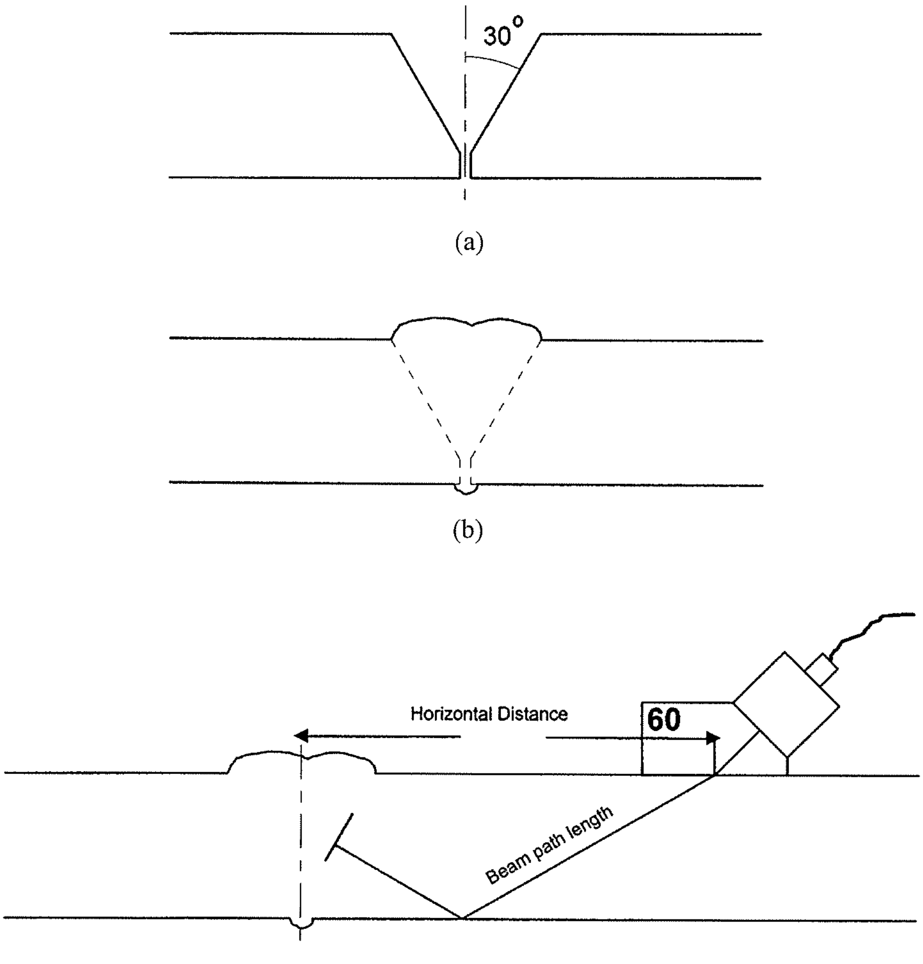
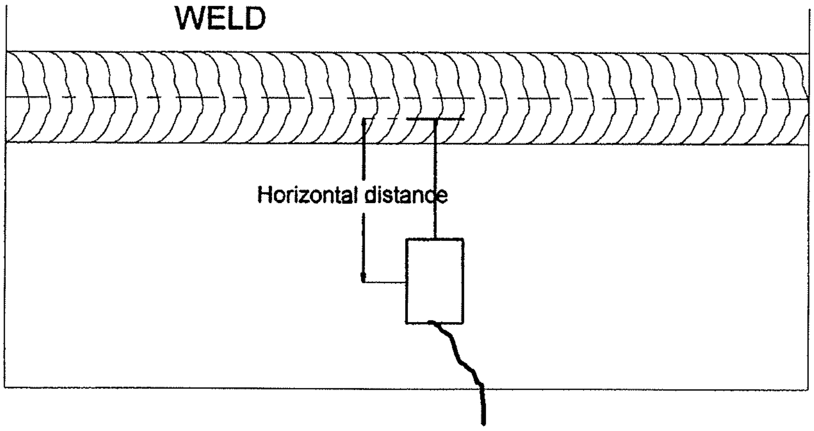
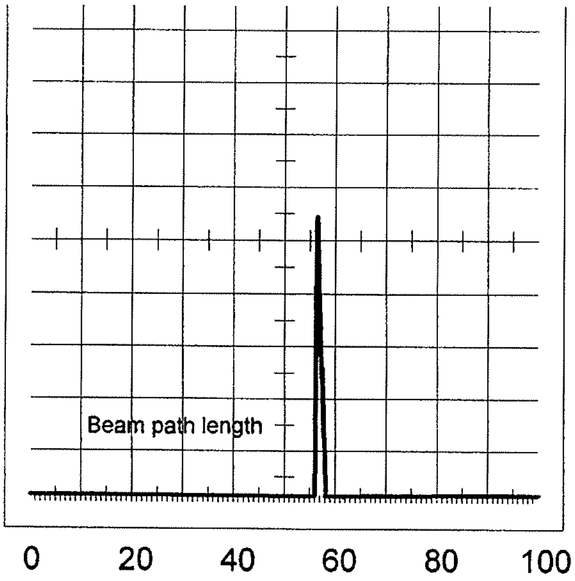


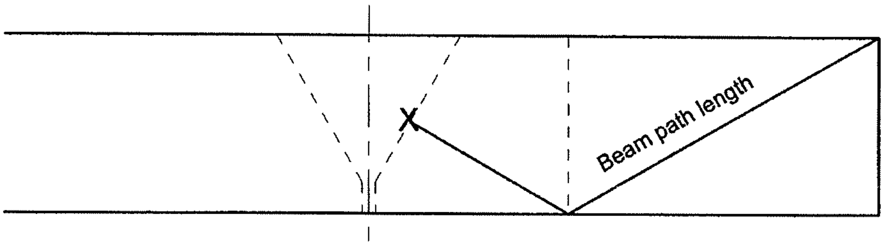
FIGURE 7-69 Discontinuity detection in weld.



(d)



(e)



(f)

FIGURE 7-69 *Continued.*