THE BRITISH INSTITUTE OF
NON-DESTRUCTIVE TESTING

PCN
PHASED ARRAYULTRASONIC TESTING
(PAUT)
MATERIAL

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1. Introduction

1.1   General Introduction to Phased Array Testing

Many people are familiar with the medical applications of ultrasonic imaging, in which high-frequency sound waves are used to create highly detailed cross-sectional pictures of internal organs. Medical sonograms are commonly made with specialized multielement probes[1] known as phased arrays and their accompanying hardware and software. But the applications of ultrasonic phased array technology are not limited to medical diagnosis. In recent years, phased array systems have been increasing in use in industrial settings to provide new levels of information and visualization in common ultrasonic tests that include weld inspection, bond testing, thickness profiling, and in-service crack detection.

During their first couple of decades, commercial ultrasonic instruments relied entirely on single element transducers that used one piezoelectric crystal to generate and receive sound waves, dual element transducers that had separate transmitting and receiving crystals, and pitch-and-catch or through-transmission systems that used a pair of single element transducers in tandem. These approaches are still used by the majority of current commercial ultrasonic instruments designed for industrial flaw detection and thickness gaging; however, instruments using phased arrays are steadily becoming more important in the ultrasonic nondestructive testing (NDT) field.

The principle of constructive and destructive interaction of waves was demonstrated by English scientist Thomas Young in 1801 in a notable experiment that utilized two point sources of light to create interference patterns. Waves that combine in phase reinforce each other, while waves that combine out-of-phase cancel each other (see Figure 1-1).
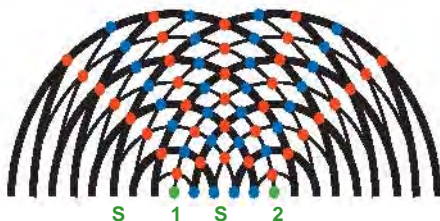
Figure 1-1 Two-point source interference pattern

Phase shifting, or *phasing*, is in turn a way of controlling these interactions by time-shifting wavefronts that originate from two or more sources. It can be used to bend, steer, or focus the energy of a wavefront. In the 1960s, researchers began developing ultrasonic phased array systems that utilized multiple point-source transducers that were pulsed so as to direct sound beams by means of these controlled interference patterns. In the early 1970s, commercial phased array systems for medical diagnostic use, first appeared using steered beams to create cross-sectional images of the human body (see Figure 1-2).

Figure 1-2 Phased arrays used for medical diagnoses

Initially, the use of ultrasonic phased array systems was largely confined to the medical field, aided by the fact that the predictable composition and structure of the human body make instrument design and image interpretation relatively straightforward. Industrial applications, on the other hand, represent a much greater challenge because of the widely varying acoustic properties of metals, composites, ceramics, plastics, and fiberglass, as well as the enormous

variety of t   untered across the scope of industrial testing. The first industrial phased array systems, introduced in the 1980s, were extremely large, and required data transfer to a computer in order to do the processing and image presentation. These systems were most typically used for in-service power generation inspections. In large part, this technology was pushed heavily in the nuclear market, where critical assessment greatly allows the use of cutting edge technology for improving probability of detection. Other early applications involved large forged shafts and low-pressure turbine components.

Portable, battery-powered phased array instruments for industrial use appeared in the early 2000s. Analog designs had required power and space to create the multichannel configurations necessary for beam steering. However, the transition into the digital world and the rapid development of inexpensive embedded microprocessors enabled more rapid development of the next generation phased array equipment. In addition, the availability of low-power electronic components, better power-saving architectures, and industry-wide use of surface-mount board designs led to miniaturization of this advanced technology. This resulted in phased array tools, which allowed electronic setup, data processing, display, and analysis all within a portable device, and so the doors were opened to more widespread use across the industrial sector. This in turn gave the ability to specify standard phased array probes for common applications.

1.2   What Is a Phased Array System?

Conventional ultrasonic transducers for NDT commonly consist of either a single active element that both generates and receives high- frequency sound waves, or two paired elements, one for transmitting and one for receiving. Phased array probes, on the other hand, typically consist of a transducer assembly with 16 to as many as 256 small individual elements that can each be pulsed separately (see Figure 1-3 and Figure 1-4). These can be arranged in a strip (linear array), 2D matrix, a ring (annular array), a circular matrix (circular array), or a more complex shape. As is the case with conventional transducers, phased array probes can be designed for direct contact use, as part of an angle beam assembly with a wedge, or for immersion use with sound coupling through a water path. Transducer frequencies are most commonly in the 2 MHz to 10 MHz range. A phased array system also includes a sophisticated computer-based instrument that is capable of driving the multielement probe, receiving and digitizing the returning echoes, and plotting that echo information in various standard formats. Unlike conventional flaw detectors, phased array systems can sweep a sound beam through a range of refracted angles or along a linear path, or dynamically focus at a number of different depths, thus increasing both flexibility and capability in inspection setups.

Figure 1-3 Typical phased array probe assemblies
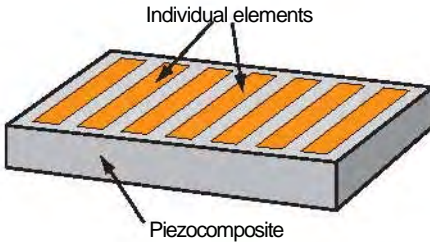
Figure 1-4 Typical multielement construction

1.3 How Does Ultrasonic Phasing Work?

In the most basic sense, a phased array system utilizes the wave physics principle of phasing. It varies the time between a series of outgoing ultrasonic pulses in such a way that the individual wavefronts generated by each element in the array combine with each other. This action adds or cancels energy in predictable ways that effectively steer and shape the sound beam. This is accomplished by pulsing the individual probe elements at slightly different times.

Frequently, the elements are pulsed in groups of 4 to 32 in order to improve effective sensitivity by increasing aperture, which then reduces unwanted beam spreading and enables sharper focusing. Software known as a *focal law calculator* establishes specific delay times for firing each group of elements in order to generate the desired beam shape, taking into account probe and wedge characteristics as well as the geometry and acoustical properties of the test material. The programmed pulsing sequence selected by the instrument's operating software then launches a number of individual wavefronts in the test material. These wavefronts, in turn, combine constructively and destructively into a single primary wavefront that travels through the test material and reflects off cracks, discontinuities, back walls, and other material boundaries like a conventional ultrasonic wave. The beam can be dynamically steered through various angles, focal distances, and focal spot sizes in such a way that a single probe assembly is capable of examining the test material across a range of different perspectives. This beam steering happens very quickly so that a scan from multiple angles or with multiple focal depths can be performed in a fraction of a second.

The returnin[...]ous elements or groups of elements and time-shifted as necessary to compensate for varying wedge delays, and then summed. Unlike a conventional single element transducer, which effectively merges the effects of all beam components that strike its area, a phased array probe can spatially sort the returning wavefront according to the arrival time and amplitude at each element. When processed by instrument software, each returned focal law represents the reflection from a particular angular component of the beam, a particular point along a linear path, and/or a reflection from a particular focal depth (see Figure 1-5 and Figure 1-6). The echo information can then be displayed in any of several formats.
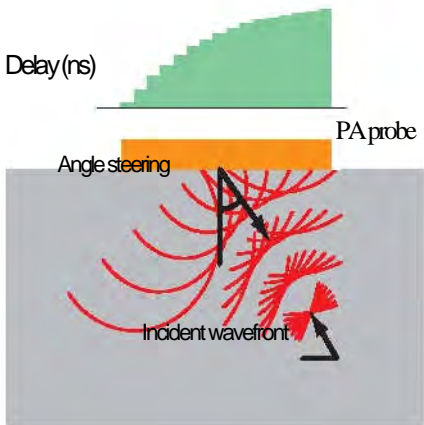
Figure 1-5 Example of an angle beam generated by a flat probe by means of the variable delay
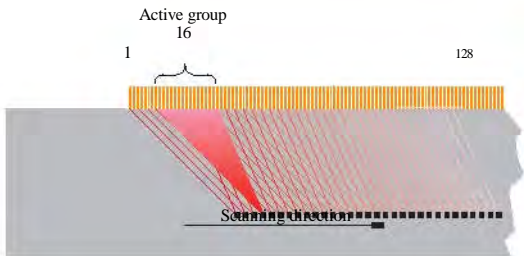
Figure 1-6 Example of focused angle beam linear scan

The main feature of phased array ultrasonic technology is the *computer-controlled excitation* (amplitude and delay) of individual elements in a multielement probe. The excitation of piezocomposite elements can generate an ultrasonic focused beam with the possibility of modifying the beamparameters such as angle, focal distance, and focal spot size through software. The sweeping beam is focused and can detect in specular mode the misoriented cracks. These cracks may be located randomly away from the beam axis. A single crystal probe, with limited movement and beam angle, has a high probability of missing misoriented cracks, or cracks located away from the beam axis (see Figure 1-7)
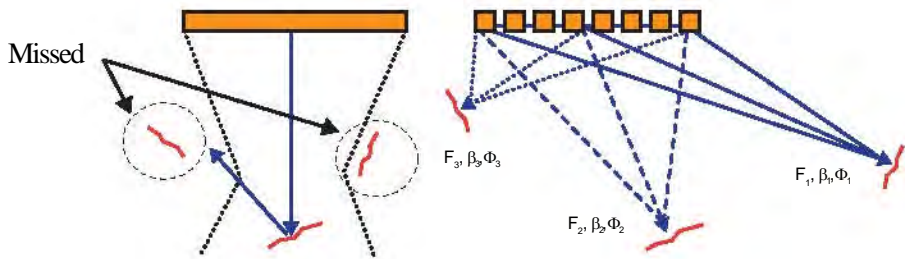
Figure 1-7 Detection of misoriented cracks by monocrystal (*left*) and multielement probes (*right*). The beam is divergent and unidirectional for the monocrystal probe, while it is focused and multiangled for the phased array probe. Cracks of most orientations can be detected by the phased array probe.

To generate a beam in phase and with a constructive interference, the various active probe elements are pulsed at slightly different times. As shown in Figure 1-2, the echo from the desired focal point hits the various transducer elements with a computable time shift. The echo signals received at each transducer element are time-shifted before being summed together. The resulting sum is an A-scan that emphasizes the response from the desired focal point and attenuates various other echoes from other points in the material.

- During transmission, the acquisition instrument sends a trigger signal to
  strument. The latter converts the signal into a high-
  reprogrammed width and time delay defined in the focal
  laws. Each element receives one pulse only. This creates a beam with a specific angle and focused at a specific depth. The beam hits the defect and bounces back.
- The signals are received, then time-shifted according to the receiving focal law. They are then reunited together to form a single ultrasonic pulse that is sent to the acquisition instrument.
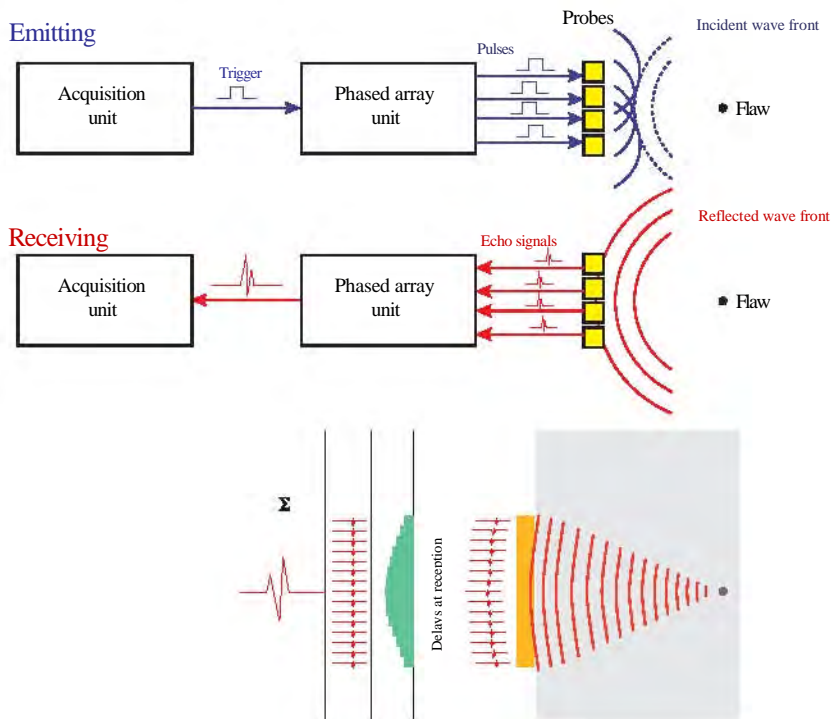
Figure 1-8 Beam forming and time delay for pulsing and receiving multiple beams (same phase and amplitude).

The beam focusing principle for normal and angled incidences is illustrated in Figure 1-9.
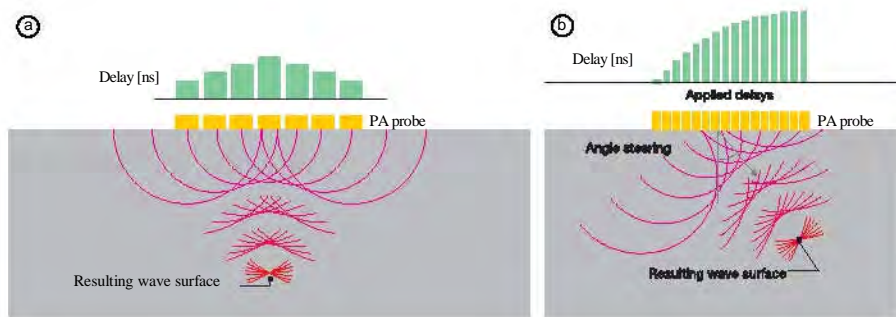
Figure 1-9 Beam focusing principle for (a) normal and (b) angled incidences.

The delay value on each element depends on the aperture of the phased array probe active element, type of wave, refracted angle, and focal depth.

There are three major computer-controlled beam scanning patterns

- *Electronic scanning*: the same focal law and delay is multiplexed across a group of active elements (see Figure 1-10); scanning is performed at a constant angle and along the phased array probe length (aperture). This is equivalent to a conventional ultrasonic transducer performing a raster scan for corrosion mapping or shear wave inspection. If an angled wedge is used, the focal laws compensate for different time delays inside the wedge.
- *Dynamic depth focusing*, or *DDF* (along the beam axis): scanning is performed with different focal depths. In practice, a single transmitted focused pulse is used, and refocusing is performed on reception for all programmed depths (see Figure 1-11).
- *Sectorial scanning* (also called *azimuthal* or *angular scanning*): the beam is moved through a sweep range for a specific focal depth, using the same elements; other sweep ranges with different focal depths may be added. The angular sectors may have different values.
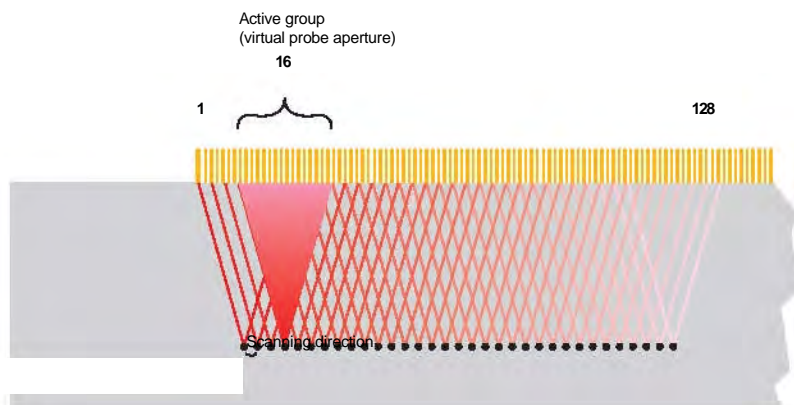
Figure 1-10 Electronic scanning with normal beam (virtual probe aperture = 16 elements).
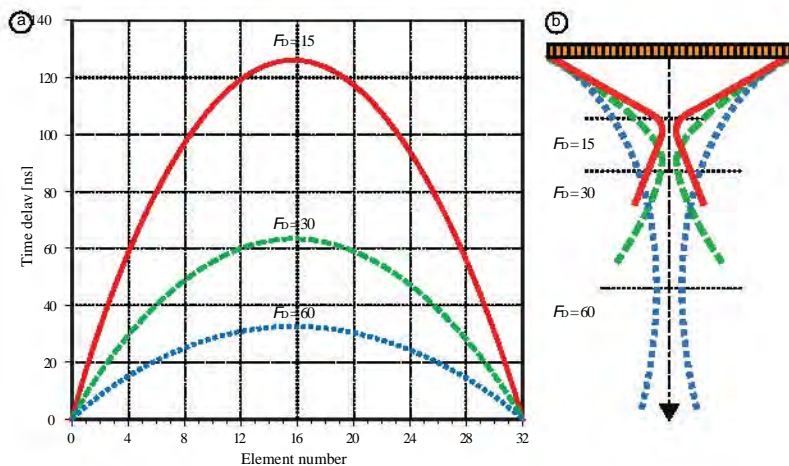
Figure 1-11 Delay values (*left*) and depth scanning principles (*right*) for a 32-element linear array probe focusing at 15-mm, 30-mm, and 60-mm longitudinal waves. Direct contact, no angled wedge.

1.4   Delay Laws, or Focal Laws

The focal law delay for probes without wedge—in direct contact with the test piece—, which were programmed to generate longitudinal waves, has a parabolic shape for depth focusing. The delay increases from the edges of the probe towards the center. The delay will be divisible in half when the focal distance is doubled (see Figure 1-11). The element timing has a linear increase when the element pitch is increasing (see Figure 1-13).

Phased array probes installed on the wedge provide delay laws with different shapes, based on Fermat's principle of minimum arrival time along a specific path (see   types of phased array probes (matrix or conical, for example) may require advanced simulation for delay law values and for beam feature evaluation.

If the beam deflection is sectorial (azimuthal), and the probe has no wedge, the delay on identical elements will depend on the element position in the active aperture and on the generated angle (see Figure 1-14). The delay value increases with refracted angle and with element number.
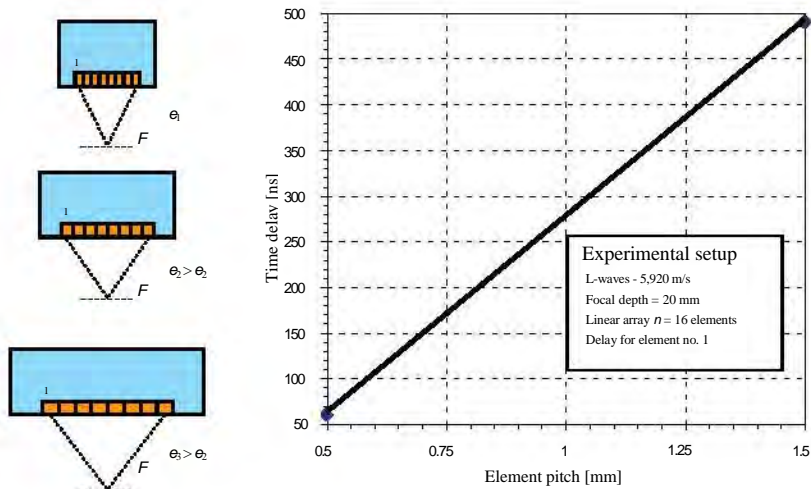
Figure 1-12 Delay dependence on pitch size for the same focal depth.
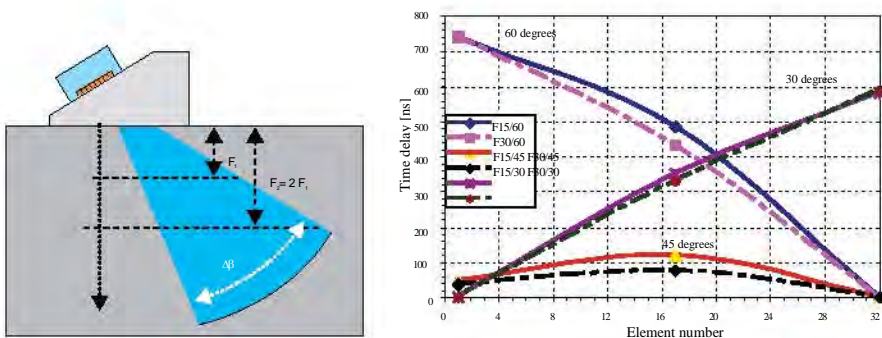
Figure 1-13 Example of delay dependence on refracted angle and element position for a robe on a 37° Plexiglas® wedge (H_1 = 5 mm).
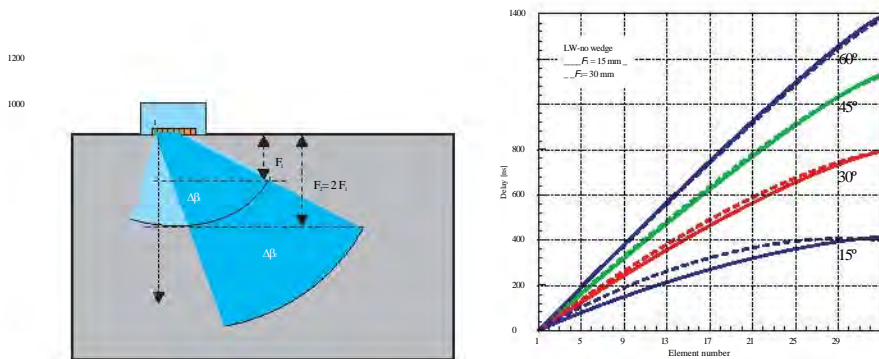
Figure 1-14 Example of delay dependence on generated angle, and element position and focal depth for a probe with no wedge (longitudinal waves, refracted angle in steel: 15-60°).

If the phased array probe is on a wedge, the delay value depends on element position and programmed refracted angle.

The delay has a parabolic shape for the angle given by Snell's law (45° in Figure 1-13). For angles smaller than one provided by Snell's law, the delay on elements increases from the back towards the front of the probe. For greater angles, the delay is higher for the back elements, because the beam generated by the front elements follows a longer path in the wedge, and thus they have to be excited first.

In all cases, the delay value on each element must be accurately controlled. The minimum delay increment determines the maximum probe frequency that can be used according to the following ratio:

$$\frac{n}{f_c}$$

1.5   Basic Components of a Phased Array System

The main components required for a basic scanning system with phased array instruments are presented in Figure 1-15.
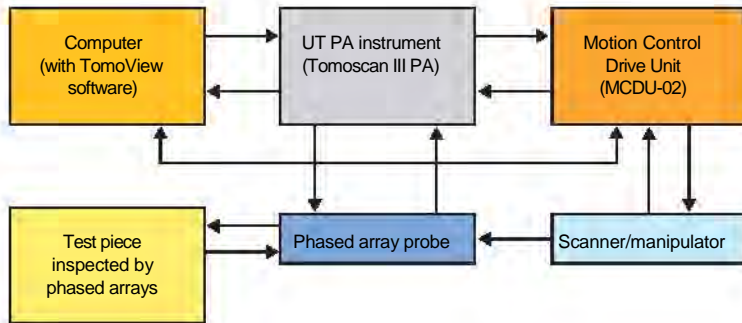
Figure 1-15 Basic components of a phased array system and their interconnectivity.

1.6 Advantages of Phased Array as Compared with Conventional UT

Ultrasonic phased array systems can potentially be employed in almost any test where conventional ultrasonic flaw detectors have traditionally been used. Weld inspection and crack detection are the most important applications, and these tests are done across a wide range of industries including aerospace, power generation, petrochemical, metal billet and tubular goods suppliers, pipeline construction and maintenance, structural metals, and general manufacturing. Phased arrays can also be effectively used to profile remaining wall thickness in corrosion survey applications.

The benefits of phased array technology over conventional UT come from its ability to use multiple elements to steer, focus, and scan beams with a single probe assembly. Beam steering, commonly referred to as *S-scanning* (*sectorial scanning*), can be used for mapping components at appropriate angles. This can greatly simplify the inspection of components with complex geometry. The small footprint of the probe and the ability to sweep the beam without moving the probe also aids the inspection of such components in situations where there is limited access for mechanical scanning. Sectorial scanning is also typically used for weld inspection. The ability to test welds with multiple angles from a single probe greatly increases the probability of detection of anomalies. Electronic focusing optimizes the beam shape and size at the expected defect location, as well as further optimizing probability of detection. The ability to focus at multiple depths also improves the ability for sizing critical defects for volumetric inspections. Focusing can significantly improve signal-to-noise ratio in challenging applications, and electronic scanning across many groups of elements allows rapid production of C-scan images. The ability to simultaneously test across multiple angles and/or to scan a larger area of the test piece through Linear scanning increases inspection speed. Phased array inspection speeds can be as much as 10 times faster as compared to conventional UT thus providing a major advantage.

The potential disadvantages of phased array systems are a somewhat higher cost and a requirement for operator training. However, these costs are frequently offset by their greater flexibility and a reduction in the time needed to perform a given inspection.

2. Phased Array Probes

2.1   Ultrasonic Beam Characteristics

Conventional longitudinal-wave ultrasonic transducers work as a piston source of high-frequency mechanical vibrations, or sound waves. As voltage is applied, the piezoelectric transducer element (often called a *crystal*) deforms by compressing in the direction perpendicular to its face. When the voltage is removed, typically less than a microsecond later, the element springs back, generating the pulse of mechanical energy that comprises an ultrasonic wave (see Figure 2-1). Similarly, if the element is compressed by the pressure of an arriving ultrasonic wave, it generates a voltage across its faces. Thus a single piezoelectric element can act as both a transmitter and receiver of ultrasonic pulses.
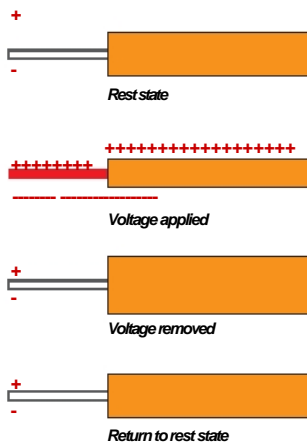
Figure 2-1 Principle of the piezoelectric transducer element

All transducers of the kind most commonly used for ultrasonic NDT

have the follo   perties:

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

Size. The diameter or length and width of the active transducer element, which is normally housed in a somewhat larger case.

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

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

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

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

Beam profile. As a working approximation, the beam from a typical unfocused disk transducer is often thought of as a column of energy originating from the active element area that expands in diameter and eventually dissipates (see Figure 2-2).
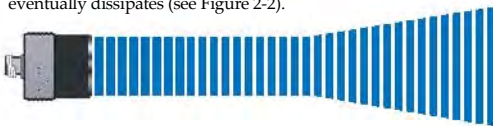
Figure 2-2 Beam profile

In fact, the actual beam profile is complex, with pressure gradients in both the transverse and axial directions. In the beam profile illustration below (Figure 2-3), red represents areas of highest energy, while green and blue represent lower energy.

Figure 2-3 Areas of energy in the beam profile

The sound field of a transducer is divided into two zones: the near field and the far field (see Figure 2-4). The *near field* is the region close to the transducer where the sound pressure goes through a series of maximums and minimums, and it ends at the last on-axis maximum at distance N from the face. Near field distance N represents the natural focus of the transducer.
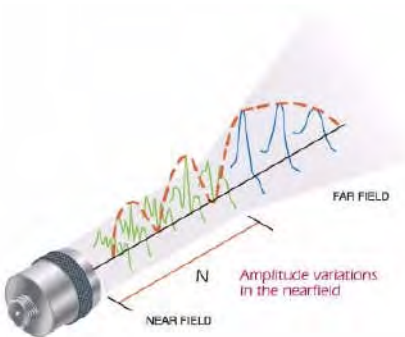
Figure 2-4 The sound field of a transducer

The *far field* is the region beyond N where the sound pressure gradually drops to zero as the beam diameter expands and its energy dissipates. The near field distance is a function of the transducer's frequency and element size, and the sound velocity in the test medium, and it can be calculated for the square or rectangular
elements commonly found in phased array testing as follows:

$$KL^2 f$$

where:

N	= near-field length
k	= aspect ratio constant (see below)
L	= length of element or aperture
f	= frequency
C	= sound velocity in test material
λ	= wavelength = c –

The aspect ratio constant is as shown in Table 2-1. It is based on the ratio betwee   of the element or aperture.

Table 2-1 Aspect ratio constant

Ratio short/long	k
1.0	1.37 (square element)
0.9	1.25
0.8	1.15
0.7	1.09
0.6	1.04
0.5	1.01
0.4	1.00
0.3 and below	0.99

In the case of circular elements, k is not used and the diameter of the element (D) is used instead of the length term:

$$N = \frac{kL^2f}{4c} \quad \text{or} \quad N = \frac{kL^2f}{4\lambda}$$

Because of the sound pressure variations within the near field, it can be difficult to accurately evaluate flaws using amplitude based techniques (although thickness gaging within the near field is not a problem). Additionally, N represents the greatest distance at which a transducer beam can be focused by means of either an acoustic lens or phasing techniques. Focusing is discussed further in section 2.7, on page 31.

2.2 Fundamental Properties of Sound Waves

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

Beam spreading. In principle, the sound wave generated by a transducer travels in a straight line until it encounters a material

boundary. What happens then is discussed below. But if the sound path length is lo   , the beam also increases in diameter, di   ht (see Figure 2-5).
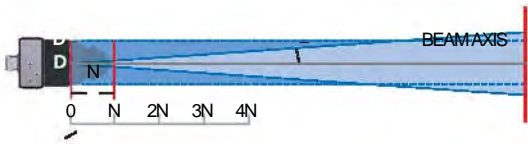
Figure 2-5 Beam spread

The beam spread angle of an unfocused circular transducer can be calculated as follows:

$$\text{Near field length} = \frac{D^2 f}{4c} = \frac{D^2}{4\lambda}$$

D   = element diameter or aperture

f = frequency

c = sound velocity in test medium

λ = wavelength = $\frac{c}{f}$

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

$$\alpha = \sin^{-1}\left(\frac{0.514c}{fD}\right)$$

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

In the case of rectangular elements, the beam spreading is asymmetrical, with a larger beam spread angle across the smaller dimension of the beam. The angle for each axis can be calculated using the formula given below, using the appropriate length or width for term L:

$$\alpha = \sin^{-1}\left(\frac{0.44c}{fL}\right) \quad \text{or} \quad = \sin^{-1}\left(\frac{0.44\lambda}{L}\right)$$

The followi   ralized changes in beam
spreading w   eter and frequency. If the
frequency is constant, then beam spreading decreases as transducer
diameter increases (see Figure 2-6 and Figure 2-7).
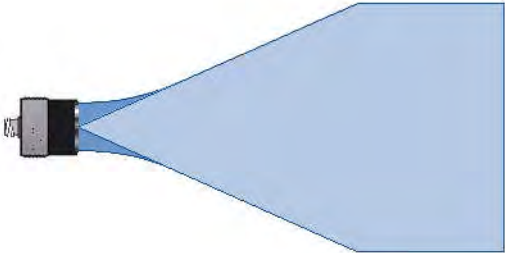
Velocity: 5850 m/s (0.230 in./µs)   Diameter: 3 mm (0.125 in.)
Frequency: 5.0 MHz

Figure 2-6 Beam spreading with a 3 mm element

Velocity: 5850 m/s (0.230 in./µs)   Diameter: 13 mm (0.5 in.)
Frequency: 5.0 MHz

Figure 2-7 Beam spreading with a 13 mm element

If the transducer diameter is constant, then beam spreading decreases as
frequency increases (see Figure 2-8 and Figure 2-9).
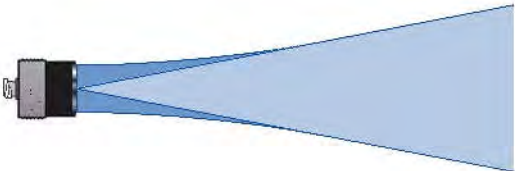
Velocity: 5850 m/s (0.230 in./µs)   Diameter: 13 mm (0.5 in.)
Frequency: 2.25 MHz

Figure 2-8 Beam spreading with a 2.25 MHz element

Velocity: 5850 m/s (0.230 in./µs)   Diameter: 13 mm (0.5 in.)
Frequency: 10.0 MHz
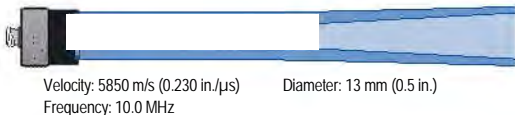
Figure 2-9 Beam spreading with a 10 MHz element

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

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

$$p = p_0 e^{-ad}$$

where:

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

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

Reflection and transmission at a perpendicular plane boundary. When a sound wave traveling through a medium encounters a boundary with a dissimilar medium that lies perpendicular to the direction of the wave, a portion of the wave energy is reflected straight back and a

portion continues straight ahead. The percentage of reflection versus transmission   tic impedances of the two materials, w   being defined as material density multiplied by speed of sound. The reflection coefficient at a planar boundary (the percentage of sound energy that is reflected back to the source) can be calculated as follows:

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

where:

R = reflection coefficient in percent

Z_1 = acoustic impedance of first medium

Z_2 = acoustic impedance of second medium

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

Refraction and mode conversion at non-perpendicular boundaries. When a sound wave traveling through a material encounters a boundary with a different material at an angle other than zero degrees, a portion of the wave energy is reflected forward at an angle equal to the angle of incidence. At the same time, the portion of the wave energy that is transmitted into the second material is refracted in accordance with Snell's Law, which was independently derived by at least two seventeenth-century mathematicians. Snell's law relates the sines of the incident and refracted angle to the wave velocity in each material as diagramed below.
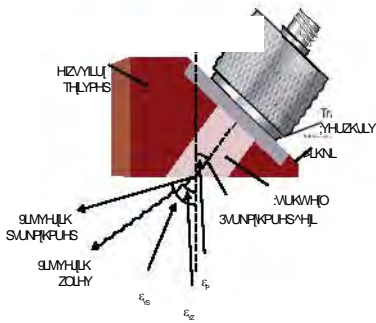
Figure 2-10 Sound wave refraction and mode conversion

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

where:

θ_i = incident angle of the wedge

θ_{rl} = angle of the refracted longitudinal wave

θ_{rs} = angle of the refracted shear wave

c_i = velocity of the incident material (longitudinal)

c_{rl} = material sound velocity (longitudinal)

c_{rs} = velocity of the test material (shear)
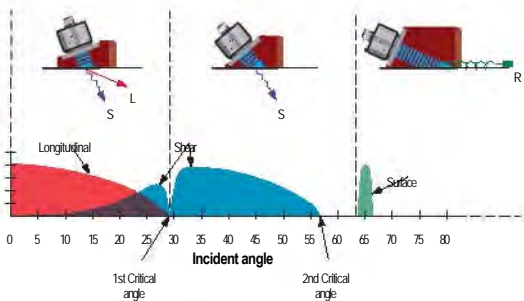
Figure 2-11 Relative amplitude of wave modes

If sound velocity in the second medium is higher than that in the first,

then above certain angles this bending is accompanied by mode conversion, inal wave mode to a shear wave mode. sed angle beam inspection techniques. As the incident angle in the first (slower) medium (such as a wedge or water) increases, the angle of the refracted longitudinal wave in the second (faster) material such as metal increases. As the refracted longitudinal wave angle approaches 90 degrees, a progressively greater portion of the wave energy is converted to a lower velocity shear wave that is refracted at the angle predicted by Snell's Law. At incident angles higher than that which would create a 90 degree refracted longitudinal wave, the refracted wave exists entirely in shear mode. A still higher incident angle results in a situation where the shear wave is theoretically refracted at 90 degrees, at which point a surface wave is generated in the second material. The diagrams in Figure 2-12, Figure 2-13, and Figure 2-14 show this effect for a typical angle beam assembly coupled into steel.
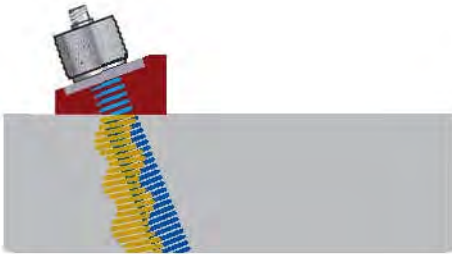
Figure 2-12 Incident angle: 10°. Strong longitudinal wave and weak shear wave.
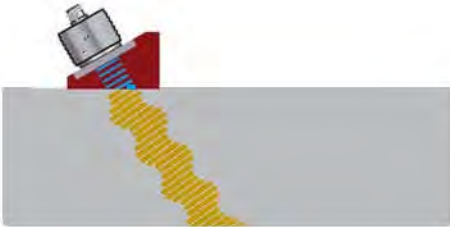
Figure 2-13 Incident angle: 30°. Beyond the first critical angle, the longitudinal wave no longer exists, and all refracted energy is contained in the shear wave.
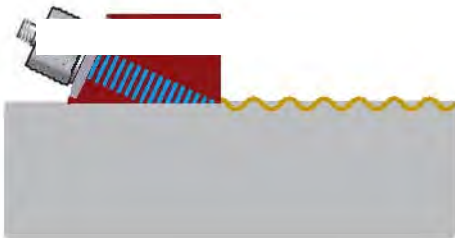
Figure 2-14 Incident angle: 65°. Beyond the second critical angle, the shear wave no longer exists, and all refracted energy is contained in a surface wave.

2.3 Phased Array Probe Characteristics

Figure 2-15 Phased array probes

An *array* is an organized arrangement of large quantities of an object. The simplest form of an ultrasonic array for NDT would be a series of several single element transducers arranged in such a way as to increase inspection coverage and/or the speed of a particular inspection. Examples of this include:

- Tube inspection, where multiple probes are often used for both crack detection, finding laminar flaws, and overall thickness measurement.
- Forged metal parts, which often require multiple probes focused at different depths to enable the detection of small defects in a zonal manner.
- A linear arrangement of probes along a surface to increase detection of laminar flaws in composites or corrosion in metals.

These inspections require high-speed, multichannel ultrasonic equipment with proper pulsers, receivers, and gate logic to process each channel as well as careful fixturing of each transducer to properly set up the inspection zones.

In its simplest form, one can think of a phased array probe as a series of individua[l elements (se]e Figure 2-16). While the elements in [most ways are like conv]entional transducers, these elements can be pulsed as a group so as to generate directionally controllable wavefronts. This "electronic beam forming" allows multiple inspection zones to be programmed and analyzed at very high speeds without probe movement. This is discussed in greater detail in later pages.

Figure 2-16 Phased array probe

While phased array probes come in a wide range of sizes, shapes, frequencies, and number of elements, what they all have in common is a piezoelectric element that has been divided into a number of segments.

Contemporary phased array probes for industrial NDT applications are typically constructed around piezocomposite materials, which are made up of many tiny, thin rods of piezoelectric ceramic embedded in a polymer matrix. While they can be more challenging to manufacture, composite probes typically offer a 10 dB to 30 dB sensitivity advantage over piezoceramic probes of otherwise similar design. Segmented metal plating is used to divide the composite strip into a number of electrically separate elements that can be pulsed individually. This segmented element is then incorporated into a probe assembly that includes a protective matching layer, a backing, cable connections, and a housing (see Figure 2-17).
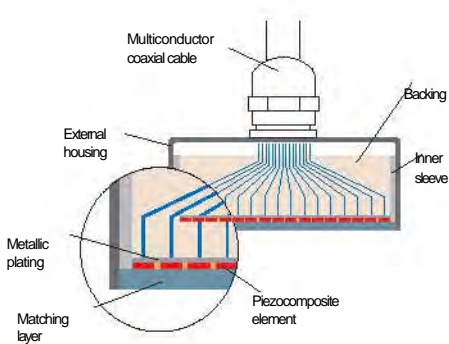
Figure 2-17 Phased array probe cross-section

Phased array prob[es are categorized] according to the

following basic parameters:

Type. Most   ngle beam type, designed for
use with either a plastic wedge or a straight plastic shoe (zero- degree
wedge), or delay line. Direct contact and immersion probes are also
available.

Frequency. Most ultrasonic flaw detection is done between 2 MHz and 10
MHz, so most phased array probes fall within that range. Lower and
higher frequency probes are also available. As with conventional
transducers, penetration increases with lower frequency, while
resolution and focal sharpness increase with higher frequency.

Number of elements. Phased array probes most commonly have 16 to 128
elements, with some having as many as 256. A larger number of elements
increases focusing and steering capability, which also increases area
coverage, but both probe and instrumentation costs increase as well. Each
of these elements is individually pulsed to create the wavefront of interest.
Hence the dimension across these
elements is often referred to as the *active or steering direction.*

Size of elements. As the element width gets smaller, beam steering capability
increases, but large area coverage requires more elements at a higher cost.

The dimensional parameters of a phased array probe are customarily
defined as follows:
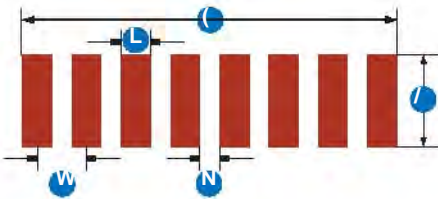
Figure 2-18 Dimensional parameters of a phased array probe

A	=	total aperture in steering of active direction
H	=	element height or elevation. Since this dimension is fixed, it is often referred to as the passive plane.
p	=	pitch, or center-to-center distance between two successive elements
e	=	width of an individual element
g	=	spacing between active elements

This information is used by instrument software to generate the desired
beam shape. If it is not entered automatically by probe recognition
software, then it must be entered by the user during setup.

2.4   Piezocomposite Materials

One of the main technical issues for large-scale applications of phased array technology in the late 1970s and mid-1980s was the manufacturing process and acoustic insulation between array elements. The high cross-talk amplitude between elements and the challenge to cut curved-shaped piezoelectric materials led to a setback in industrial development. The common piezoelectric materials are listed in Table 2-2.

Table 2-2 Main properties of commonly used piezoelectric materials.[1,7]

Symbol / Unit	Quartz	BaTiO$_3$	PbNb$_2$O$_6$	PZT-4	PZT-5A	PVF2
d_{33} (pC/N)	2.3	190	85	289	400	20
g_{33} 10-3 Vm/N	57	12.6	42.5	26.1	26.5	190
d_{33} g_{33} 10-15 N/m	133	2394	3612	7542	10,600	3,800
k_t	095	0.38	0.32	0.51	0.49	0.1
k	5	1700	225	1300	1700	11
Z (10^6 Rayl)	15.2	25.9	20	30	29	4
Mechanical Q	2,500		24	500	80	3-10

The amount of acoustic energy transferred to the load (test piece) reaches a maximum when the acoustic impedance is matched between the probe and the test piece. Some applications require an immersion technique and some use direct contact with aluminum and/or steel. Most shear-wave and longitudinal-wave applications for weld inspections require phased array probes mounted on a wedge. Impedance matching between the probe/wedge and the test piece may be achieved by mechanical (matching layer) or

electrical (fine tuning with the KLM model) methods. The main properties of matching layers are listed in section 2.4.1, "Matching Layer and Cable Requirements."

2.4.1   Matching Layer and Cable Requirements

The key points of matching layer and cable requirements are:

- Optimization of the mechanical energy transfer
- Influence on the pulse duration
- Contact protection for piezocomposite elements (wear resistance)
- Layer thickness of $\lambda/4$

The maximum electrical efficiency is obtained when the probe is matched to the electrical impedance of both the transmitter and the receiver. The KLM model[6] takes into account all the steps along the transmission line of electrical signals.

A good cable should have the following properties:

- Minimum gain drop due to cable length
- Low impedance—the ideal is 50 Ω
- Elimination/reduction of the cable reflections (cable speed: 2/3 v_{light})
- Mechanical endurance for bending, mechanical pressure, accidental drops
- Water resistance for all wires
- Avoidance of internal wire twists

A high value of $d_{33} g_{33}$ represents a good transmitting-receiving energy. A low mechanical Q means that the transducer has a higher bandwidth and better axial resolution. The damping material placed behind the crystal can increase the ban   n properties of the backing material are l   Backing Material."

2.4.2   Backing Material

The key features of backing material are:

- Attenuation of high-amplitude echoes reflected back from the crystal face (high acoustic attenuation)
- Influence on pulse duration (damping)

2.5 Piezocompos

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biomedical applicatic

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epoxy matrix, as
polymer resin has a
towards the test piec

For example, PZT
different polymer re
material (see Table 2.

Table 2-3 Values of d

1-3 P
PZT + si
PZT rod
PZT rod
PZT rod

The properties of 1
effective medium th
Figure 2-19].

Figure 2-19 The 1-3 composite coordinates according to Smith's theory.[3,5]

2.6   Types of Phased Array Probes for Industrial Applications

The phased array probes used for industrial applications and their types of focusing/beam deflections are listed in Table 2-4 and presented in Figure 2-20 to Figure 2-24.

Table 2-4 Typical phased array probes widely available.

Type	Deflection	Beam shape	Figure
Annular	Depth - z	Spherical	Figure 2-20
1-D Linear planar	Depth, angle	Elliptical	Figure 2-21
2-D matrix	Depth, solid angle	Elliptical	Figure 2-22
2-D segmented annular	Depth, solid angle	Spherical/ elliptical	Figure 2-23
1.5-D matrix	Depth, small solid angle	Elliptical	Figure 2-24
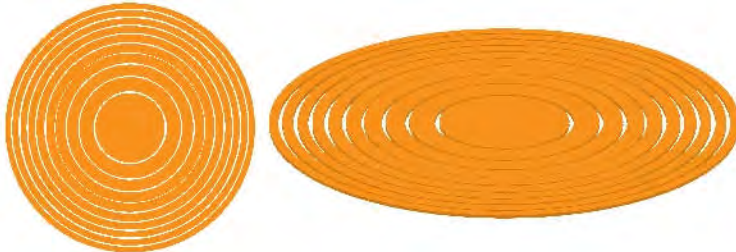
ar phased array probes of equal Fresnel surfaces.

Figure 2-21 1-D linear phased array probe.

Figure 2-22 2-D matrix phased array probe.
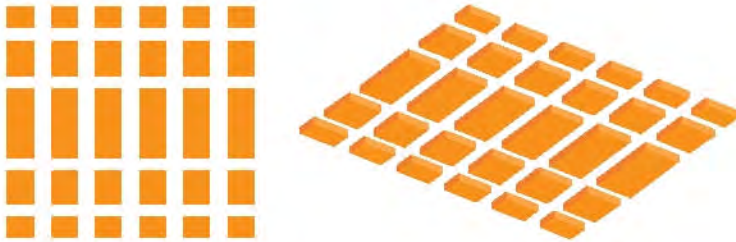
Figure 2-23 1.5-D matrix phased array probe.
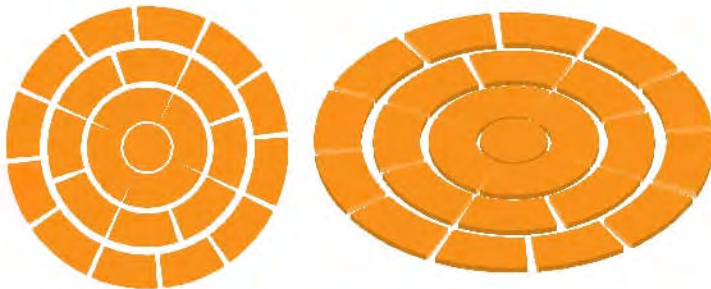
Figure 2-24 Rho-theta (segmented annular) phased array probe.

Other types of phased array probes are presented in Figure 2-25 to Figure 2-29.
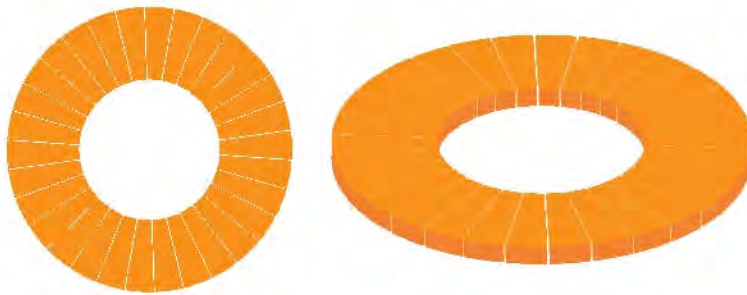
Figure 2-25 1-D circular phased array probes ("daisy probes").

Pulse-echo
or
transmit-receive mode

Planar
or
curved interface
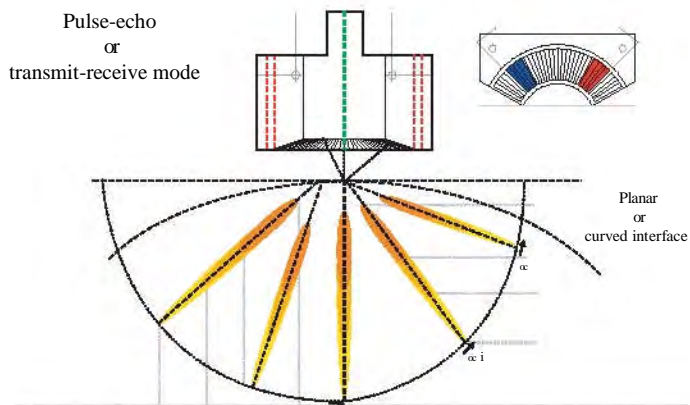
Figure 2-26 Cluster phased array probe for small diameter pipe/tube inspection showing typical beam angles (R/D Tech U.S. patent 2004/0016299AL).
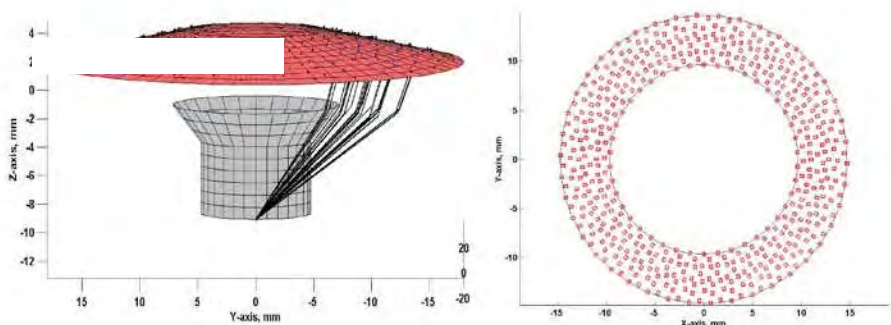
Courtesy of Lockheed Martin AS and USAF, USA

Figure 2-27 2-D matrix conical phased array probe (R/D Tech U.S. patent 10-209,298).
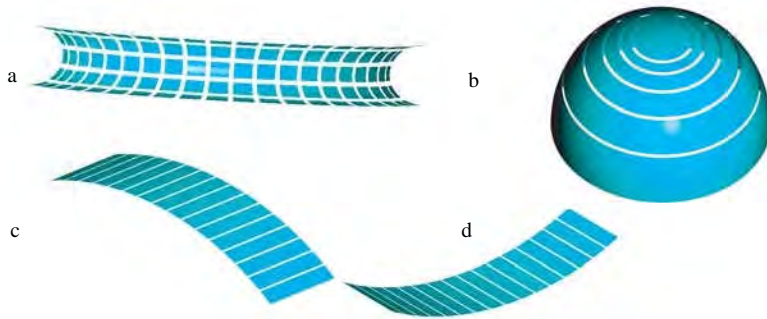
Figure 2-28 Mechanically focused phased array probes: (a) toroidal convex prefocused;
(b) annular concave; (c) linear concave; (d) linear convex.

Examples of focusing patterns for the commonly used probes are presented in
Figure 3-14 to Figure 3-16.
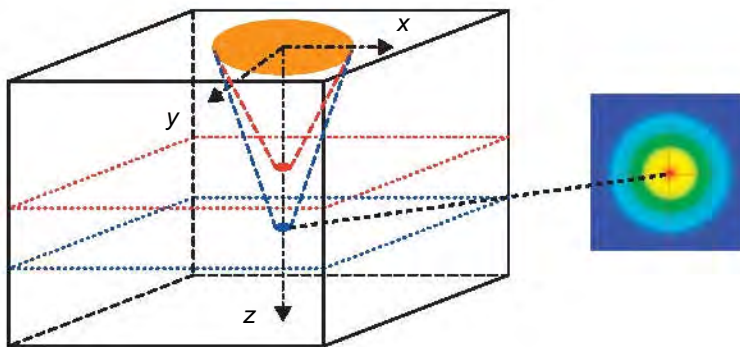
Figure 2-29 Spherical focusing (1-D depth) pattern and simulation of the beam profile for an
annular phased array probe.
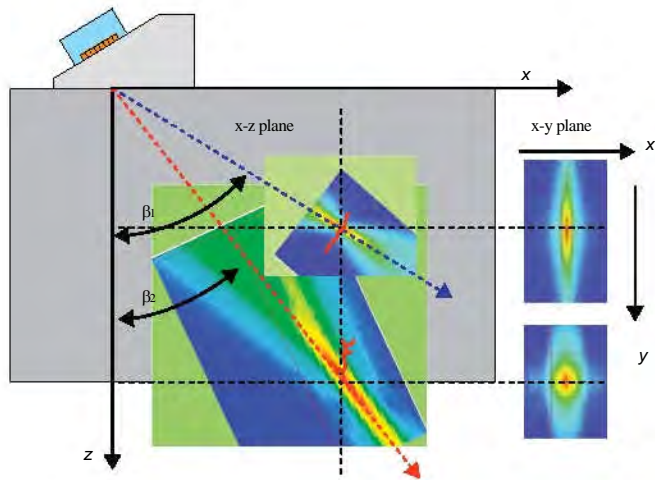
Figure 2-30 Cylindrical focusing pattern (2-D; depth and angle) of linear phased array probe for detecting a SCC at the inner surface and a fatigue crack at mid-wall; simulation of beam profile for both depths.
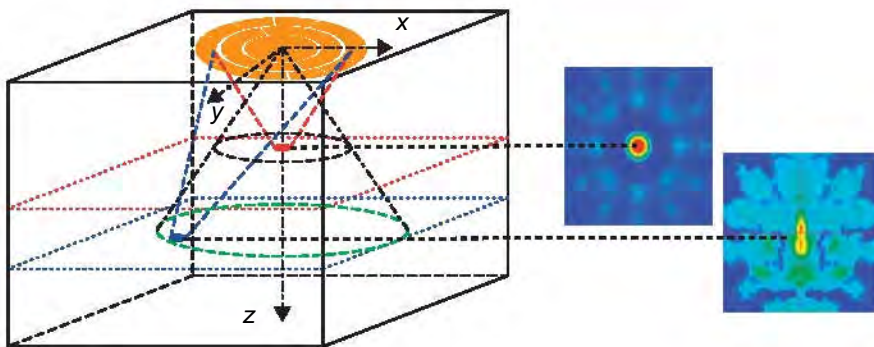
F al focusing pattern (3-D solid angle) of segmented annular phased array probe and beam simulation at two depths and two angles. Note the noise increase due to the grating lobes.
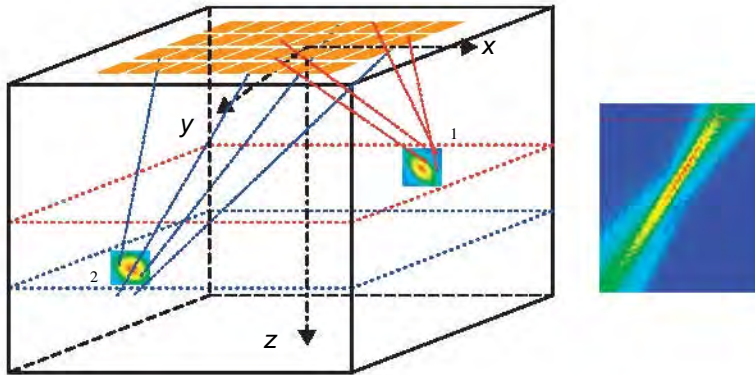
Figure 2-32 Elliptical focusing pattern (3-D solid angle) of 2-D matrix phased array probe and beam simulation for two depths and two angles.

2.7   Linear Arrays

Linear arrays are the most commonly used phased array probes for industrial applications. Their main advantages are:

- Easy design
- Easy manufacturing
- Easy programming and simulation
- Easy applications with wedges, direct contact, and immersion
- Relatively low cost
- Versatile

The characteristic features of linear arrays are detailed in sections 2.7.1,

2.7.1   Active Aperture

The *active aperture* (A) is the total probe active length. Aperture length is given by formula (below) [see also Figure 2-33]:

$$A = n \bullet e + g \bullet (n\text{ - }1)$$

where:

A = active aperture
g = gap between two adjacent elements. A practical value is $e < \lambda / 2$.

n	= number of elements
λ	= wavelength
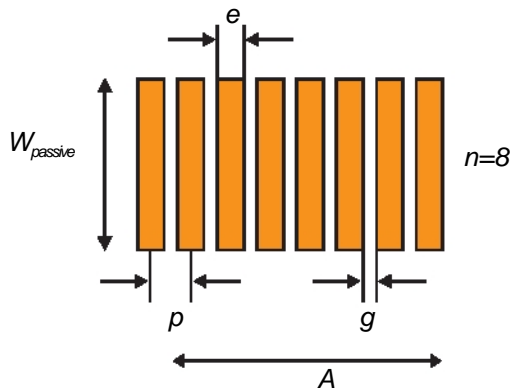
Figure 2-33 Active and passive aperture.

2.7.2   Effective Active Aperture

The *effective active aperture* (A_{eff}) is the projected aperture seen along the refracted rays (see Figure 2-34).

$$A_{\text{eff}} = \frac{A \bullet \cos \beta_R}{\cos \alpha_I}$$
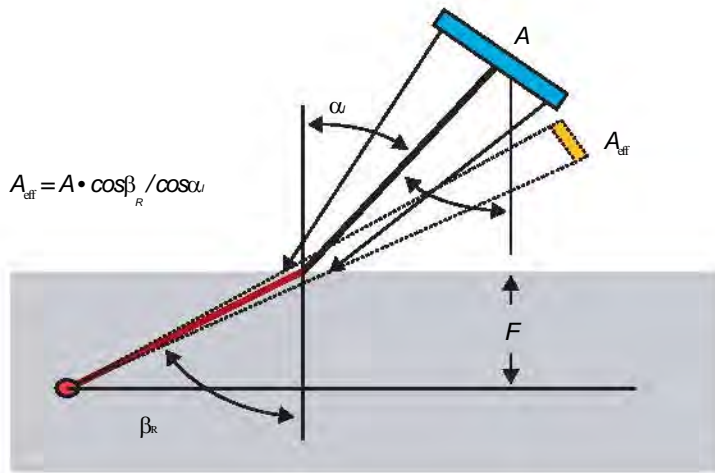
Figure 2-34 Effective aperture definition.

$$A_{eff} = A \cdot cos\beta_R / cos\alpha_I$$

2.7.3 Minimum Active Aperture

The *minimum active aperture* (A_{min}) is the minimum active aperture to get an effective focusing at the maximum refracted angle.

where:

v_I	= velocity i
v_R	= velocity i
f	
F	= focal dept
β_R	maximum r

2.7.4 Passive Ape

The *passive aperture*
Recommended pass
focal depth range:

Its contribution to the focal depth (near-field length) is given (for nonfocused probes) by formula (below:

$$N_0 = \frac{(A^2 + W^2)(0.78 - 0.27W/A)}{\pi\lambda}$$

A good practical estimation is given by formula (below):

$$N_0 = \frac{0.25\,A^2}{\lambda}$$

The passive aperture contributes to sensitivity and defect length sizing. The maximum efficiency for a linear array probe is obtained with $W_{passive} = A$.

The passive aperture also affects the beam-diffracted pattern and the beam width (see Figure 3-20). Generally, design phased array probes with $W_{passive}/p > 10$ and/or keep $W_{passive} = (0.7$ to $1.0)A$ (applicable to nonfocused probes).
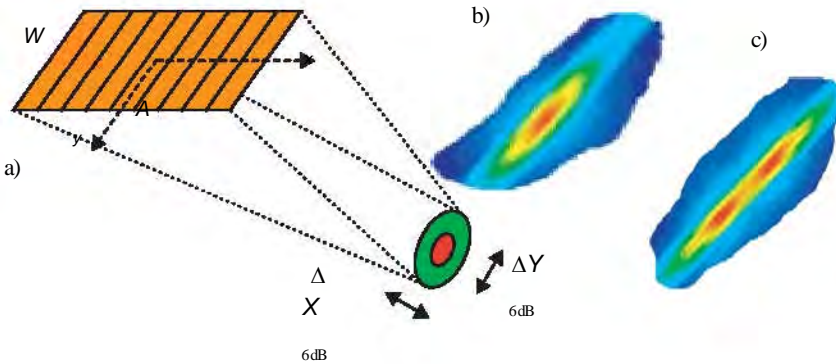
Figure 2-35 Influence of passive aperture width on beam width and shape: (a) deflection principle and beam dimensions; (b) beam shape for W = 10 mm; (c) beam shape for W = 8 mm, 5 MHz shear wave, pitch p = 1 mm; n = 32; F = 50 mm in steel.

2.7.5   Elementary Pitch

The *elementary pitch* (p) is the distance between the centers of two adjacent elements:

$$p = e + g$$

2.7.6   Element Gap

The *element gap* (*g*) [*kerf*] is the width of acoustic insulation between two adjacent elements.

2.7.7   Element Width

The *element width* (*e*) is the width of a single piezocomposite element. The general rule is keep $p < 0.67 \cdot \lambda$; to avoid grating lobes at large steering angles:

$$e_{\text{design}} < \lambda / 2$$

New modelling from the UK and PipeWIZARD® probe design proved the element pitch may be larger than the wave length, but the steering capabilities are limited.

2.7.8   Maximum Element Size

The *maximum element size* (e_{max}) is the width of a single piezocomposite crystal, and depends on the maximum refracted angle.

$$e_{\text{max}} = \frac{0.514 \cdot \lambda}{\sin \alpha_{R\text{max}}}$$

2.7.9   Focal Depth

The *focal depth* is the distance along the acoustic axis for the maximum amplitude response

There are four types of focusing options

- On the z-axis (variable depth)   Projection
- On the x-axis (constant depth, angular)   True depth
- On the UT path (xz plane)   Half path
- On a specific line equation in the xz plane   Focal plane
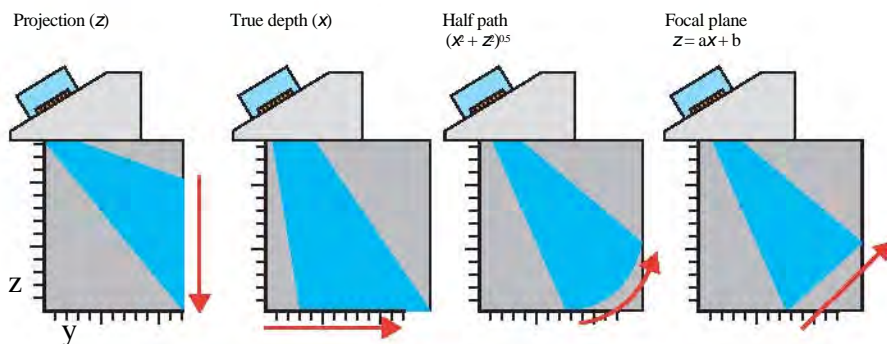
Figure 2-36 Types of focusing for linear phased array probe.

2.7.10 Depth of Field

Depth of field ($L_{-6\,dB}$), or *focal length*, is the length measured at the –6 dB drop along the acoustic axis, taking the focal depth as a reference point.

2.7.11 Focal Range

The *focal range* is the scanning distance either in depth or in ultrasonic path for multichannel focal laws or with sweep angles (see Figure 2-37). The cutoff lower value is normally –6 dB; for some applications, the cutoff value is –3 dB
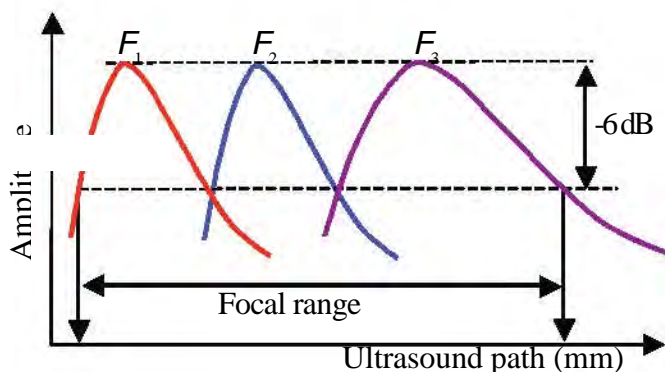
Figure 2-37 Focal range definition for –6 dB cutoff (pulse-echo).

2.7.12 Near-Surface Resolution

Near-surface resolution (dead zone) is the minimum distance from the scanning surface where a reflector (SDH, FBH) amplitude has more than a 6-dB resolution compared with the decay amplitude from the main bang (initial pulse) for normal beam (see Figure 2-38). The dead zone increases along with the gain increase.

2.7.13 Far-Surface Resolution

Far-surface resolution is the minimum distance from the inner surface where the phased array probe can resolve the amplitude ($\Delta A > 6$ dB) to specific reflectors (SDH or FBH) located at a height of 1 mm to 5 mm from the flat/cylindrical backwall (see Figure 2-38).
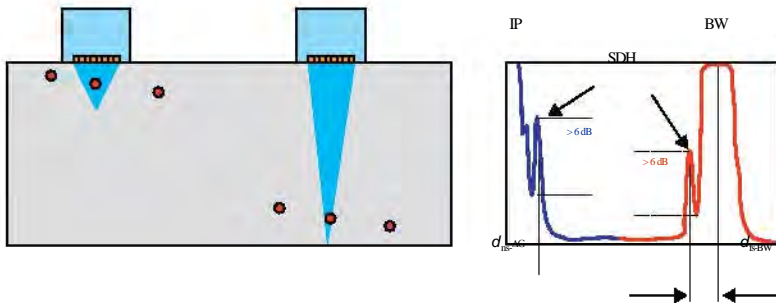
Figure 2-38 The near-surface and far-surface resolution definitions.

2.7.14 Lateral and Axial Resolution

Lateral resolution and *axial resolution* are defined below. Note that the phased array probe is moving for lateral resolution and is static for axial resolution. A sho   smaller beam length increases both resolutions.

Lateral resolution:

$$\Delta d = \frac{\Delta X_{-6\text{dB}}}{4}$$

Axial resolution:

$$\Delta z = \frac{v_{\text{test piece}} \Delta \tau_{-20\text{dB}}}{2}$$

where $\Delta\tau_{-20\,dB}$ is the time resolution at a -20 dB drop-off.

2.7.15   Angular Resolution

The *angular resolution* is the minimum angular value between two A-scans where adjacent defects located at the same depth are resolvable (see Figure 2-39).
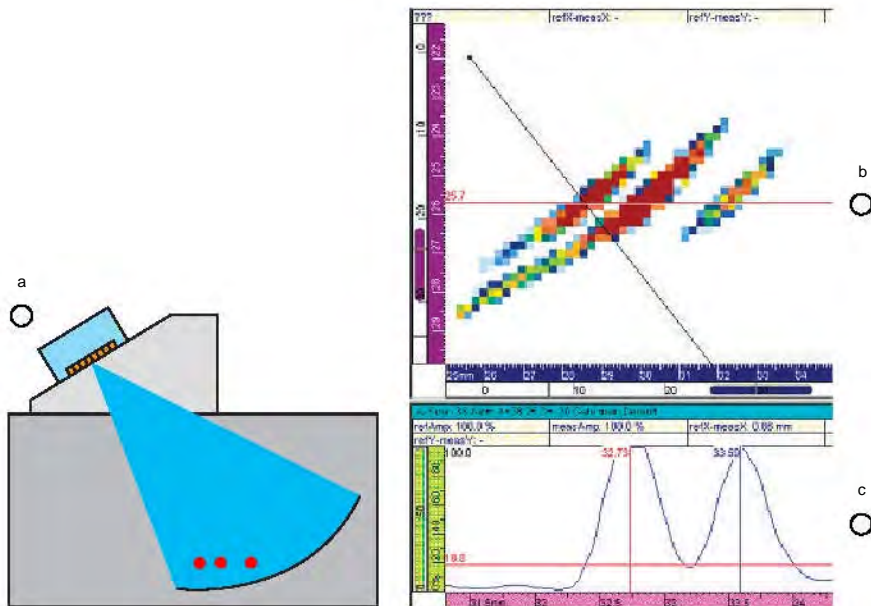
Figure 2-39 Angular resolution and detection of three 0.5-mm SDHs spaced apart by 0.8 mm and 1.2 mm. SDHs are located at z = 25.7 mm. Principle (a); angle-corrected true depth (b); and echo dynamic (c).

2.7.16

The *main lobe* is the acoustic pressure directed towards the programmed angle.

2.7.17   Side Lobes

Side lobes are produced by acoustic pressure leaking from probe elements at different and defined angles from the main lobe.

2.7.18   Grating Lobes

Grating lobes are generated by acoustic pressure due to even sampling across the probe elements (see Figure 2-40).

Their locations are given by formula (below):

$$\beta_{grating} = \sin^{-1}(m\lambda/p)$$

where:

$$m = \pm1, \pm2, \pm3,\dots$$
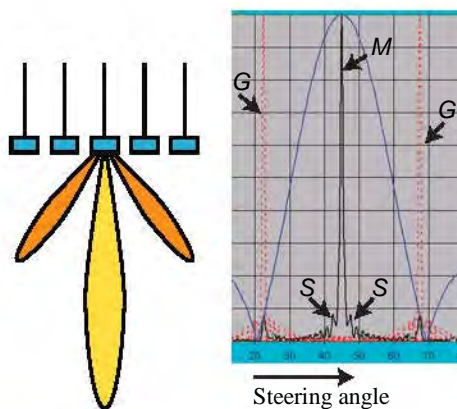
Figure 2-40 Directivity plot for a phased array probe: M = main lobe; S = side lobes; G = grating lobes. $\beta_{grating}$ is shown in orange; the main lobe, in yellow.

N.   _nization is achieved by:

- Minimizing the main lobe width
- Suppressing the side lobes
- Eliminating the grating lobe(s)

2.7.19   Beam Apodization

Beam apodization is a computer-controlled feature that applies lower voltage to the outside elements in order to reduce the side lobes.

Note: The Tomoscan FOCUS™ beam apodization is performed during the receiving stage. The gain applied to each element of the probe can be adjusted individually, but the pulse voltage is kept the same for each element.

2.7.20   Grating Lobe Amplitude

Grating lobe amplitude depends on pitch size, number of elements, frequency, and bandwidth (see Figure 2-41 and Figure 2-42).
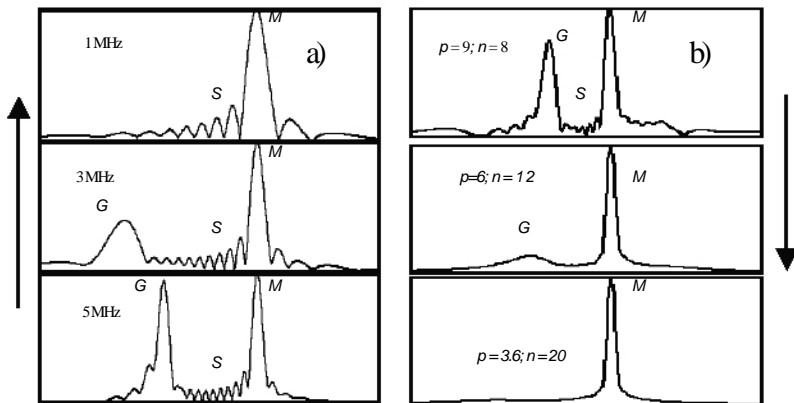
Figure 2-41 Grating lobe dependence on: (a) frequency; (b) pitch size and number of elements (same aperture of 72 mm).
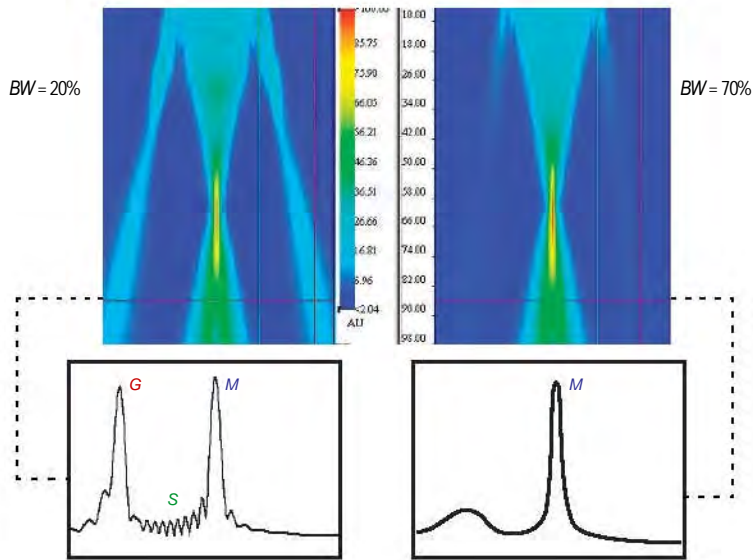
Figure 2-42 Influence of damping (BW_{rel}) on grating lobes for a 1-MHz probe focusing at $z = 60$ mm (simulation using PASS).

Grating lobes may be reduced though:

- Decreased frequency
- Reduced pitch size
- Increased bandwidth, which spreads out the grating lobes
- Reduced sweeping range (addition of a wedge)
- Subdicing (cutting elements into smaller elements)
- Randomized element spacing (using irregular element positioning to break up the grating lobes)

2.8 Dynamic Depth Focusing

Dynamic depth focusing (DDF) is a programmable, real-time array response on reception by modifying the delay line, gain, and excitation of each element as a function of time (see Figure 2-43). DDF replaces multiple focal laws for the same focal range by the product of the emitted beam with separate "focused beams" at the receiving stage. In other words, DDF dynamically changes the focal distance as the signal returns to the phased array probe. DDF significantly increases the depth-of-field and SNR.
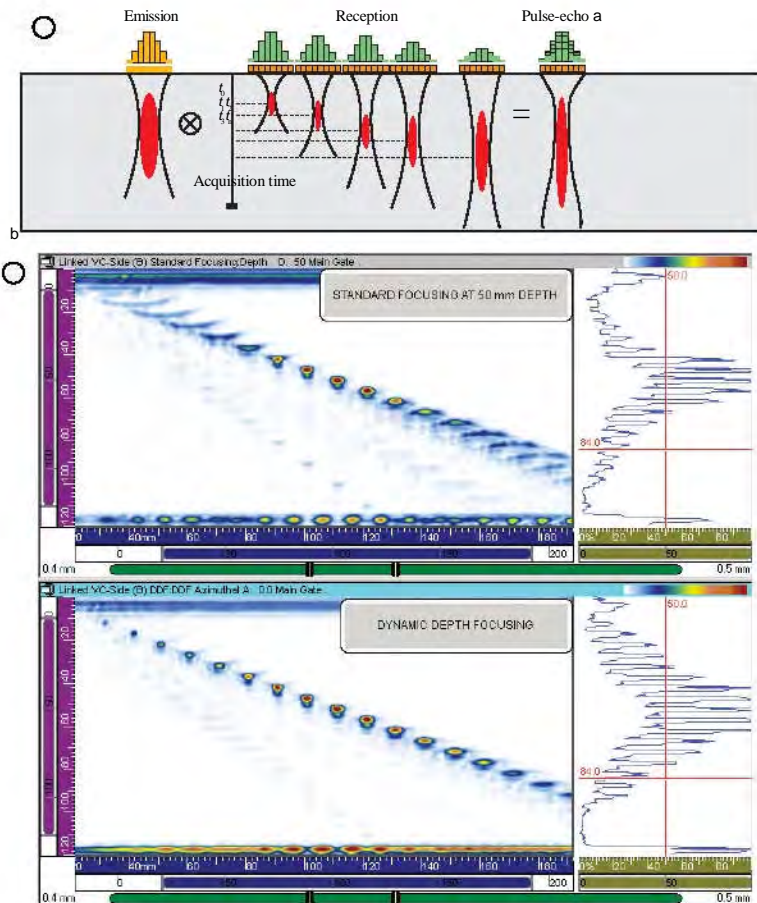
Figure 2-43 Dynamic depth focusing (DDF): (a) principle-resulting beam by product; (b) comparison between standard phased array focusing (*top*) and DDF on the depth-of-field (*bottom*). Note the detection of two SDHs in the near-surface zone by DDF that are missed by standard phased array focusing.

2.8.1   DDF Beam Divergence

The *DDF beam divergence on acoustic axis* ΔX_{-6} dB (SDH) is the beam width measured using the echo-dynamic amplitude from side-drilled hole reflectors when the DDF board is enabled.

A comparison of DDF with the standard phased array probes is presented in Figure 2-44. Note the narrow beam of the DDF compared to standard phased array focusing.
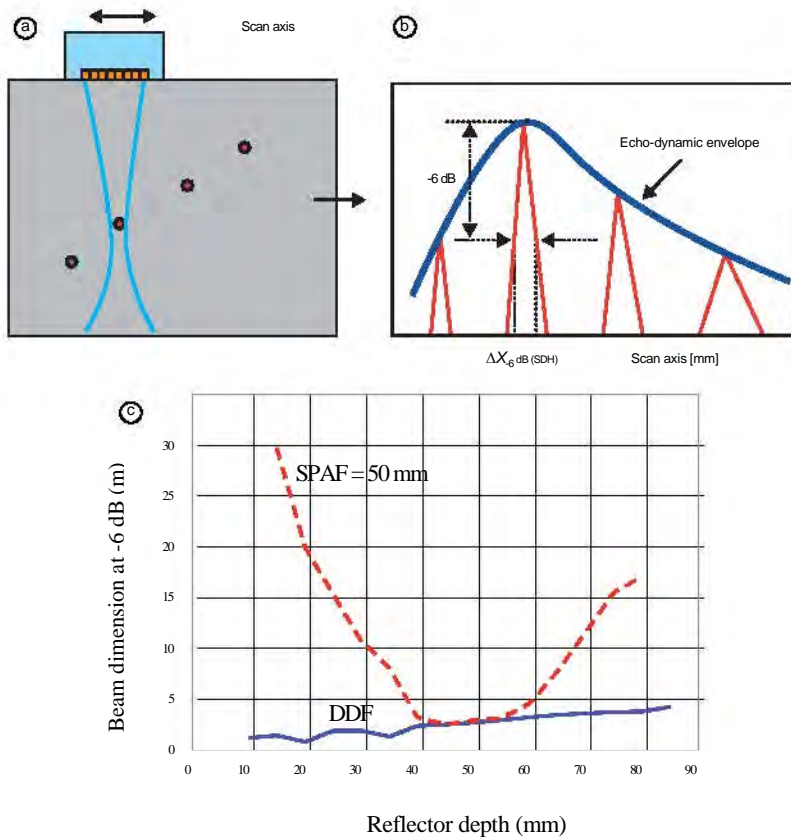
Figure 2-44 Beam divergence: (a) principle; (b) longitudinal waves at 0°; (c) comparison between standard phased arrays (SPAF) and DDF.

2.8.2 DDF Advantages

DDF has the following advantages:

- The depth-of-field generated by an optimized DDF is improved by a factor of four in practical applications with respect to standard focusing.
- The beam spot produced by DDF is always as small as the one produced by standard focusing, or smaller.
- The use of DDF creates very small beam spreads. Half angles as small as 0.30 and 0.14 degrees were obtained with linear and annular array probes.
- DDF diminishes the beam spread without altering the dimension of the beam obtained with the standard phased array.

- The SNR_{DDF} is greater than the SNR_{SPAF}.
- File size is greatly reduced because only one A-scan is recorded at each mechanical position.
- Effective PRF is increased because only one A-scan is needed to cover a long sound path instead of multiple pulses from individual transducers.

All of these properties make the use of DDF suitable for applications such as boresonic, titanium billet, and blade root inspections[8]

2.9 Phas

Phased array probe assemblies usually include a plastic wedge. Wedges are used in both shear wave and longitudinal wave applications, including straight beam linear scans. These wedges perform basically the same function in phased array systems as in conventional single element flaw detection, coupling sound energy from the probe to the test piece in such a way that it mode converts and/or refracts at a desired angle in accordance with Snell's law. While phased array systems do utilize beam steering to create beams at multiple angles from a single wedge, this refraction effect is also part of the beam generation process. Shear wave wedges look very similar to those used with conventional transducers, and like conventional wedges they come in many sizes and styles. Some of them incorporate couplant feed holes for scanning applications. Some typical phased array probe wedges are seen in Figure 2-45.

Figure 2-45 Phased array probe wedges

Zero-degree wedges are basically flat plastic blocks that are used for coupling sound energy and for protecting the probe face from scratches or abrasion in straight linear scans and low-angle longitudinal wave angled scans (see Figure 2-46).

Figure 2-46 A zero-degree wedge

2.10   Ph

Whenever waves originating from two or more sources interact with each other, there are phasing effects leading to an increase or decrease in wave energy at the point of combination. When elastic waves of the same frequency meet in such a way that their displacements are precisely synchronized (in phase, or zero-degree phase angle), the wave energies add together to create a larger amplitude wave (see Figure 2-47a). If they meet in such a way that their displacements are exactly opposite (180 degrees out of phase), then the wave energies cancel each other (see Figure 2-47c). At phase angles between 0 degrees and 180 degrees, there is a range of intermediate stages between full addition and full cancellation (see Figure 2-47b). **By varying the timing of the waves from a large number of sources, it is possible to use these effects to both steer and focus the resulting combined wavefront.** This is an essential principle behind phased array testing.

Waves in phase — Reinforcement

Intermediate condition

Waves out of phase — Cancellation
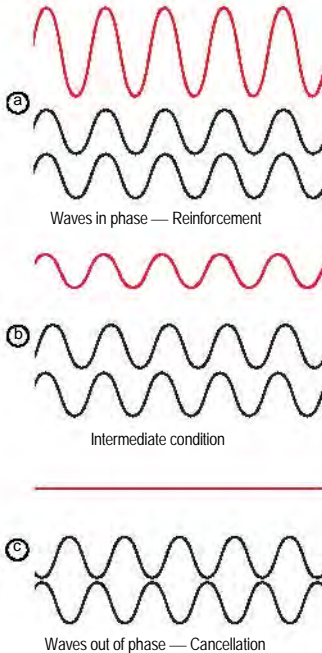
Figure 2-47 Phasing effects: combination and cancellation

In conventional transducers, constructive and destructive interference effects creat   es and the various pressure gradients the   l angle beam transducer uses a single element to launch a wave in a wedge. Points on this wavefront experience different delay intervals due to the shape of the wedge. These are mechanical delays, as opposed to the electronic delays employed in phased array testing. When the wavefront hits the bottom surface it can be visualized through Huygens' principle as a series of point sources. The theoretically spherical waves from each of these points interact to form a single wave at an angle determined by Snell's law.

In phased array testing, the predictable reinforcement and cancellation effects caused by phasing are used to shape and steer the ultrasonic beam. Pulsing individual elements or groups of elements with different delays creates a series of point source waves that combine into a single wavefront that travels at a selected angle (see Figure 2-48). This electronic effect is similar to the mechanical delay generated by a conventional wedge, but it can be further steered by changing the pattern of delays. Through constructive interference, the amplitude of this combined wave can be considerably greater than the amplitude of any one of the individual waves that produce it. Similarly, variable delays are applied to the echoes received by each element of the array. The echoes are summed to represent a single angular and/or focal component of the total beam. In addition to altering the direction of the primary wavefront, this combination of individual beam components allows beam focusing at any point in the near field.
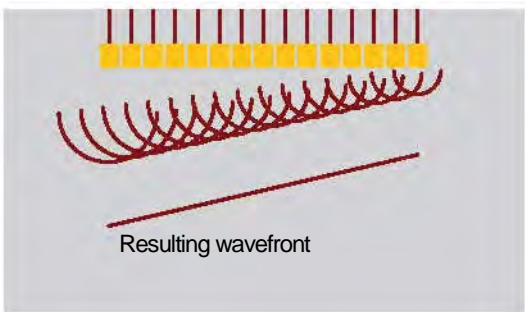
Figure 2-48 Angled waveform

Elements are usually pulsed in groups of 4 to 32 in order to improve effective sensitivity by increasing aperture, which reduces unwanted beam spreading and enables sharper focusing.

The returning echoes are received by the various elements or groups

of elements and time-shifted as necessary to compensate for varying wedge dela   conventional single element transducer,   ects of all beam components that strike its area, a phased array probe can spatially sort the returning wavefront according to the arrival time and amplitude at each element. When processed by instrument software, each returned focal law represents the reflection from a particular angular component of the beam, a particular point along a linear path, and/or a reflection from a particular focal depth. The echo information can then be displayed in any of several standard formats.

As noted previously, phased array beams are generated by pulsing the individual probe elements or groups of elements in a particular pattern. Phased array instruments generate these patterns based on information that has been entered by the user.

Software known as a *focal law calculator* establishes specific delay times for firing each group of elements in order to generate the desired beam shape through wave interaction, taking into account probe and wedge characteristics as well as the geometry and acoustical properties of the test material. The programmed pulsing sequence selected by the instrument's operating software, then launches a number of individual wavefronts in the test material. These wavefronts in turn combine constructively and destructively into a single primary wavefront that travels through the test material and reflects off cracks, discontinuities, back walls, and other material boundaries as with any conventional ultrasonic wave. The beam can be dynamically steered through various angles, focal distances, and focal spot sizes in such a way that a single probe assembly is capable of examining the test material across a range of different perspectives. This beam steering happens very quickly, so that a scan from multiple angles or with multiple focal depths can be performed in a fraction of a second.

2.11   Beam Shaping and Steering

The response of any ultrasonic test system depends on a combination of factors: the transducer used, the type of instrument used and its settings, and the acoustic properties of the test material. The responses produced by phased array probes, like those from any other ultrasonic transducers for NDT, are related both to transducer design parameters (such as frequency, size, and mechanical damping), and to the parameters of the excitation pulse that is used to drive the probe.

Four important probe parameters have a number of interrelated effects on performance.

Frequency. As noted in the previous section, the test frequency has a significant effect on near-field length and beam spreading. In practice, higher frequencies can provide better signal-to-noise ratio than lower frequencies, because they offer potentially sharper focusing and thus

a tighter, more optimized focal spot. At the same time, penetration in any test material increases because material attenuation in lications involving very long sound paths or test materials that are highly attenuating or scattering require the use of lower frequencies. Commonly, industrial phased array probes are offered with frequencies between 1 MHz and 15 MHz.

Element size. As the size of individual elements in an array decreases, its beam steering capability increases. The minimum practical element size in commercial probes is typically near 0.2 mm. However, if the element size is less than one wavelength, strong unwanted side lobes will occur.

Number of elements. As the number of elements in an array increases, so can the physical coverage area of the probe and its sensitivity, focusing capability, and steering capability. At the same time, use of large arrays must often be balanced against issues of system complexity and cost.

Pitch and aperture. Pitch is the distance between individual elements; *aperture* is the effective size of a pulsing element that is usually comprised of a group of individual elements that are pulsed simultaneously (virtual aperture). To optimize steering range, pitch must be small. For optimum sensitivity, minimum unwanted beam spreading, and strong focusing, the aperture must be large. Today's phased array instruments most commonly support focal laws for up to 16-element apertures. More advanced systems allow up to 32- or even 64-element apertures.

The key concepts for a general understanding phased array beam can be summarized as follows: A group of elements is fired with a programmed focal law. This builds the desired probe aperture and beam characteristics.

Decreasing pitch and elements width with a constant number of elements	*Increases beam steering capability*
Increasing pitch or frequency	*Creates unwanted grating lobes*
Increasing element width	*Creates side lobes (as in conventional UT), reduces beam steering*
Increasing active aperture by using many small elements with small pitch	*Increases focusing factor (sharpness of beam)*

As noted in previous pages, the essence of phased array testing is an ultrasonic beam whose direction (refracted angle) and focus can be steered electronically by varying the excitation delay of individual elements or groups of elements. This beam steering permits multiple angle and/or multiple point inspection from a single probe and a single probe position (see Figure 2-49).
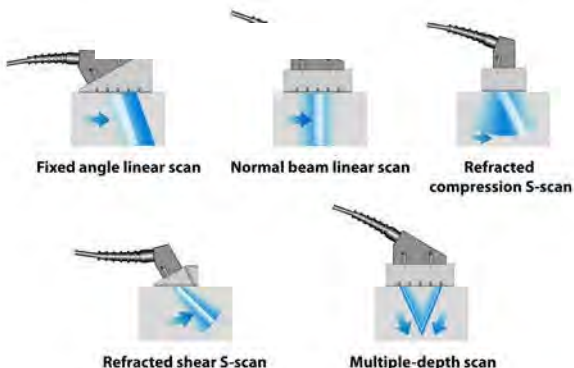
Figure 2-49 Focal law sequences

As previously explained, ultrasonic beam characteristics are defined by many factors. In addition to element dimension, frequency, and damping that govern conventional single element performance, phased array probe behavior is affected by how smaller individual elements are positioned, sized, and grouped to create an effective aperture equivalent to its conventional counterpart.

For phased array probes N elements are grouped together to form the effective aperture for which beam spread can be approximated by conventional transducer models (see Figure 2-50).
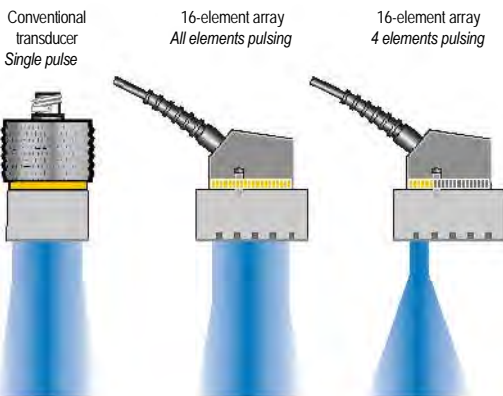
Figure 2-50 Effective aperture

For phased array probes, the maximum steering angle (at -6 dB) in a given case i   equation. It can be easily seen that sm   preading and hence higher angular energy content, which can be combined to maximize steering. As element size decreases, more elements must be pulsed together to maintain sensitivity.

$$\sin\theta_{st} = 0.514 \frac{\lambda}{e}$$

where:

$\sin\theta_{st}$	= sine of the maximum steering angle
λ	= wavelength in test material
e	= element width
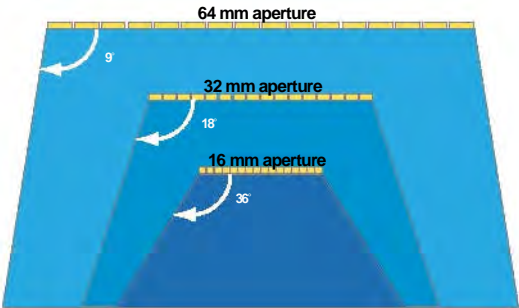
Figure 2-51 Beam steering limits: When the element number is constant, 16 as shown, the maximum beam steering angle increases as the aperture size decreases.

Recalling that the practical limit for phased array probe manufacturing restricts the smallest individual element width to 0.2 mm, the active aperture for a 16-element probe with 0.2 mm elements would be 3.2 mm. Creating an aperture of 6.4 mm would require 32 elements. While these probes would no doubt maximize steering, the small apertures would limit static coverage area, sensitivity, penetration, and focusing ability.

The steering range can be further modified by using an angled wedge to change the incident angle of the sound beam independently of electronic steering.

From the beam spread angle, the beam diameter at any distance from the probe can be calculated. In the case of a square or rectangular phased array probe, beam spreading in the passive plane is similar to that of an unfocused transducer. In the steered or active plane, the beam can be electronically focused to converge acoustic energy at a

desired depth. With a focused probe, the beam profile can typically be represented   e in the case of single-axis focusing) tha   nen diverges at an equal angle beyond the focal point, as described as follows:

The near-field length and hence the natural divergence of an ultrasonic beam are determined by aperture (equal to element diameter in the case of conventional monolithic transducers) and wavelength (wave velocity divided by frequency). For an unfocused circular probe, the near-field length, beam spread angle, and beam diameter can be calculated as follows:

$$\text{Near-field length} = \frac{D^2 f}{4c} = \frac{D^2}{4\lambda}$$

where:

D	= element diameter or aperture
f	= frequency
c	= sound velocity in test medium
λ	= wavelength = $\dfrac{c}{f}$

For the formula for square or rectangular elements.

2.12 Beam Focusing with Phased Array Probes

Sound beams can be focused like light rays, creating an hourglass-shaped beam that tapers to a minimum diameter at a focal point and then expands once past that focal point (see Figure 2-52).
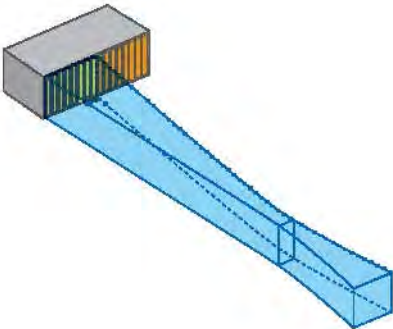
The depth at which the beam from a phased array focuses can be varied by ch   r-field length in a given material defi   h a sound beam can be focused. A beam cannot be focused beyond the end of the near field in the test material.

A focused probe's effective sensitivity is affected by the beam diameter at the point of interest. The smaller the beam diameter, the greater is the amount of energy that is reflected by a small flaw. Additionally, the small beam diameter at the focus can improve lateral resolution. The -6 dB beam diameter or width of a focused probe at the focal point can be calculated as follows:

$$\text{-6 dB beam diameter or width} = \frac{1.02\,Fc}{fD}$$

where:

F	= focal length in test medium
c	= sound velocity in test medium
D	= element diameter or aperture

For rectangular elements, this is calculated separately for the active and passive directions.

From these formulas it can be seen that as the element size and/or the frequency increase, the beam spread angle decreases. A smaller beam spread angle in turn can result in higher effective sensitivity in the far-field zone due to the beam energy dissipating more slowly. Within its near field, a probe can be focused to create a beam that converges rather than diverges. Narrowing the beam diameter or width to a focal point increases sound energy per unit area within the focal zone and thus increases sensitivity to small reflectors. Conventional transducers usually do this with a refractive acoustic lens, while phased arrays do it electronically by means of phased pulsing and the resulting beam shaping effects.

In the case of the most commonly used linear phased arrays with rectangular elements, the beam is focused in the steering direction and unfocused in the passive direction. Increasing the aperture size increases the sharpness of the focused beam, as can be seen in these beam profiles (see Figure 2-53). Red areas correspond to the highest sound pressure, and blue areas to lower sound pressure.
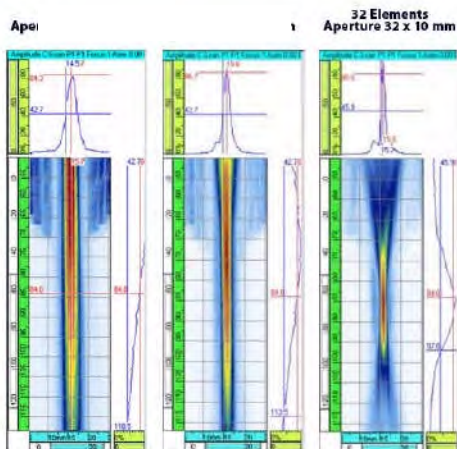
Figure 2-53 Beam focusing with different aperture sizes

2.13   Grating Lobes and Side Lobes

Another phenomenon associated with phased array probes is the generation of unwanted grating lobes and side lobes. These two closely related phenomena are caused by sound energy that spreads out from the probe at angles other than the primary sound path. Side lobes are not limited to phased array systems—side lobes also occur with conventional transducers as element size increases. Grating lobes only occur in phased array probes as a result of ray components associated with the regular, periodic spacing of the small individual elements. These unwanted ray paths can reflect off surfaces in the test piece and cause spurious indications on an image. The amplitude of grating lobes is significantly affected by pitch size, the number of elements, frequency, and bandwidth. The beam profiles shown in Figure 2-54 compare two situations where the probe aperture is approximately the same, but the beam on the left is generated by six elements at 0.4 mm pitch, and the beam on the right by three elements at 1 mm pitch. The beam on the left is somewhat shaped as a cone, while the beam on the right has two spurious lobes at an approximate 30 degree angle to the center axis of the beam.
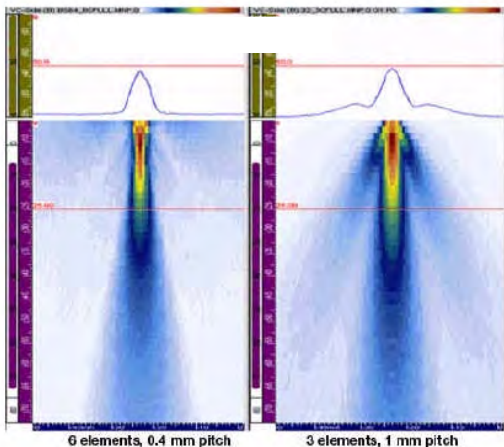
6 elements, 0.4 mm pitch   3 elements, 1 mm pitch
Figure 2-54 Beam profiles with different number of elements

Grating lobes occur whenever the size of individual elements in an array is equal to or greater than the wavelength. There are no grating lobes when the element size is smaller than half a wavelength. (For element sizes between one-half and one wavelength, the generating of grating lobes depends on the steering angle.) Thus the simplest way to minimize grating lobes in a given application, is to use a probe with a small pitch. A specialized probe design incorporating subdicing (cutting elements into smaller elements) and varying element spacing, also reduces unwanted lobes.

2.14 Phased Array Probe Selection Summary

Designing phased array probes is always a compromise between selecting the proper pitch, element width, and aperture. Using a high number of small elements to increase steering, reduces side lobes and provides focusing, but can be limited by cost of manufacturing and instrument complexity. Most standard instruments support apertures of up to 16 elements. Separating elements at greater distances can seem to be the easy way of gaining aperture size, but this creates unwanted grating lobes.

It is important to note that vendors of phased array probes often offer standard probes that have been designed with these compromises in mind, resulting in optimized performance for the intended use. Actual probe selection is ultimately driven by the end application needs. In some cases, multiangle steering is required over small metal paths so large aperture sizes are not needed or desired. In other cases, the application, which may be to cover large areas for laminar defects, require large apertures and linear scan format with multiple grouped elements where steering is not required at all. In general, the user can apply the best practice from their conventional UT knowledge for freq

3. Basics of Phased Array Imaging

Both conventional and phased array ultrasonic instruments utilize high-frequency sound waves to check the internal structure of a test piece or measure its thickness. They both rely on the same basic laws of physics that govern sound wave propagation. Similar concepts are employed in both ultrasonic technologies to present ultrasonic data.

Conventional ultrasonic instruments for NDT commonly consist of either a single active element that both generates and receives high- frequency sound waves, or two paired elements, one for transmitting and one for receiving. A typical instrument consists of a single channel pulser and receiver that generates and receives an ultrasonic signal with an integrated digital acquisition system, which is coordinated with an onboard display and measurement module. In more advanced units, multiple pulser receiver channels can be used with a group of transducers to increase zone of coverage for evaluating different depths or flaw orientations, and can further provide alarm outputs. In more advanced systems, conventional ultrasonics can be integrated with positional encoders, controllers, and software as part of an imaging system.

Phased array instruments, on the other hand, are naturally multichanneled as they need to provide excitation patterns (focal laws) to probes with 16 to as many as 256 elements. Unlike conventional flaw detectors, phased array systems can sweep a sound beam from one probe through a range of refracted angles, along a linear path, or dynamically focus at a number of different depths, thus

increasing both flexibility and capability in inspection setups. This added ability to ger   n one probe, adds a powerful advantage i   the ability to "visualize" an inspection by creating an image of the inspection zone. Phased array imaging provides the user with the ability to see relative point-to-point changes and multiangular defect responses, which can assist in flaw discrimination and sizing. While this can seem inherently complex, it can actually simplify expanding inspection coverage with increased detection by eliminating the complex fixtures and multiple transducers that are often required with conventional UT inspection methods.

The following sections further explain the basic formats for conventional and phased array data presentation.

3.1 A-Scan Data

All ultrasonic instruments typically record two fundamental parameters of an echo: how large it is (amplitude) and where it occurs in time with respect to a zero point (pulse transit time). Transit time, in turn, is usually correlated to reflector depth or distance, based on the sound velocity of the test material and the following simple relationship:

$$Distance = Velocity \times Time$$

The most basic presentation of ultrasonic waveform data is in the form of an *A-scan*, or waveform display, in which echo amplitude and transit time are plotted on a simple grid with the vertical axis representing amplitude and the horizontal axis representing time. The example in Figure 3-1 shows a version with a rectified waveform; unrectified RF displays are also used. The red bar on the screen is a gate that selects a portion of the wave train for analysis, typically the measurement of echo amplitude and/or depth.
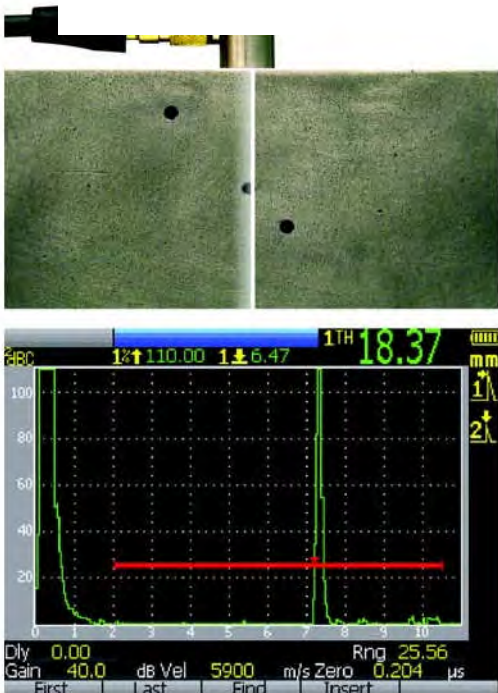
Figure 3-1 A-scan data

3.2   Single Value B-Scans

Another way of presenting the A-scan data is as a *single value B-scan*. This format is commonly used with conventional flaw detectors and corrosion thickness gages to plot the depth of reflectors with respect to their linear position. The thickness is plotted as a function of time or position, while the transducer is scanned along the part to provide its depth profile. Correlating ultrasonic data with the actual transducer position allows a proportional view to be plotted and allows the ability to correlate and track data to specific areas of the part being inspected. This position tracking is typically done through the use of electromechanical devices known as *encoders*. These encoders are used either in fixtures, which are manually scanned, or in automated systems that move the transducer by a programmable motor-

controlled scanner. In either case, the encoder records the location of each data ac   d user-defined scan pattern and index res

In the case shown in Figure 3-2, the B-scan shows two deep reflectors and one shallower reflector, corresponding to the positions of the side-drilled holes in the test block.
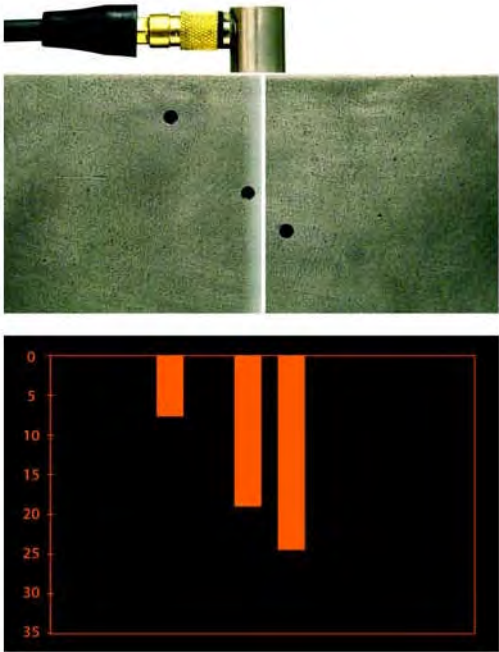
Figure 3-2 B-scan data

3.3 Cross-sectional B-Scans

A *cross-sectional B-scan* provides a detailed end view of a test piece along a single axis. This provides more information than the single value B-scan presented earlier. Instead of plotting just a single measured value from within a gated region, the whole A-scan waveform is digitized at each transducer location. Successive A-scans are plotted over the elapsed time or the actual encoded transducer

positions so as to draw cross-sections of the scanned line. This allows the user to v   rface reflectors within the sample. With   data is often stored at each location, and may be recalled from the image for further evaluation or verification.

To accomplish this, each digitized point of the wave form is plotted so that color representing signal amplitude appears at the proper depth.

Successive A-scans are digitized, related to color, and "stacked" at user-defined intervals (elapsed time or position) to form a true cross- sectional image (see Figure 3-3).
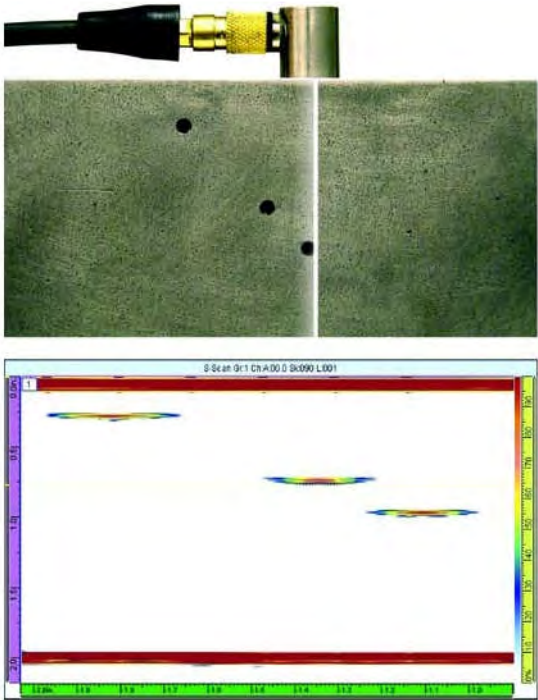
Figure 3-3 Cross-sectional B-scan

3.4 Line

A phased array system uses electronic scanning along the length of a linear array probe to create a cross-sectional profile without moving the probe. As each focal law is sequenced, the associated A-scan is digitized and plotted. Successive apertures are "stacked" creating a live cross-sectional view. In practice, this electronic sweeping is done in real time so a live cross section can be continually viewed as the probe is physically moved. Figure 3-4 is an image made with a 64- element linear phased array probe. In this example, the user programmed the focal law to use 16 elements to form an aperture and sequenced the starting element increments by one. This resulted in 49 individual waveforms that were stacked to create the real-time cross- sectional view across the probe's 1.5 in. length.
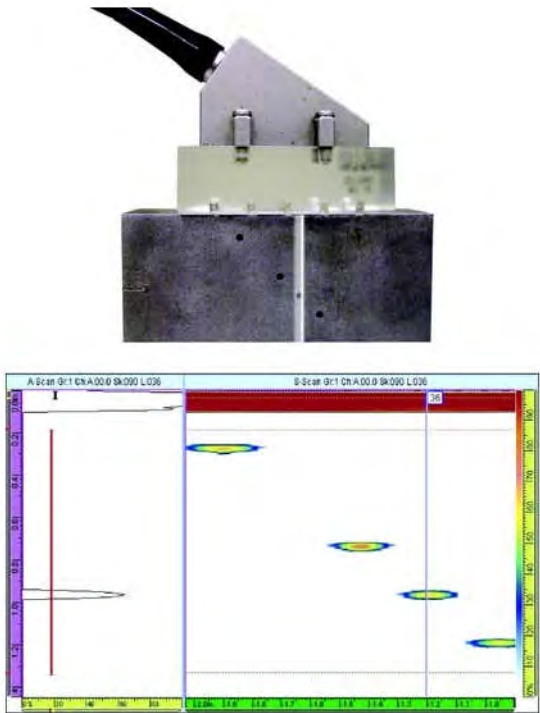
Figure 3-4 Normal beam linear scan

It is also possible to scan at a fixed angle across elements (see Figure 3-5). As disc   his is very useful for automated w   ent linear phased array probe with wedge, shear waves can be generated at a user-defined angle (often 45, 60, or 70 degrees). With aperture sequencing through the length of the probe, full volumetric weld data can be collected without physically increasing the distance to weld center line while scanning. This provides for single-pass inspection along the weld length.
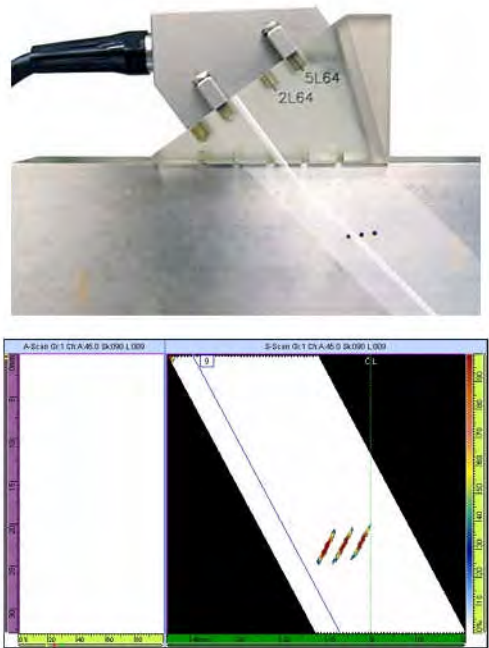
Figure 3-5 Angle beam linear scan

3.5   C-Scans

Another presentation option is a *C-scan*. A C-scan is a two- dimensional presentation of data displayed as a top or planar view of a test piece. It is similar in its graphic perspective to an x-ray image, where color represents the gated signal amplitude or depth at each point in the test piece mapped to its position. Planar images can be

generated o   to the X-Y position, or on cylindrical parts by tracking axial and angular positions. For conventional ultrasound, a mechanical scanner with encoders is used to track the transducer's coordinates to the desired index resolution.

A C-scan from a phased array system is very similar to one from a conventional probe. With phased array systems, however, the probe is typically moved physically along one axis while the beam electronically scans along the other, according to the focal law sequence. Signal amplitude or depth data is collected within the gated region of interest just as in conventional C-scans. In the case of phased arrays, data is plotted with each focal law progression, using the programmed beam aperture.

Figure 3-6 is a C-scan of a test block using a 5 MHz, 64-element linear array probe with a zero-degree wedge. Each focal law uses 16 elements to form the aperture, and at each pulsing the starting element increments by one. This results in forty-nine data points that are plotted (horizontally in the image of Figure 3-6) across the probe's 37 mm (1.5 in.) length. As the probe is moved forward in a straight line, a planar C-scan view emerges. Encoders are normally used whenever a precise geometrical correspondence of the scan image to the part must be maintained, although nonencoded manual scans can also provide useful information in many cases.

Generalized beam profile and
direction of motion

Phased array C-scan image
showing hole position
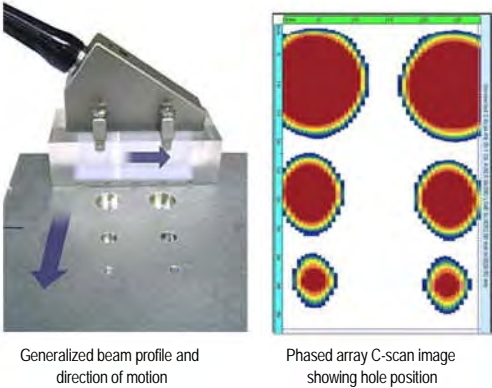
Figure 3-6 C-scan data using 64-element linear phased array probe

While the graphic resolution might not be fully equivalent to a conventional C-scan because of the larger effective beam size, there are other considerations. The phased array system is field portable, which the conventional system is not, and it costs about one-third the price. Additionally, a phased array image can often be made in a few

seconds, while a conventional immersion scan typically takes several minutes.

Linear phased array probes are also commonly used for performing refracted shear wave inspections along the length of welds. Figure 3-7 shows a 2.25 MHz 64-element phased array probe mounted on an angled wedge to create shear waves at a user-defined angle, typically 45, 60, or 70 degrees. With the probe positioned perpendicular to the weld, the aperture can be sequenced over the length of the probe. This effectively allows the refracted shear wave to move through the weld volume without mechanical movement of the probe from the weld's centerline. Full volumetric data can be presented by sliding the probe parallel to the weld line. Using an encoder, data can be plotted in a C-scan like format where amplitude of the reflector is plotted as a function of aperture position (Y-axis) and distance traveled along the weld (X-axis). This scanning format is often referred to as a "one-line scan." For producing repeatable results, a mechanical scanner is suggested. In Figure 3-7, a reflection from the un-ground weld bottom is plotted along the whole weld length at the top of the image. The A-scan and cursors mark a large indication from an area of the weld with lack of side wall fusion.
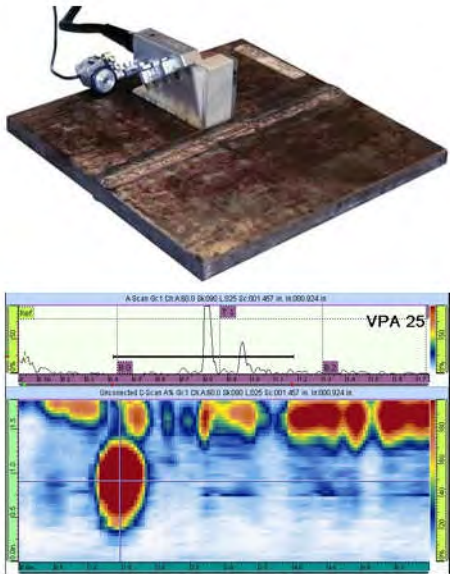
Figure 3-7 One-line scan for weld inspection using an encoded 2.25 MHz 64-element probe steered at 60 degrees

3.6 S-Sc

Of all imaging modes discussed so far, the *S-scan* is unique to phased array equipment. In a linear scan, all focal laws employ a fixed angle with sequencing apertures. S-scans, on the other hand, use fixed apertures and steer through a sequence of angles.

Two main forms are typically used. The most familiar, very common in medical imaging, uses a zero-degree interface wedge to steer longitudinal waves, creating a pie-shaped image showing laminar and slightly angled defects (see Figure 3-8).
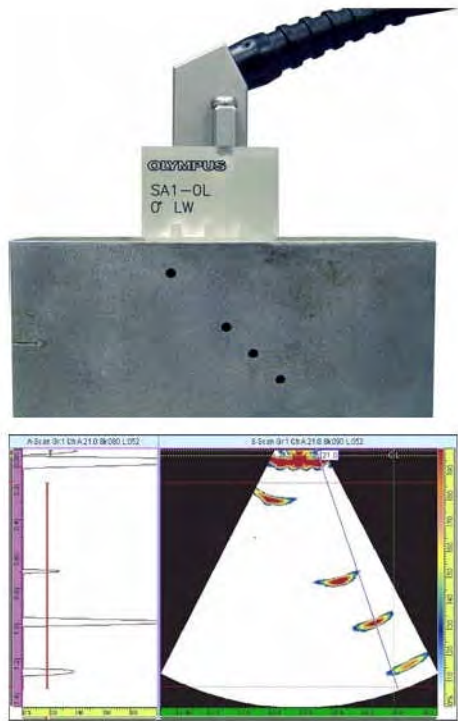
Figure 3-8 -30° to +30° S-scan

The second format employs a plastic wedge to increase the incident beam angle to generate shear waves, most commonly in the refracted

angle range of 30 to 70 degrees. This technique is similar to a conventiona   hat the beam sweeps through a range of a   ngle determined by a wedge. As with the linear sectorial scan, the image presentation is a cross-sectional picture of the inspected area of the test piece (see Figure 3-9).
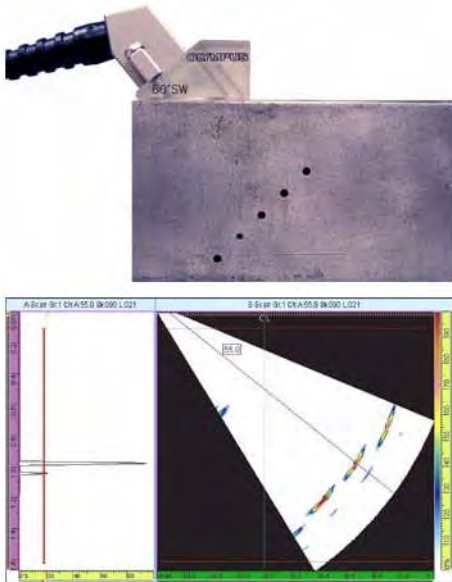
Figure 3-9 +35° to +70° S-scan

The actual image generation works on the same stacked A-scan principle that was discussed in the context of linear scans introduced in the previous section. The user defines the angle start, end, and step resolution to generate the S-scan image. Notice that the aperture remains constant, each defined angle generating a corresponding beam with characteristics defined by aperture, frequency, damping, and the like. The waveform response from each angle (focal law) is digitized, color-coded, and plotted at the appropriate corresponding angle, building a cross-sectional image.

In actuality the S-scan is produced in real time so as to continually offer dynamic imaging with probe movement. This is very useful for defect visualization and increases probability of detection, especially

with respect to randomly oriented defects, as many inspection angles can be used a

3.7 Combined Image Formats

Phased array images are powerful in their ability to provide real-time visualization of volumetric data. Through the electronic scanning process, imaging truly becomes real-time and is used in both manual and automated systems to increase probability of detection. Especially in automated and more capable phased array instruments, the ability to display multiple image types and store complete raw waveform information for the entire inspection, allows post-scanning analysis of the inspection results. Because all the ultrasonic waveform data is collected, this post-analysis enables the reconstruction of sectorial scans, C-scans, and/or B-scans with corresponding A-scan information at any inspection location. For example, the screen in Figure 3-10 simultaneously displays the rectified A-scan waveform, a sector scan, and a planar C-scan image of the weld profile.
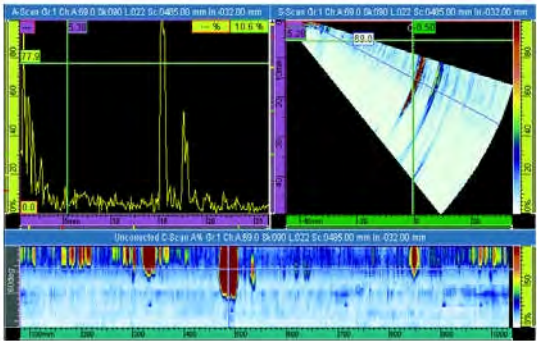
Figure 3-10 Multiple image types display

3.8 Scan Rate and Data Acquisition

When generating B-scans or C-scans, a phased array probe can be moved either by hand or by an automated scanning fixture. In either case, data acquisition can be free-running based solely on the instrument's update rate, or correlated to the probe position through the use of electromechanical encoders. As noted above, correlating ultrasonic data with the actual probe position allows a proportional view to be plotted and data to be matched to specific areas of the part being inspected. The encoder records the location of each data

acquisition with respect to a desired user-defined scan pattern and index resolut

In order to avoid gaps in data acquisition, it is important to consider the speed at which the probe is moving and the distance resolution of the encoder. In short, the instrument's data acquisition rate must be greater than the scanning speed, divided by the encoder resolution. The acquisition rate is determined by instrument design and setup, most importantly by the pulse repetition frequency (PRF), and by the number of focal laws being generated for each acquisition, both of which are setup variables. The PRF divided by the number of focal laws represents the fastest possible acquisition rate for a phased array system. However, that number can be further adjusted by factors such as averaging, digital sampling rate, and processing time. Consult the instrument manufacturer for details.

Once the acquisition rate has been established, the maximum scan speed can be calculated based on the desired encoder resolution, or vice versa. The effect of an excessive scanning speed for a given encoder resolution can be seen in the scan images in Figure 3-11.

<div style="border:1px solid">

⚠️ **IMPORTANT**

1. $\text{Acquisition rate} > \dfrac{\text{Scanning speed}}{\text{Scan axis resolution}}$

2. If the same PRF is set for all A-scans, then:

$\text{Acquisition rate} < \dfrac{\text{Recurrence}}{\text{Number of focal laws}}$

</div>

$$\text{Acquisition rate} > \frac{\text{scanning speed}}{\text{encoder resolutions}}$$

20 mm/s → 10 mm/s →
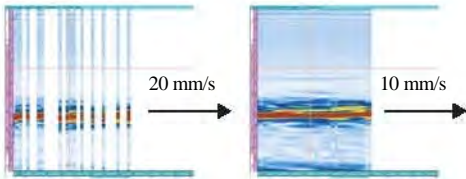
Figure 3-11 Example of the scanning speed influence on acquisition rate

3.9 Scanning Patterns

Reliable defect detection and sizing is based on scan patterns and specific functional combinations between the scanner and the phased array beam.

The inspection may be:

- *automated*: the probe carrier is moved by a motor-controlled drive unit;
- *semiautomated*: the probe carrier is moved by hand, but the movement is encoded; or
- *manual* (or *free running*): the phased array probe is moved by hand and data are saved based on acquisition time(s).

The acquisition may be triggered by the encoder position, the internal clock, or an external signal.

R/D Tech systems can provide the following inspection types:

- Tomoscan III, Tomoscan FOCUS™: automated, semiautomated, manual
- OmniScan® PA: automated, semiautomated, manual
- QuickScan™ PA, PipeWIZARD®:   automated   (semiautomated   for   calibration/mechanical settings)

The probe carrier may be moved in any of the inspection sequences presented in Table 3-1.

Table 3-1 Scan

Scanning pattern
Bidirectional
Unidirectional
Linear
Skewed
Helical
Spiral
Custom

3.9.1

In a *bidirectional seq*
backward directions

3.9.2   Unidirection

In a *unidirectional se*
along the scan axis (

Figure 3-12 Bidirectional (*left*) and unidirectional (*right*) raster scanning. The red line represents the acquisition path.

3.9.3 Linear Scan

A *linear scan* is a one-axis scanning sequence using only one position encoder (either scan or index) to determine the position of the acquisition.

The linear scan is unidimensional and proceeds along a linear path. The only settings that must be provided are the speed, the limits along the scan axis, and the   isitions (which may depend on the encoder resolution). Linear scans are frequently used for such applications as weld inspections and corrosion mapping. Linear scans with electronic scanning are typically an order of magnitude faster than equivalent conventional ultrasonic raster scans.

Linear scans are very useful for probe characterization over a reference block with side-drilled holes (see Figure 3-13).

Figure 3.13 Linear scan pattern for probe characterization.

3.9.4 Skewed Scan

The *skewed scan sequence* (also called *angular scan* under the TomoView™ 2.2 software) is a form of the normal bidirectional scan sequence. This sequence allows the scan and index probe path to be skewed by a software-selectable angle generated by small increments (closer to encoder resolution) on scan and index axis. This angle is different from the mechanical axes. The detail of Figure 4-3 shows the actual probe movement with average line trajectory to approximate this angled scan path.

This sequence is useful when the scanners axes and the inspected part cannot be placed in the best scan path relative to each other, and/or the defect location and orientation requires a specific scan pattern (line) for optimum detection and sizing. Selecting a specific scan path angle that best suits the inspected part or defect orientation can thus eliminate expensive scanner modifications, drastically reducing the file size and speeding up the defect analysis time.

The skewed scan sequence has the following features:

1. The skewed scan is used to inspect complex geometry components with defect orientation at an angle versus orthogonal axis.
2. The skewed scan allows you to adopt the linear array probe to a particular *specimen geometry*.
3. a factor of 2-3. Defect
4. amplitude increases by 6-8 dB.
5. You may increase the scanning speed by a factor of 2-4.
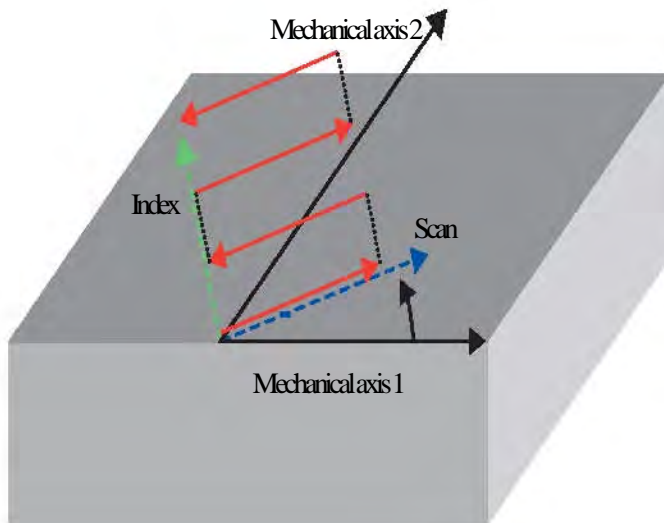
Courtesy of Ontario Power Generation Inc., Canada

Figure 3-14 Example of skewed (angular) bidirectional scanning. *Left*: probe scanning pattern versus the mechanical axes on a complex part; *right*: probe trajectory (red line) is skewed versus mechanical rectangular axes for an optimum angle to detect cracks in stress area.

3.9.5   Helical Scan

The *helical sequence* is used to inspect *cylindrical surfaces*. The scanner performs a helicoidal movement around the cylinder.

Two independent encoders control the sequence. The *scan-axis* encoder controls the continuous rotation around the cylinder, while the *index-axis* encoder controls the continuous movement along the length of the cylinder. A synchronization signal can be used to reset the scan-axis encoder to position zero after every rota⸱⸱⸱⸱⸱⸱⸱⸱⸱⸱⸱⸱ ⸱⸱⸱⸱⸱⸱er.

The combinations of these two movements will create a helicoidal scan pattern (see Figure 3-15).
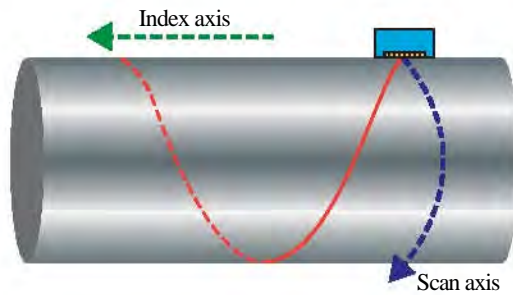
Figure 3-15 Helical surface scan on cylindrical parts. The red line is the acquisition path.

3.9.6   Spiral Scan

The *spiral sequence* is designed to inspect *circular surfaces* such as disc surfaces. The inspection mechanism performs a spiral movement on the circular surface (see Figure 3-16). Two independent encoders control the sequence. The *scan-axis* encoder controls the theta angle (θ) in the continuous rotation around the surface center; while the *index-axis* encoder controls the rho position (ρ) in the continuous movement along the radius. A signal can be used to reset the scan-axis encoder to position zero after every rotation.
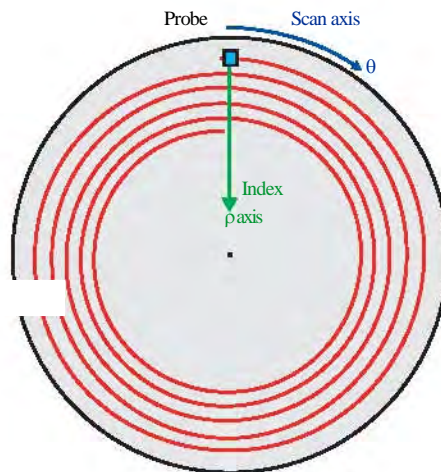
Figure 3-16 Spiral surface scan pattern. The red line is the acquisition path.

3.9.7 Beam Directions

The beam direction of the phased array probe may have the directions showing in Figure 3-17 compared with the scan and index axes. These directions are defined by the *probe skew angle*.
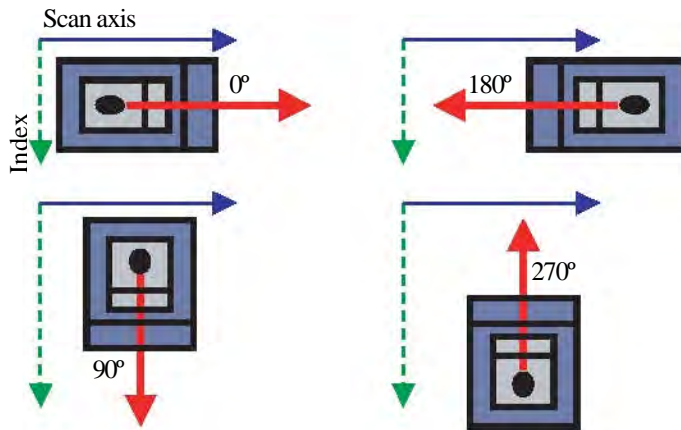
Figure 3.17 Probe position and beam direction related to scan and index axis. Skew angle must be input in the focal law calculator.

The limits of the inspection surface, as well as the spacing between acquisitions (resolution on each axis), will determine the scanning surface and pixel size of the ultrasonic data.

An example of setting up a scanning sequence using TomoView™ 2.2R9 is presented in Figure 3-18.
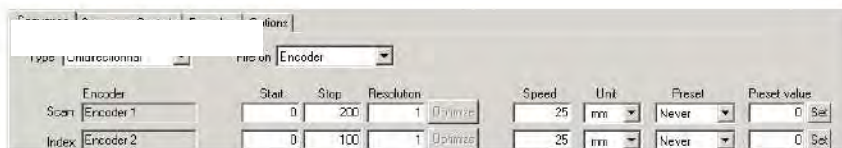
Figure 3-18 Unidirectional sequence of a 200-mm by 200-mm area. Pixel size of the C-scan is of 1 mm by 1 mm. Scanning speed on both axes is 25 mm/s.

3.9.8 Other Scanning Patterns

The part, the probe movement, and the beam direction may generate scanning patterns for any of the following combinations (see Table 3-2 and Figure 3-19 to Figure 3-21).

Table 3-2 Inspection sequence dependence on part, scanner, and beam.

Part	Scanner	Beam	Sequence
Fixed	Fixed	Linear (translation)	Linear scan
Fixed	Index axis	Linear (rotation)	Helicoidal
Translation	Fixed	Linear (rotation)	Helicoidal
Fixed	Scan axis	Linear (90° skew)	Unidimensional
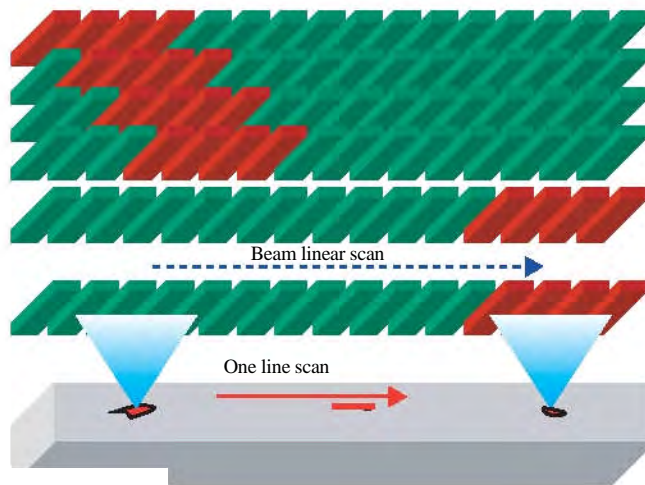
Figure 3-19 Beam electronic scan generating a linear scan pattern. Part and probe are not moving.
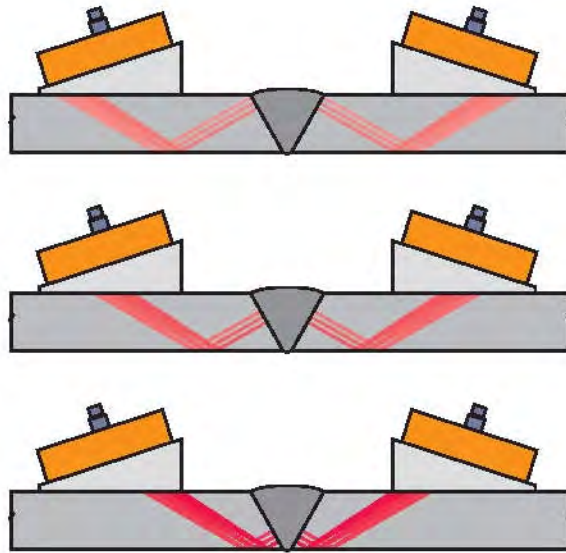
Figure 3-20 Electronic and linear scan of a weld (principle). Index axis (raster scan in conventional UT) is eliminated through electronic scan from the probe arrays, which increases speed and reliability. Note that wedges are usually used.
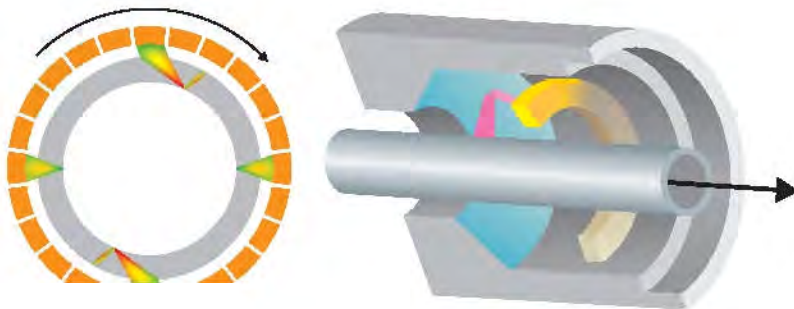
Figure 3-21 Generation of a helical scan by a combination of part translation and beam rotation.

3.9.9   Time-Base Scanning

If the encoder is set on time (clock), then the acquisition is based on scanning time (seconds) [see Figure 3-22].

The acquisition time for a time-base sequence is calculated by the total number of acquisitions, divided by the acquisition rate:

$$T_{\text{time-base}} = \frac{N_{\text{acquisitions}}}{N_{\text{A-scans/s}}}$$

(4.1)
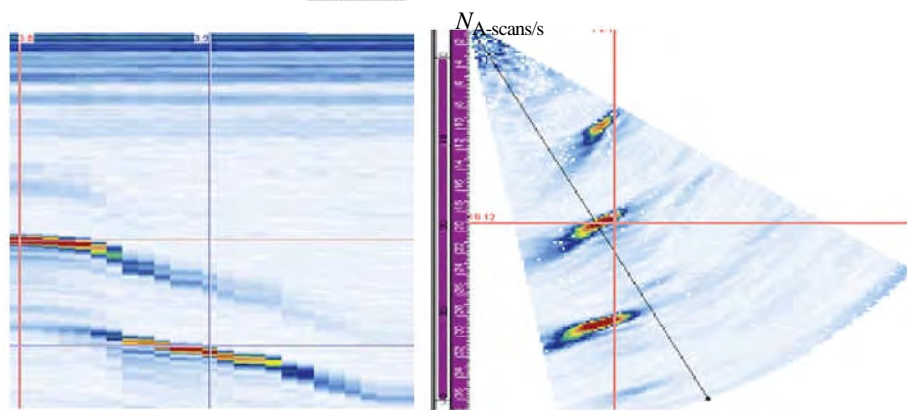
Figure 3-22 Time-base sequence examples: B-scan (*left*) and S-scan (*right*).

4. Phased Array Instrumentation

There is a wide variety of phased array probes commercially available. While the linear array probe is certainly the most commonly used configuration, customized probes with high element counts and varying element placements, are also available. They are often designed to meet demanding application needs that require high- speed, full volumetric coverage, and/or complex beam steering. To meet these needs, there are varying levels of phased array instrumentation now commercially available in three general classifications: field portable manual, field portable automated, and rack instruments for in-line inspection.

4.1   Important Specifications

When evaluating conventional flaw detectors, a number of functional characteristics are often specified. These characteristics are generally shared with phased array instruments. Not all of the items listed below are available in all instruments.

Pulser and receiver

Parameters that largely define the operating range of transducers that can be used with the instrument

Pulser	Receiver
Available spike pulser	Overall bandwidth
Available square wave pulser	Available narrowband filters
Pulser repetition frequency	Time-varied gain
	Overall dynamic range

Measurement and display

Parameters defining the general measurement and display modes of an instrument:

• Number of alarm/measurement gates

- A-scan display modes: Rectification (RF, Full Wave, Half Wave), Maximum, C̶ lled, and Peak Memory
- Range
- Measurement resolution
- Measurement types (that is, sound path, depth, distance from front of probe, dB, dB to curve, etc.)
- Single value B-scan mode (not available on most flaw detectors)

Sizing options

A variety of flaw detection standards and codes have been developed and are in practice for sizing a variety of defects using conventional ultrasonics. These apply to the inspection of welds as well as to a variety of metallic and composite structures. Certain inspections require that a specific code be followed. As a result, a wide variety of tools are now available in conventional digital flaw detectors to automate data acquisition and record test results as required by codes.

Inputs and outputs

Inputs and outputs generally define how the instrument can be used with external devices and/or software:

- Number and type of alarm outputs
- USB for printing, saving, or data transfer
- Availability of encoder inputs for linking data to position
- Trigger input for external control of pulser firing and acquisition cycle

Additional phased array specifications

Because of the multielement nature of phased array instruments, there are additional key specifications that need further consideration and review.

Number of pulsers. Defines the maximum number of elements that can be grouped to form an active aperture or virtual probe aperture.

Number of channels. Defines the total number of channels that can be used for sequencing apertures that leads to the potential increase in coverage from a single probe footprint.

XX:YY. Naming convention used, where XX = number of pulsers, and YY = total number of available channels. The number of channels is always greater or equal to number of pulsers. Instruments from 16:16 to 32:128 are available in field portable packaging. Higher pulser and receiver combinations are available for in-line inspections and/or systems that use larger element count probes.

Focal laws. The number of focal laws that can be combined to form an

image is often specified. In general, higher XX:YY configurations can support mo   ter element apertures and/or more apertu   that more focal laws does not always mean more functionality. Take the example below: a 64-element probe performing a 40 to 70 degrees sectorial scan of three side-drilled holes, comparing steering with 1 degree (31 laws), 2 degree (16 laws), and 4 degree (8 laws) steps over a 2 in. (50 mm) metal path (see Figure 4-1, Figure 4-2, and Figure 4-3). While the image is slightly better defined with finer angle increments, detection at a coarser resolution is adequate. Unless the beam diameter is drastically reduced with focusing, sizing from images does not dramatically change either.
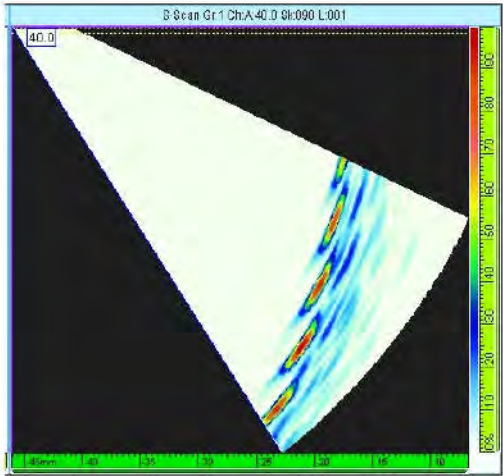
Figure 4-1 40 to 70 degrees S-scan: steering with 1 degree (31 laws) steps
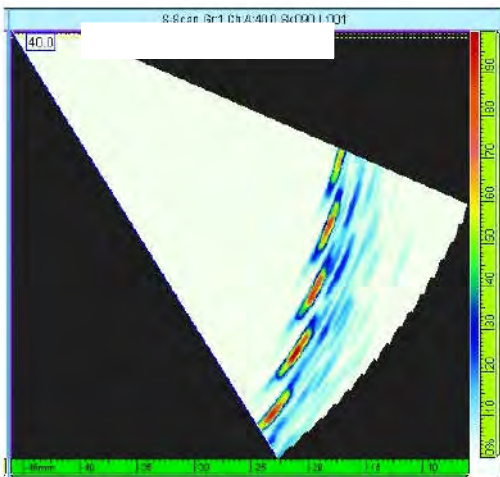
Figure 4-2 40 to 70 degrees S-scan: steering with 2 degree (16 laws) steps
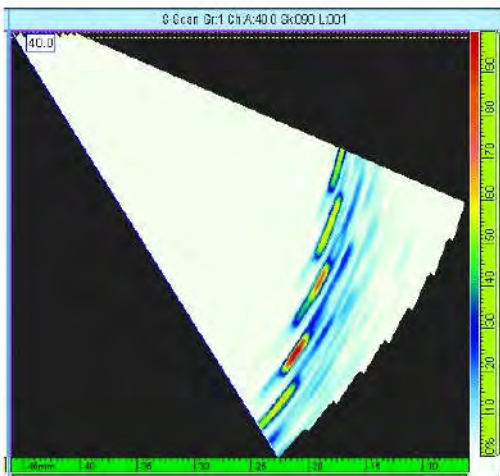
Figure 4-3 40 to 70 degrees S-scan: steering with 4 degree (8 laws) steps

Table 4-1 shows examples for the number of focal laws required to perform line   ns of virtual probe apertures and total ele   -1.

Table 4-1 Number of elements and focal laws required for linear scans

Linear scan			
Aperture	Total elements	Element step	Number of laws
4	16	1	13
8	16	1	9
4	32	1	29
8	32	1	25
16	32	1	17
48	64	1	61
16	64	1	57
8	64	1	49
16	128	1	121
8	128	1	113
16	256	1	249
	256	1	241

It is readily apparent that a 16:16 configuration used with a 16- element probe to produce a 1 degree S-scan may only require 31 laws, while a 16:128 or 32:128 instrument configuration used in the linear scan mode with a 128-element probe might very well require up to 121 focal laws.

PRF/Display update rate. Instruments can vary greatly in display update in various image modes. For phased array imaging modes:

PRF × Number of focal laws = Maximum image display rate

An example of a reduced four-focal-law linear scan sequence with a 60 Hz image display update, is shown in Figure 4-4 for conceptualization.
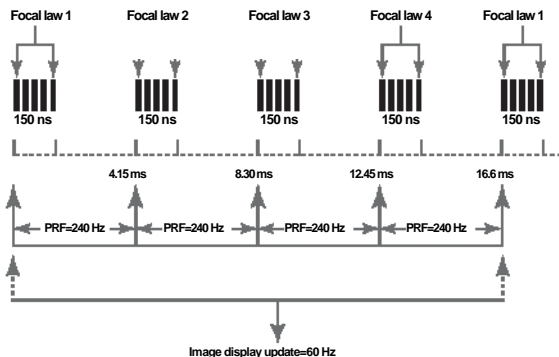
Figure 4-4 Example of a reduced four-focal-law linear scan sequence

The actual image display rate can be affected by other parameters. The A-scan refresh rate of a single focal law varies between instruments. In some instruments, the A-scan PRF rate is limited by the maximum image display update, whether it is shown with the phased array image or even when maximized to a full A-scan. For this reason, in some applications it might be important to verify the A-scan PRF when derived from a focal law sequence in various image display modes.

Probe recognition. The ability to recognize phased array probes reduces operator setup time and potential errors by automatically configuring an instrument setup with the proper number of elements and probe geometry.

Image types. Sectorial and linear scans are typically available in phased array instruments. The ability to stack these image modes to create amplitude and depth C-scans, allows planar images to be formed and provides expanded means for sizing defects.

Waveform storage. The ability to store raw RF waveforms allows data to be reviewed off-line. This is particularly useful when collecting data over a large area.

Multigroup support. More capable phased array instruments allow multiple focal law groups to be sequenced on one or more connected probes. This is especially useful in cases where it is important to collect volumetric data which is to be analyzed off-line. For example, a 5 MHz, 64-element probe can be programmed to use elements 1-16 for a 40 to 70 degree S-scan, while a second group can be used to perform a 60 degree linear scan with an aperture of 16 elements, stepping by one element over the entire 64-element length.

Encoding. There are two classes of instruments generally available: manual and

A manual phased array instrument works much like a conventional flaw detector as it provides real-time data. Along with an A-scan, the instrument also shows real-time S-scan or linear-scan images, which can aid in detection and discontinuity analysis. The ability to use and visualize more than one angle or position at a time in a test is the main reason for using this type of instrument. In some cases, such as crack sizing, the image can be used as a tool to help size crack depth.

A phased array instrument with an encoder interface merges probe positional data, probe geometry, and programmed focal law sequences to allow top-, end-, and side-view images of test specimen. In instruments that also store full waveform data, images can be reconstructed to provide cross-sectional views along the length of the scan or regenerate planar C-scans at various levels. These encoded images allow planar sizing of defects.

Reference cursors. Instruments provide various cursors that can be used on an image as aids for interpretation, sizing, and depth measurement. In an S-scan, it is possible to use cursors for measuring crack height. An approximate defect size can be measured when using encoded data sets. The images that follow show some examples of available cursors.

In the simplest display below (Figure 4-5), the blue cursor shows the angular component of the S-scan that is represented by the A-scan, the horizontal red lines mark the beginning and end of the data gate used for measurement, and the vertical green line marks the position on the image that corresponds to the front of the wedge. The latter is commonly used as a reference point for calculating reflector location, noting that near-surface reflectors might be located under the wedge, since the exact beam index point (BIP) for a phased array probe varies with angle and/or aperture group.
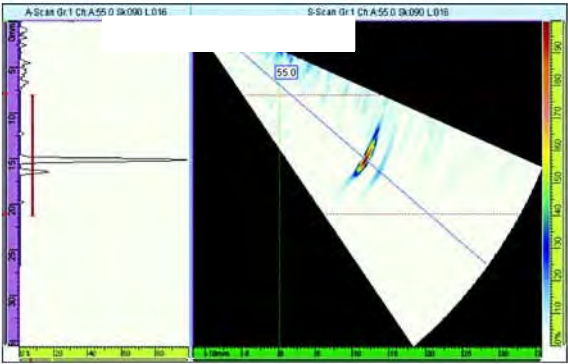
Figure 4-5 Angular cursor

The S-scan image in Figure 4-6 includes horizontal cursors representing the end of the first and second leg sound paths in the test material. It also shows the angular cursors marking the three most common test angles of 45, 60, and 70 degrees. In addition, the A-scan is marked with a vertical cursor at the 80 % amplitude point that is commonly used as a reference level.
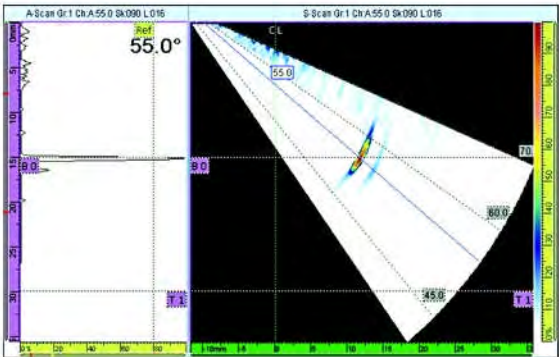
Figure 4-6 Angular and horizontal cursors

Advanced interpretive software further enhances visualization and analysis. The display in Figure 4-7 shows a single-angle A-scan, a S-scan, a ray-tracing diagram with a weld overlay that shows the position of reflectors within a weld, and a summary chart showing the

calculated position and measured amplitude of each indication.

Entry	Scan ...	Index ...	Group	Chan ...	A% %	DA^ mm	PA^ mm	SA^ mm
1 *	0.00	12.50	1	70.0°	51.3	20.33	15.23	59.44
2 *	0.00	12.50	1	50.0°	51.3	43.11	7.24	67.07
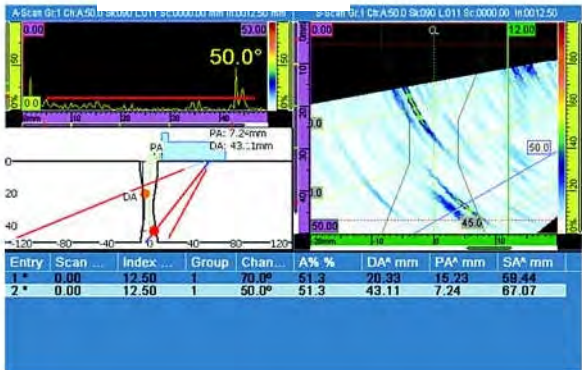
Figure 4-7 Multiple display formats

4.2   Calibration and Normalization Methods

Zero calibration. Because wedge delay varies with the angle in a phased array system, it is necessary to vary the probe zero offset across the angles. Typically, default zero profiles based on wedge geometry are programmed in instrument software, but these default profiles can be adjusted for higher accuracy through a calibration procedure by sweeping the beam across a reference reflector at a fixed depth or distance.

Gain normalization. Because beam formation relies on varying element delays and groups, it is important to normalize the amplitude response from each focal law to compensate for both element-to- element sensitivity variations in the array probe and for varying wedge attenuation and energy transfer efficiency at different refracted angles. Calibration of wedge delay and sensitivity over the entire inspection sequence not only provides clearer image visualization, but also allows measurement and sizing from any focal law. Olympus nondestructive testing instruments offer full calibration, whereas many other instruments in the industry can only calibrate one focal law at any one time. The Olympus instruments provide full Angle- Corrected Gain (ACG) and Time-Corrected Gain (TCG), as required by ASME Section V.

In the Figure 4-8 example, prior to gain normalization, the response from a reference reflector at 65 degrees, is significantly lower than from the same reflector at 45 degrees.
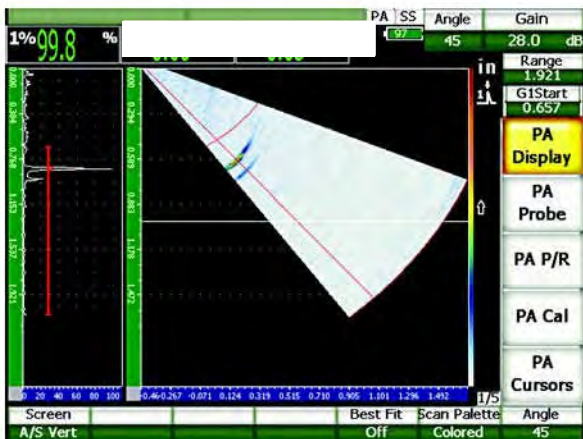
Figure 4-8 Response prior to gain normalization

Following normalization, the instrument adjusts the reference gain to equalize the response from the reference hole across all angles, as shown in Figure 4-9.
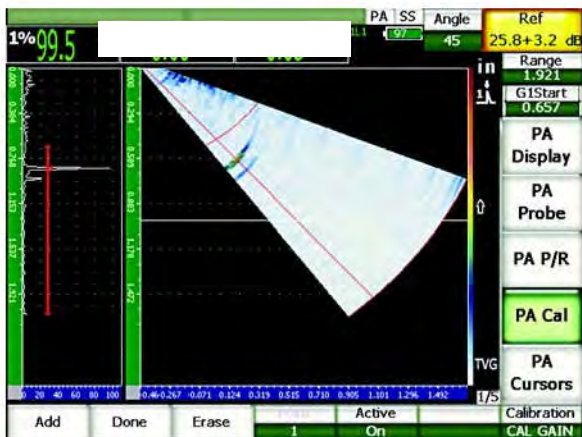
Figure 4-9 Response following gain normalization

TVG/DAC for phased array. For sizing defects, A-scan amplitude techniques using DAC curves or time-corrected gain, are common. These methods account for material attenuation effects and beam spreading by compensating gain levels (TVG/TCG) or drawing a reference DAC curve based on same size reflector response as a function of distance. As in conventional UT sensitivity calibrations,

some phased array instruments allow a TVG curve to be built at multiple points over all the defined focal laws. In these instruments, the view can be switched from TVG to DAC curve at any time. This allows the use of sizing curves across different angles in the case of S-scans or at any virtual aperture in linear scans. With TCG/TVG applied, the detection and visualization of defects throughout the part's volume is greatly enhanced.

5. Phased Array Test Setup and Display Format

This chapter provides further insight into how phased array images are constructed. In particular, it further explains required inputs, and the relationships of the various phased array display types with respect to the actual probe assembly and part being inspected. The chapter also explains the typically available A-scan views associated with the phased array image.

5.1 Instrument Setup Considerations

Figure 5-1 Typical phased array inspection using the OmniScan

As discussed previously, there are many factors that need to be identified in order to properly perform any ultrasonic inspection. In summary, there are material-specific characteristics and transducer characteristics needed to calibrate the instrument for a proper inspection.

Material

1. Velocity of   ds to be set in order to properly measure depth. Care must be taken to select the proper velocity mode (longitudinal or shear). Compressional straight beam testing typically uses longitudinal waves, while angle beam inspections most often use shear wave propagation.

2. Part thickness information is typically entered. This is particularly useful in angle beam inspections. It allows proper depth measurement relative to the leg number in angle beam applications. This also allows correct position markers on S-scans.

3. Radius of curvature should be considered when inspecting nonflat parts. This curvature can be algorithmically accounted for to make more accurate depth measurements.

Probe

1. The frequency must be known to allow for proper pulser parameters and receiver filter settings.

2. Zero Offset must be established in order to offset electrical and mechanical delays resulting from coupling, matching layer, cabling, and electronic induced delays for proper thickness readings.

3. The amplitude response from known reflectors must be set and available for reference in order to use common amplitude sizing techniques.

4. Angle of sound beam entry into the material being inspected.

5. For phased array probes, the number of elements and pitch need to be known.

Wedge

1.   Velocity of sound propagation through the wedge.
2.   Incident angle of the wedge.
3.   Beam index point or front of probe reference. 4.
     First element height offset for phased array.

In conventional ultrasonic testing, all of the above steps must be taken prior to inspection to achieve proper results. Because a single element probe has a fixed aperture, the entry angle selection, zero offset, and amplitude calibration are specific to a single transducer or transducer/wedge combination. Each time a transducer or its wedge is changed, a new calibration must be performed.

Using phased array probes, the user must follow these same principles. The main advantage of phased array testing is the ability to change aperture, focus, and/or angle dynamically, essentially allowing the use of several probes at one time. This imparts the additional requirement of extending calibration and setup requirements to each phased array probe state (commonly referred to as a focal law). This

not only allows accurate measurements of amplitude and depth across the entire p   also provides accurate and enhanced vi   hat phased array instruments produce.

One of the major differences between conventional and phased array inspections, occurs in angle beam inspections. With conventional UT, input of an improper wedge angle or material velocity will cause errors in locating the defect, but basic wave propagation (and hence the resultant A-scan) is not influenced, as it relies solely on mechanical refraction. For phased array, however, proper material and wedge velocities, along with probe and wedge parameter inputs, are required to arrive at the proper focal laws to electronically steer across the desired refracted angles and to create sensible images. In more capable instruments, probe recognition utilities automatically transfer critical phased array probe information and use well-organized setup libraries to manage the user selection of the correct wedge parameters.

The following values must normally be entered in order to program a phased array scan:

Probe parameters

- Frequency
- Bandwidth
- Size
- Number of elements
- Element pitch

Wedge parameters

- Incident angle of the wedge
- Nominal velocity of the wedge
- Offset Z = height to center of first element
- Index offset X = distance from front of wedge to first element
- Scan offset Y = distance from side of wedge to center of elements
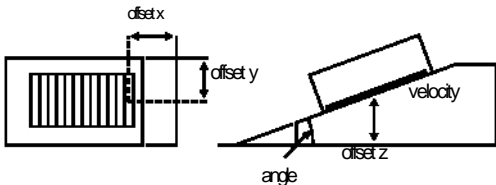
Figure 5-2 Wedge parameters

Focal law setup

The instrum   and wedge settings entered, either manu   obe recognition. Along with typical UT settings for the pulser, receiver, and measurement gate setup, the user must also set probe beam and electronic steering (focal law) values.

Required user inputs

- Material velocity
- Element quantity (the number of elements used to form the aperture of the probe)
- Selection of the total number of elements to be used to set probe aperture
- Element step (defines how the defined aperture moves across the probe) for linear scans
- Desired focus depth, which must be set less than the near-field length (N) to effectively create a focus
- Angle(s) of inspection

For S-scans, the latter parameter is expanded into three settings:

- The first angle of the scan - The last

angle of the scan

- The increment at which angles are to be stepped

5.2 Normal Beam Linear Scans

Normal beam linear scans are usually easy to conceptualize on a display because the scan image typically represents a simple cross-sectional view of the test piece. As described in chapter 3, a phased array system uses electronic scanning along the length of a linear array probe to create a cross-sectional profile without moving the probe. As each focal law is sequenced, the associated A-scan is digitized and plotted. Successive apertures are "stacked," creating a live cross-sectional view. The effect is similar to a B-scan presentation created by moving a conventional single element transducer across a test piece and storing data at selected intervals. To gain the full advantages of linear array scanning, a minimum of 32 elements is typically used. It is even more common to use 64 elements. More elements allow larger apertures to be stepped across the probe, providing greater sensitivity, increased capacity of focusing, and wider area of inspection.

In practice, this electronic sweeping is done in real time so a live part cross section can be continually viewed as the probe is physically moved. The actual cross section represents the true depth of reflectors in the material as well as the actual position typically relative to the front of the probe assembly. Figure 5-3 is an image of holes in a test block made with a 5L64-A2, 64-element, 5 MHz linear phased array

probe. The probe has a 0.6 mm pitch.

In this exam   cal law to use 16 elements to
form an aperture and sequenced the starting element increments by one. So
aperture 1 consists of elements 1 through 16, aperture 2 consists of
elements 2 through 17, aperture 3 consists of elements 3 through 18, and so
on. This results in 49 individual waveforms that are stacked to create the
real-time, cross-sectional view across the probe's length.

Direction of scan
Scan area
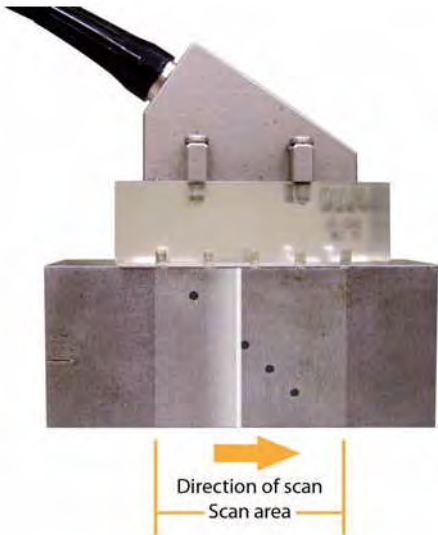
Figure 5-3 Normal beam linear scanning

The result is an image that clearly shows the relative position of the holes
within the scan area (see Figure 5-4). The image is displayed along with the
A-scan waveform from a single selected aperture, in
this case the 30th aperture out of 49, formed from elements 30-46,
marked by the user-controlled blue cursor. This is the point where the beam
intersects the second hole.
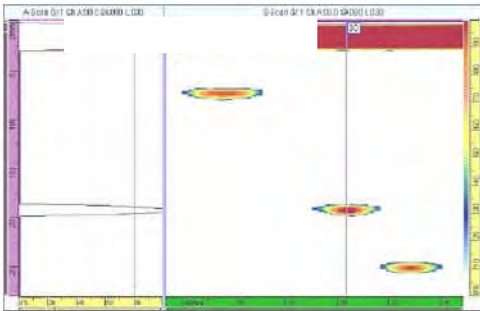
Figure 5-4 Normal beam linear scan

The vertical scale at the left edge of the screen indicates the depth or distance to the reflector represented by a given peak in the A-scan. The horizontal scale of the A-scan indicates relative echo amplitude. The horizontal scale under the linear scan image shows the reflector position with respect to the leading edge of the probe, while the color scale on the right edge of the screen relates image color to signal amplitude.

Alternately, the instrument can be set to display an "all laws" A-scan, which is a composite image of the waveforms from all apertures. In this case, the A-scan includes the indications from all four holes within the gated region. This is a particularly useful mode in zero- degree inspections, although it can also be confusing when working with complex geometries that produce numerous echoes. In the Figure 5-5 example, the screen shows an "all laws" A-scan in which the signals from all apertures is summed, thus showing all three hole indications simultaneously.

Figure 5-5 Normal beam linear scan image with all laws A-scan

Yet another A-scan source mode on some more advanced instruments allows the A   st or maximum signal within the gated reg

5.3   Angle Beam Linear Scans

A linear scan can also be programmed at a single fixed angle, much like the beam from a conventional single-element angle beam transducer. This single-angle beam scans across the length of the probe, allowing the user to test a larger volume of material without moving the probe (Figure 5-6). This can cut inspection time, especially in weld scanning applications, where the entire volume of the weld can be tested with a probe at a fixed standoff distance.
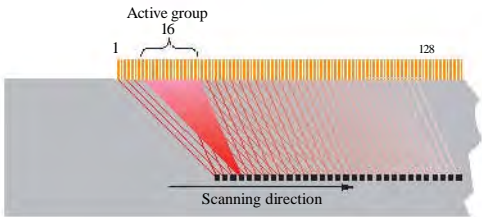
Figure 5-6 Single-angle beam scanning across the length of the probe

In the example of Figure 5-7, the beam is sweeping across the test piece at a 45 degree angle, intercepting each of three holes as it moves (*top*). The beam index point (BIP), the point at which the sound energy exits the wedge, also moves from left to right in each scan sequence. The A-scan display, at any given moment, represents the echo pattern from a given aperture, while the S-scan shows the summed view from all the beam positions (*bottom*).
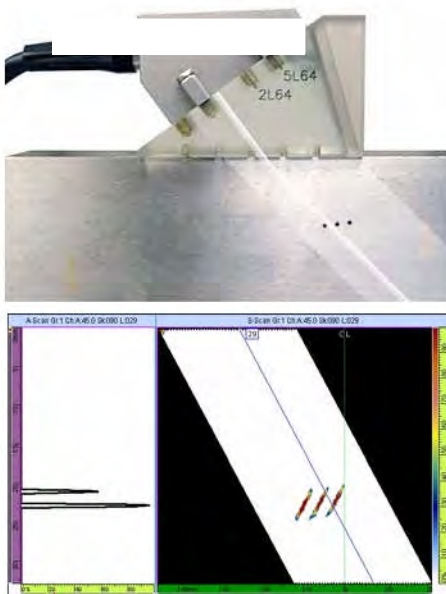
Figure 5-7 Angle beam linear scan (*top*), with A-scan and linear scan display (*bottom*)

In any angle scan not involving very thick materials, it is also necessary to consider the actual position of reflectors that fall beyond the first leg, the point at which the beam first reflects from the bottom of the test piece. This is usually a factor in tests involving typical pipes or plates. In the case of Figure 5-8, as the beam scans from left to right, the beam component from the center of the probe reflects off the bottom of the steel plate and hits the reference hole in the second leg.
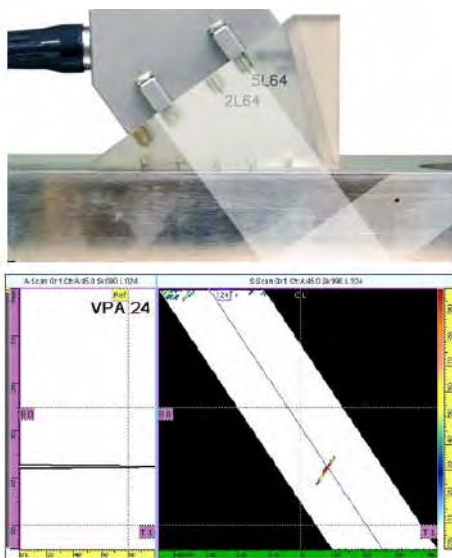
Figure 5-8 Measurement to second leg reflector

The screen display has been set up to show, by means of the dotted horizontal cursors, the positions of the end of the first leg and the end of the second leg on the image. Thus, this hole indication, which falls between the two horizontal cursors, is identified as being in the second beam leg. Note that the depth scale on the left edge of the screen is accurate only for the first leg. To use the scale beyond that, it would be necessary to subtract the test piece thickness (in this case 25 mm) to determine the depth of second leg indicators, or twice the test piece thickness for third leg indicators. Most instruments are able to do this automatically and display the result, as noted in chapter 4.

5.4 S-Scans

In the case of S-scans, interpretation can be more complex because of the possibility of multiple leg signals that have reflected off the bottom and top of the test piece. In the first leg (the portion of the sound path up through the first bounce off the bottom of the part), the display is a simple cross-sectional view of a wedge-shaped segment of the test piece. However, beyond the first leg, the display requires more careful interpretation, as it also does when using a conventional flaw detector.

A conventional flaw detector, used with common angle beam assemblies, displays a single-angle A-scan. Modern digital instruments use trigonometric calculation based on measured sound path lengths and programmed part thicknesses to calculate the reflector depth and surface distance. Part geometry might create simultaneous first-leg and second-leg indications on the screen, as seen here in Figure 5-9 with a 5 MHz transducer and a 45 degree wedge. In this case, a portion of the beam reflects off the notch on the bottom of the part and a portion reflects upward and off the upper- right corner of the block. Leg indicators and distance calculators can
then be used to confirm the position of a reflector (see Figure 5-10).

Figure 5-9 Conventional angle beam test

The first-leg indication is a large reflection from the notch on the bottom of the test block. In Figure 5-10, the depth indicator (upper-left corner of screen image) shows a value corresponding to the bottom of a 25 mm thick block, and the leg indicator (lower-right corner of screen image) shows that this is a first-leg signal.
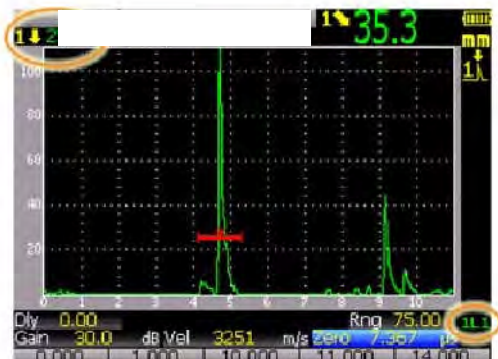
Figure 5-10 First-leg indication

The second-leg indication is a small reflection from the upper corner of the block. In Figure 5-11, the depth indicator shows a value corresponding to the top of a 25 mm thick block, and the leg indicator shows that this is a second-leg signal. (The slight variation in depth and surface distance measurements from the expected nominal values of 0 mm and 50 mm respectively, is due to beam spreading effects.)

Figure 5-11 Second-leg indication

When the same test is performed with a 5 MHz phased array probe assembly scanning from 40 to 70 degrees, the display shows an S-scan

that is plotted from the range of angles, while the accompanying A-scan typic   ular component of the scan. Trigonometr.   ed sound path length and programmed part thickness to calculate the reflector depth and surface distance at each angle. In this type of test, part geometry might create simultaneous first-leg and second-leg indications on the screen as well as multiple reflectors from a single angle. Leg indicators in the form of horizontal lines overlayed on the waveform and image segment the screen into first, second, and third leg regions, while distance calculators help confirm the position of a reflector.

In the Figure 5-12, Figure 5-13, and Figure 5-14 S-scan examples, we see three indications from a single probe position as the beam sweeps through a 40 degree to 70 degree scan. The 58 degree beam component creates a reflection from the notch on the bottom of the test block and a first-leg indication. The 69 degree component reflects from the bottom corner of the block, creating another first-leg indication. Meanwhile, the 42 degree component bounces off the bottom and top surfaces of the block and creates another reflection from the bottom corner, that one being the third leg.
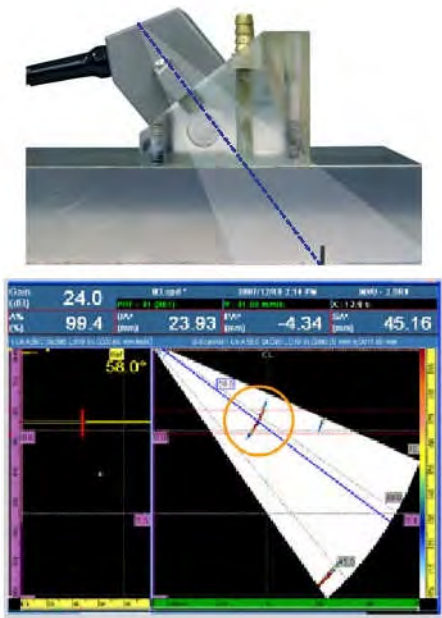
Figure 5-12 The 58° beam component
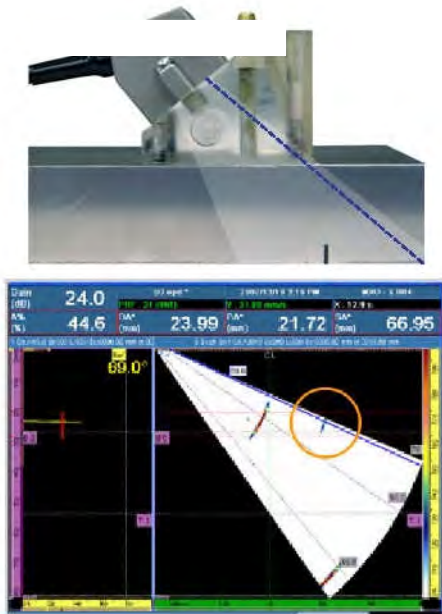
Figure 5-13 The 69° beam component

Figure 5-14 The 42° beam component

5.5 Interpreting Reflector Positioning

Phased array instruments, like quality conventional ultrasonic flaw detectors, offer software tools for identifying the position of defects and other reflectors. Typically, these instruments locate: (1) a reflector in terms of its horizontal position with respect to the probe; (2) its depth with respect to the material surface; and (3) the sound path distance between the beam index point and the reflector. In addition, when skip paths are employed, the instrument should identify the skip leg in which the reflector occurs.

First, it is important to remember that the beam index point (the point at which the center of the sound beam exits the wedge) is a fixed location for a conventional wedge (Figure 5-15a), and a moving point for phased array wedges (Figure 5-15b). In the case of linear scans, the beam index point moves progressively along the length of the probe as the scan progresses. In the case of S-scans, different angular components exit the wedge at different points.

Figure 5-15 Beam index points on a conventional wedge (a) and phased array wedge (b)

Conventional flaw detectors normally use the single beam index point of the wedge as the reference from which depths and distances are calculated. Because the beam index point of a phased array probe is variable, a common way of referencing a flaw position is in relation to the front edge of the wedge rather than the BIP. The dimensions shown in Figure 5-16 can then be calculated from the beam information:
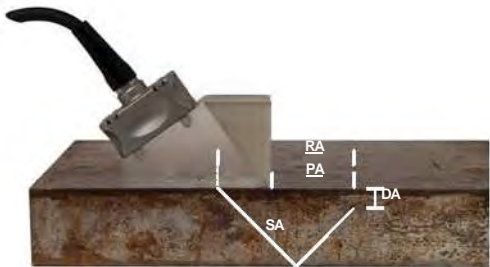
Figure 5-16 Dimensions for referencing a flaw position

DA = depth of the reflector in Gate A

PA = forward position of the reflector with respect to the tip of the wedge

RA = distance between the wedge reference point and the reflector

SA = sound path length to the reflector

In this display format, the transition between the first and second leg and second and third leg regions of the display, is marked by dotted horizontal lines. In the example below, the bottom-corner reflector occurs at the transition between the first and second leg zones (Figure 5-17), and the top-corner reflector is at the transition between the

second and third legs (Figure 5-18). In addition, the position readouts at the top of th   n.

Figure 5-17 Bottom corner reflector

Figure 5-18 Top corner reflector

In a sense, the screen image projects the second leg as a continuation of the beam in a straight direction. While the beam actually reflects upward from the bottom of the test piece, the screen image displays it as if the beam were to continue along the same axis (see Figure 5-19).
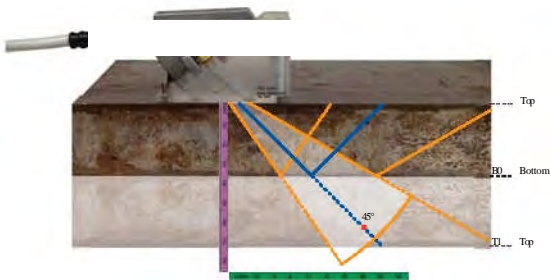
Figure 5-19 Display of the second leg compared to the path in the test piece

How To Easily Demo the OmniScan MX "Manual"

Overview
- ◆ The philosophy behind OmniScan
- ◆ Startup
- ◆ Tips
- ◆ Suggested inspection demo:
  - – 0° Linear Scan (with calibration)
  - – Angle Linear Scan
  - – Sectorial Scan

1

The OmniScan Philosophy

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Navigation
- ◆ The OmniScan navigation is based on an essentially very simple structure. Indeed, each parameter is classified into a specific sub-category, which is included within a global category.

  Menu > Sub-Menu > Parameters

- ◆ For instance, if the rectification display mode must be adjusted, go to:

  (1)   (2)   (3)

  UT Setting > Receiver > Rectifier =

  RF
  HW+
  HW-
  FW

3

Navigation – Menu (UT Setting)

Navigation – Sub-Menu (Receiver)

Navigation – Parameters (Rectifier)

Menu Description

◆ There are 3 different menu levels:

Setup

Inspection

Tools

Menu Description – **Setup**

Wizard

- **Using the Wizard menu, a complete application setup can be created. This step-by-step approach prevents the user from missing a parameter change. A very useful online help feature gives specific information on the parameters to be set.**
- **Calibration is also an important part of the setup creation step. Thus, the Wizard menu also includes complete step-by-step calibration assistance.**

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Menu Description – **Inspection**

UT Settings → ◆ **All parameters that are regularly modified during inspection can be found in this menu.**

Gate/Alarm → ◆ **Gate position and mode, alarm conditions, and sizing curve (DAC/TCG) parameters are available in this menu.**

Measurements → ◆ **Manages the options related to various measurement options and statistical tools**

Display → ◆ **Manages the options related to the data views and the information visible on screen**

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Menu Description – **Tools**

File → ◆ **Allows the user to open or save a file. It also allows one to format and build an inspection report.**

Preferences → ◆ **All parameters that are seldom modified are available in this menu. For example, the measurement unit (mm or in.) is selected and kept in memory.**

PA <> UT → ◆ **Used to switch between Phased Array and Conventional UT operating mode.**

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Startup

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What Do You Need?

◆ There are two ways to demonstrate the OmniScan "Manual":

1. Using:
   - "Manual" module (16:16M or 16:64M)

2. Using:
   - "Automated" module (16:16, 16:128, 32:32 or 32:128)
   - "Manual" demo simulator

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1. "Manual" module

OmniScan MX Mainframe

"M series" 16:16M or 16:64M
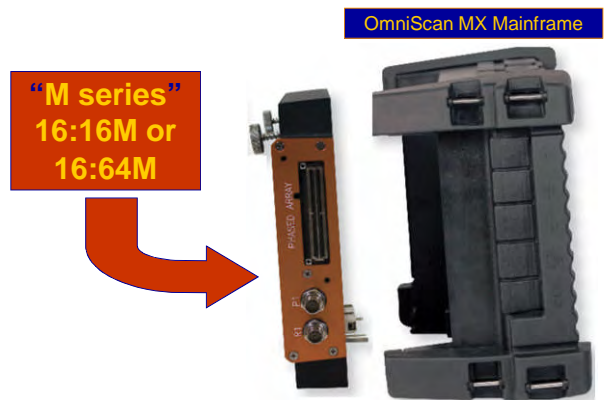
1. "Manual" module

◆ The OmniScan MX automatically detects the "Manual" module and boots up the right interface (MXU-M).

You can go directly to slide 22 to continue your demo if you are using a 16:16M or 16:64M

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2. "AUT" module + "Manual" simulator

OmniScan MX Mainframe

"AUT" 16:16 16:128 32:32 32:128

2. "AUT" module + "Manual" simulator

◆ Using your PC, create a new folder on your OmniScan CF card and name it "Demo_No".
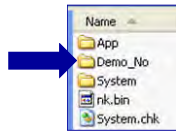
◆ In this "Demo_No" folder, create a ".txt" file.

Right click > New > Text Document >
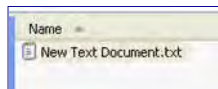
17

2. "AUT" module + "Manual" simulator

◆ Rename this new ".txt" file as "*SimulateManualAcquisitionModule.demo*"
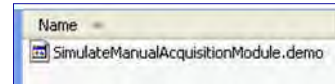
◆ Then, put the CF card back in the OmniScan.

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2. "AUT   ual" simulator

To use the "Manual" simulator:

◆ Turn-on the OmniScan ⏻

◆ Go to:
  – **Preferences** > **Service** > **File Manager**

◆ Push the "OK" button 2 times(✓ x 2)

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Menu Description – **Tools**

| File | → | ◆ Allows the user to open or save a file. It also allows one to format and build |
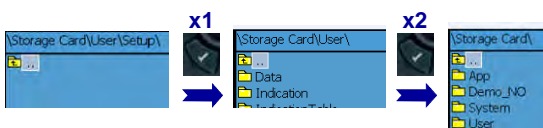
2. "AUT" module + "Manual" simulator

◆ Scroll down on "Demo_No" and then press the "Rename" button
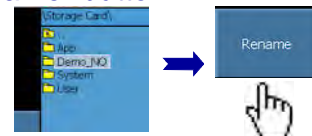
◆ Rename "Demo_No" as "Demo" and then push "OK" (✓)

◆ Push on the "Close" button

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2. "AUT" module + "Manual" simulator

◆ Shutdown the OmniScan (hold ⓿)

Note: do not save the setup (No)

◆ Turn-on the OmniScan ⓿

You are now in simulation mode of the "Manual" module !

◆ **<u>NOTE</u>**:
– *To turn-off the "Manual" simulator, just rename "Demo" as "Demo_NO", using the same steps as earlier through the OmniScan File Manager.*

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Tips

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Tip 1: Set the brightness to max.!

◆ To save battery energy, the OmniScan screen brightness is set by default to 25%. During your demo, in order to display a better screen appearance, you should set this value to the max. value.

◆ Go to:
– **Preferences** > **Pref**. > **Bright**. = Max.

◆ *Note*:
– Max. = 75% in battery
– Max. = 100% in AC powered mode

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Tip 2: Set unit (mm or in.)

◆ Depending on where you are in the world, you might want to change the measurement unit.

◆ Go to:
– **Preferences** > **Pref**. > **Units** = mm or in.

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Tip 3: Wizard = Step-by-step assistance!

- For each step, online help gives specific information on the parameters to be set. Thus, if you are not sure, take time to read about what the parameters mean.
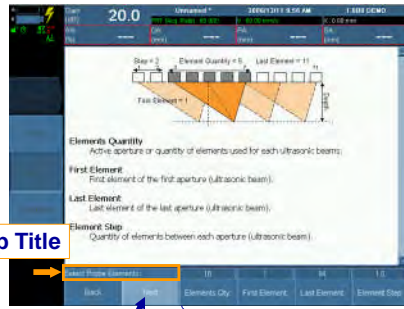
- Wizards are guided by a step-by-step menu using "Next" and "Back" navigation.

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Suggested Inspection Demo

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c

Suggested inspection demo

- 0° Linear Scan
  - Create a 0° linear scan using the "Group" and "Focal Law" wizards.
  - Show results
  - Perform a calibration using the "Calibration" wizard.

  - *Note:*
    - *Performing a calibration with a 0° linear scan is the easiest way to demo the Omni*
    For an efficient and quick dem
    perform calibration only with this scan mode.

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Suggested inspection demo

- Angle Linear Scan
  - Create a 45° linear scan using the "Group" and "Focal Law" wizards.
  - Show results
- Sectorial Scan (without calibration)
  - Create a 30° to 60° sectorial scan using the "Group" and "Focal Law" wizards.
  - Show results

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Basic Steps for Setting up Phased Array Scan on OmniScan 2.0 Software

Group Wizard

The best place to start is the Group Wizard as it will set many parameters from other menus in one easy step by step process. The Group Wizard encompasses the parameters contained in the Probe/Part menu.

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Choose to Modify or Add a Group

Choose "modify" to set up first scan or change an existing group, "add" to add another scan using MultiGroup if you have this option. With MultiGroup you can set up to 8 simultaneous scans as well as multi-probe applications.
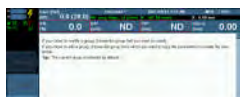
31

Define Your Part

Choose plate if flat. Select material for an approximate velocity determination. Enter part thickness. By entering a true part thickness you enable the Omniscan to calculate true depth/thickness readings off of leg skips and multiples.

Select Group Type

PA for phased array, UT for conventional ultrasound connected through the phased array connector. To use the PA channels as conventional channels off of the PA connection you will require an adapter to break out the individual PA channels.

Choose Connection

Choose applicable pulser/reciever connections. If you have one probe connected via the PA connection, the OmniScan will disable this selection. With an extension cable or Y-adapter you can choose the connection.

When using multiple probes on a 16:128 via the Y-adapter, probe 1 will be elements 1-64,(con. 1), probe 2 will be 65-128 (con.65).

c

Select Probe

OmniScan probes will Auto detect.

If using a non-OmniScan connector probe-you must toggle off auto detect first and then select your probe.

Select probe by case style, then by model number-(inscribed on probe case).

Select Wedge

Select your wedge from the list.

Select wedge by case style then model number- labeled on wedge

Custom Wedge files entered into the OmniScan will appear in the User field selection.
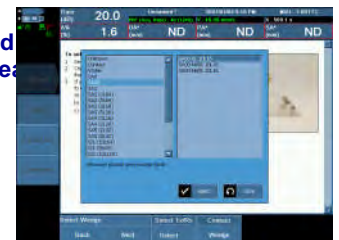
Define Offsets

**Useful for taking readings from
a reference position, ex: side
of plate and weld centerline.
Input offsets in applicable
axis as needed.**
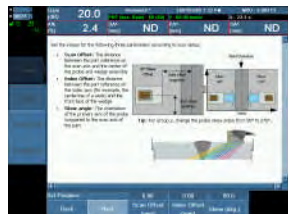
**Skew –change to reflect side
from which inspection is
done from.**

**Proper offset input is critical
for data correlation in
encoded scans and**

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End of Wizard

**Press Continue to continue
into the Law (Focal) Wizard**

**The Focal Law
Wizard will
encompass the
Focal Law menu
parameters.**
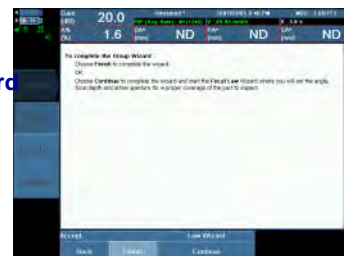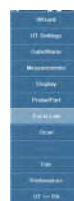
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Choose Your Scan Type

**Sectorial Scan- multiple angle
inspection ex: 35-70 degree
shear wave with an angle
beam wedge**

**Linear Angle- 1 fixed angle
being rastered through the
probe- ex: 45 degree SW that
begins in the back of the
probe and rasters forward
to the front. Mimics moving
a 45 degree conventional probe
forward and aft.**

**Linear at 0- For o degree
encoded scans where you
will overlap in the index axis**
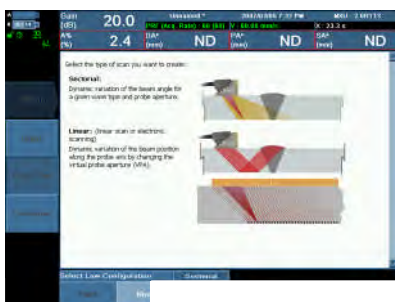
39

Choose Wave Type

**Shear Wave or
Longitudinal Beam- the
approximate values will
be displayed based on
your material selection
in the last wizard.**
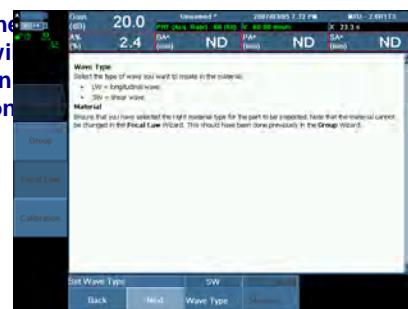
40

Select Probe Elements-Sectorial Scan

Must define Aperture Size (element quantity)
-groups of elements that will fire together to form an individual beam.

As well as where in the probe to start firing-element is almost always in the back of the probe.

In Sectorial scans we choose 1 group of elements that will be repeatedly pulsed to form our entire angular sweep.

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Select Probe Elements-Linear Scan

In addition to aperture (element Qty.) and a start element (first element), in Linear scans we must also define where to stop the electronic raster (Last Element). We must also define how "move" through the probe between pulses (element step).

With an Element Qty. of 16, first element of 1, last element 64, and Element step of 1 the Omniscan will:

First pulse: fire elements 1-16 to form a beam at chosen angle

Second Pulse: "move" 1 and fire 2-17 ,

Third pulse: "move"1 and fire 3-18

This will continue until we reach our stop (49-64) and repeat.

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Choose Your Angle(s)

Sectorial Scan- choose a start (min) and stop (max) angle for the scan. ex: 35 min 70 max will create a 35-70 Degree Sectorial scan.
Linear Scan- choose 1 angle to be rastered through the probe. Ex: 45 degree linear Scan.
Angle Step- 1 degree step for the above Sectorial will fire a beam at and display data from every 1 degree between 35 and 70 degrees.= (.1, .5, 1 degree options are common) 1 degree step is usually suffic   en beams fired. This will be disabled for Li
Focus Depth- Choose a depth to focus at, limited to Near Field for true focus.
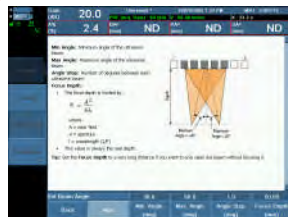
43

Generate Focal Law
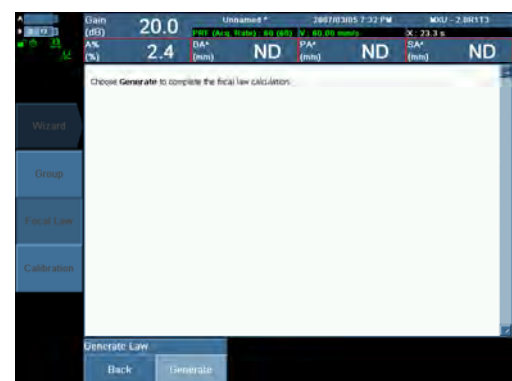
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Data- File/Save Mode Menu

Choose how you would like to record data.

Inspection Data-full a-scan info for post processing etc, larger data files-recommended

Screen- Jpg. of screen for custom report

Also indication table and report options but these can be generated from the Inspection Data during post analysis.

45
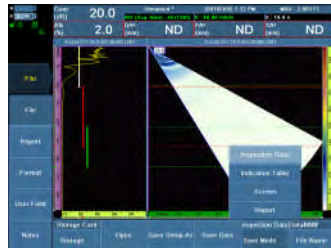
Choose the items to be included in the report if one is generated.

For most detailed report turn on all fields and choose table for defect table and screen shots of each indication selected by the operator.. Can also add notes, headers, and user fields to meet your specific needs.
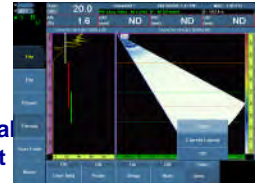
46

Display-Display/Selection Menu

Choose the display you want to view while scanning.

If using c-scan define the type.

With a MultiGroup file define whether only the selected group (current) or all groups will be displayed.
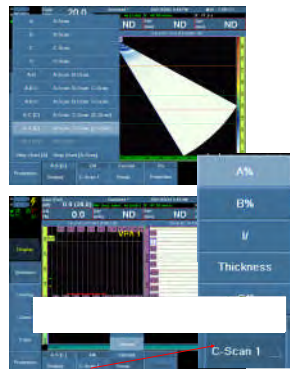
47

Display-Display/Overlay Menu

Turn on/off useful features like reference lines (overlay), analysis cursors, gates, sizing curves etc. Also change the UT unit- true depth, sound path, time, to fit your inspection.

48

Choose an Inspection Range-UT Settings/General Menu

Define the start and width of your range. Gain can also be adjusted from this menu.

49

Pulser-UT Settings/ Pulser Menu

Configure Pulser settings. For most inspections set voltage to low at first. Can usually leave PRF and PW to optimum as the software will optimize based on scan setup parameters.
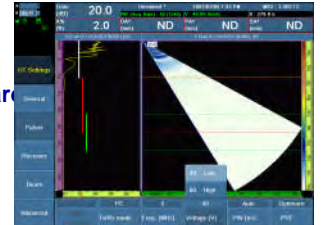
50

Receiver-UT Setting/ Receiver Menu

Usually set receive filter to Auto for most inspections and the software will narrow the bandwidth to the probe connected. Choose rectifier. Choose averaging if needed.

Video filter will clean up both A-scan and image displays. Video filter can not be used for RF selection.
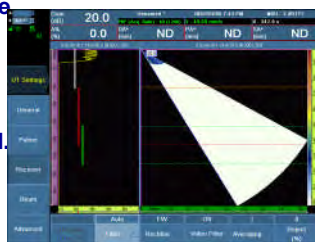
51

Preferences-Pref. Menu

Can adjust screen brightness (up to 75% on battery, 100% on AC), indoor/outdoor scheme, and choose English or metric units
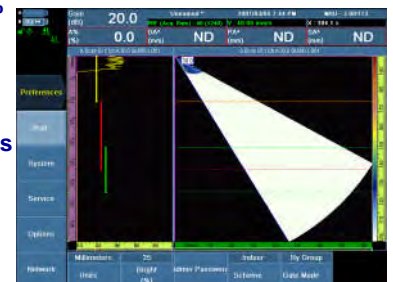
52

Readings Fields-Measurements/Reading Menu

There are two lists to configure with real time readings that will also be included in the report and defect table.

Predefined groups have been formed for many of the common inspections.

Toggle between lists

53

Gate Settings-Gate/Alarm- Gate and Alarm Menu

3 gates- A,B, I available with a variety of ways to configure Including alarms and operators for and/or type situations.

In the gate menu toggle parameters setting to switch between position or mode parameter adjustments.

54

Scan Menu-For Encoded Scans

Encoder Menu-choose encoder, set polarity (direction of travel), type of encoder, resolution, start point of scan.

Inspection Menu-Choose type of scan, clock or encoder, and view scan speed.

Area menu- define length and width of scan in each axis and set resolution.

Start Menu-Define what to do upon start acquisition input

Data Menu- Define data parameters for storage

55

Calibrations

Add Calibrations to your setup and you are ready to go!

Velocity

Wedge Delay

Sensitivity

DAC/TCG

Code Dependant

56

Performing a Linear Scan Velocity/Wedge Delay/Sensitivity Calibration- Shear Wave PA

Starting Point

◆ This procedure takes for granted that all parameters to set up the equipment and scan (Probe/Part and PGM Probe Menus) have been implemented and calibration is the next step.

58

Equipment Used for this Procedure

◆ 16:128 Omniscan
◆ 5L16 probe
◆ SA1-N45S wedge
◆ Type II IIW Block
◆ Commercial Gel Couplant

59

Preliminary Settings

◆ Set Rulers to Sound Path for easiest Calibrations on IIW Block

◆ Display A-S
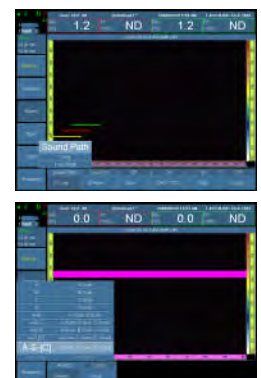
60

Preliminary Settings

◆ Set Units to Inches
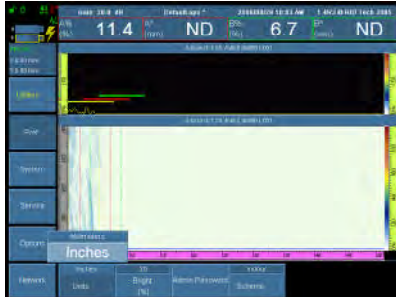
61

Preliminary Settings

◆ Set the SA (Sound Path) reading field

62

Velocity Calibrations

◆ Velocity calibrations set the acoustic velocity to that of the material for accurate position determination and sizing of reflectors.
◆ The material list will get you close to the desired shear or longitudinal velocity in most cases.
◆ A velocity calibration will fine tune this selection to your material.
◆ Velocity calibration requires two distinct points separated in time/space to calculate velocity through the medium. Radii, given depth reflectors, or thickness can all be used to perform this calibration.
◆ Reflectors may not show at there exact S.P. or depth after a velocity calibration is done until w calculated.

63

Velocity Calibration-Radius

◆ Enter Calibration Menu and select Velocity
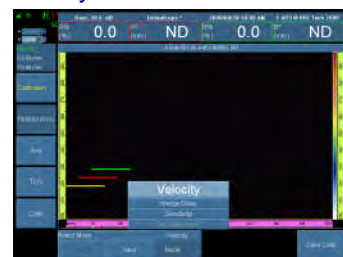
64

Velocity Calibration-Radius

- Be sure you can see both radii-adjust range as needed and adjust gain to keep the peaks on screen.
- Select radius and input 2,4 –the sound path distance to the radii.

Velocity Calibration-Radius

- Peak up the 2" radius

- Move the gate over the reflector in all angles
- Push get position to acquire the point.
- Repeat for 4" radius
- Verify the velocity given-accept or Restart
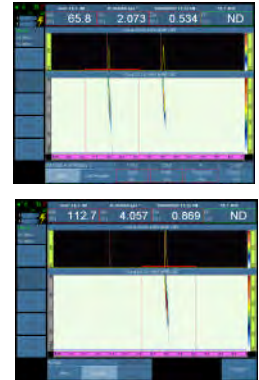
Wedge Delay

- Wedge Delay will enter compensation for the travel of the beams through the wedge medium and account for the various exit points.
- Wedge delay needs only 1 distinct reflector-radius, given depth reflector, or a thickness.
- After velocity and wedge calibrations, accurate measurements c

Wedge Delay Calibration-Radius

- Enter the calibration menu

- Select Wedge Delay

- Select radius and input 2" or 4" and a tolerance
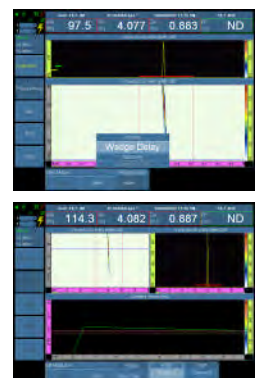
Wedge Delay Calibration-Radius

◆ Set the gate to encompass the signal from your selected radius
◆ Move the probe as needed so the radius is seen through all the vpas.
◆ Calibrate
◆ Accept or Restart-green line should fall between red tolerance lines
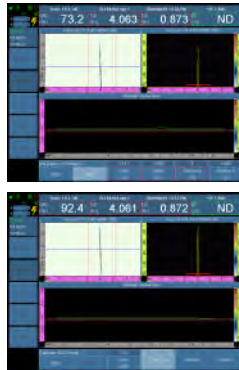
69

Sensitivity Calibrations

◆ Sensitivity calibrations equalize the sensitivity (amplitude) to a given reflector through all the angles or vpas.
◆ This will insure no matter what angle or vpa the reflector is seen at the % FSH is the same for rejection or detection purposes as well as for the amplitude based color coded imaging selections.
◆ Radius, point reflectors, and thicknesses can all be used to achieve this depending on inspection criteria.

70

Sensitivity Calibration-SDH

◆ Enter Calibration menu and select Sensitivity

◆ Choose a reference screen height to equalize sensitivity to (80% FSH) and a tolerance
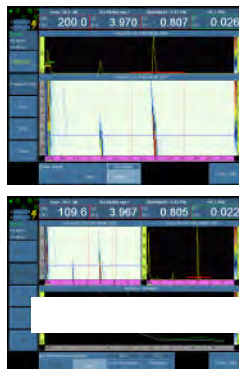
71

Sensitivity Calibration-SDH

Set the gate to encompass the SDH reflection.

Move the probe forward and Backward to ensure the gate covers the reflector through a The vpas.

72

Sensitivity Calibration-SDH

- Move the probe forward and backwards to build the green line as the reflector is seen by the vpas.
- Ensure the green line is on-screen across the whole screen-not to low or over the tolerance lines.
- Can add comp. gain if needed to bring the line on-screen if a vpa does not see it well
- Can reduce gain if a vpa is seeing the reflector with too much amplitude.

73

Sensitivity Calibration-SDH

- Applying even pressure, move the probe forward and back so all the vpas pick up the reflector.
- Couplant should be even and probe should be kept in the same plane.
- Using water and laying the IIW block down on its edge as a guide can assist.
- Go back and forth a few times then press Calibrate

74

Sensitivity Calibration-SDH

- Rerun the probe through the angles-green line should be within red tolerance lines throughout the horizontal screen length
- Accept or restart the calibration
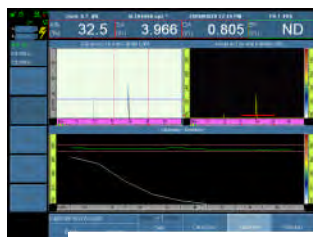
75

Sensitivity Calibration-SDH

- To verify sensitivity go to Display menu
- Select rulers
- Change UT unit to true depth
- Go to Readings-cursors
- Move probe so reflector is seen in each vpa-move data cursor through each vpa-stopping to move probe and peak reflector at each-looking at A% to verify sensitivity within tolerance for each vpa
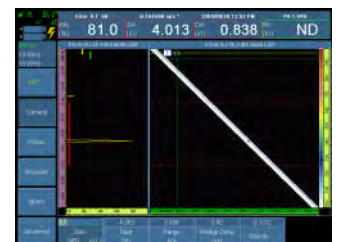
76

Performing a Sectorial Scan Sensitivity/ Velocity/Wedge Delay Calibration-Shear Wave PA Using a SDH at a Known Depth 2.0 SW

Calibrations-Required items

- ◆ Calibration block with 2 same size reflectors at known depths- (Navships block with SDHs)
- ◆ Couplant-water works best
- ◆ Guide to keep from skewing- use a ruler, set the block on its side, or on IHC wedges can screw down one sides carbide pins.

78

Velocity Calibration

- ◆ The velocity calibration will fine tune the velocity to that of the calibration block. It will require two reflectors of the same size at two different known depths.
- ◆ In many cases the default material velocity set by the operator in the group wizard is sufficient and this calibration can be skipped because wedge delay will adjust accordingly to allow accurate measurements.
- ◆ If performed the velocity calibr done before the wedge delay

79

Select Velocity Calibration

- ◆ Go to the Wizard- Calibration menu
- ◆ Select Ultrasound and Velocity
- ◆ Start the wizard

80

Select A-Scan

- Put the probe on your block over the first reflector.
- Choose an angle near the middle of your angle sweep using the angle function.
- Adjust range as needed to ensure you will see the 2 reflectors you have chosen.

81

Set Depth 1 and 2

- Select depth from echo type
- Set depth 1 and depth 2 to your reflector depths.

82

Set Gate A on Depth 1

- Move probe back and forth over the first reflector building an envelope. Use a guide so you do not skew right or left.
- Ensure you peak the reflector.
- Adjust the gate to encompass the reflector.
- Get position.

83

Set Gate A on Depth 2

- Repeat the peaking process on your second reflector.
- Adjust the gate to encompass this reflector.
- Get position.

84

Accept or Restart

- View the velocity determination
- If it is sensible accept the calibration, if not restart.

85

Wedge Delay-Depth Reflector

- Wedge Delay will enter compensation for the travel of the beams through the wedge medium and account for the various exit points.
- Wedge delay needs only 1 distinct reflector- a known depth reflector will be used here.
- After wedge calibrations, accurate measurements can be taken.

86

Wedge Delay Calibration-Depth

- Enter the calibration menu

- Select Ultrasound and Wedge Delay-Start

- Select depth and input depth to the reflector and a tolerance
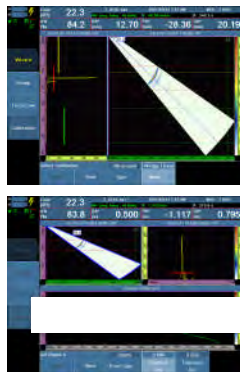
87

Set Section

- Decide if you want to calibrate the whole angular sweep or break it up into separate calibrations- for most setups with a good calibration block you can calibrate the whole sweep. Hit Next

88

Set Gate A on Depth A

Put the probe on the block so you can see the chosen depth reflector.

Adjust the gate start/width/threshold to encompass the reflector. Move the probe forward and backwards to ensure gate is encompassing reflector through all angles and there are no other reflectors that will affect calibration.

89

Calibrate and Accept

◆ Move the probe forward and backward applying even pressure and avoiding skewing right or left.

◆ Move in both directions until the green line is built across the whole angular range. Adjust gain as needed.

◆ Hit calibrate.

90

Accept or Restart

◆ After hitting calibrate-rerun the probe through the angular range verifying you are within the set tolerance.

◆ Accept or Restart.

91

Verifying Wedge Delay

◆ Set the DA reading from the Measurement-Readings menu

◆ Turn on the Highest % feature in the Display-Properties-Source menu

◆ Run the probe through the angular sweep while observing the DA reading.

92

Sensitivity Calibrations

◆ Sensitivity calibrations equalize the sensitivity (amplitude) to a given reflector through all the angles.

◆ This will insure no matter what angle the reflector is seen at the % FSH is the same for rejection or detection purposes as well as for the amplitude based color coded imaging selections.

93

Sensitivity Calibration

◆ Enter Calibration menu and select Sensitivity

◆ Choose a reference screen height to equalize sensitivity to (80% FSH) and a tolerance

94

Getting Started

◆ Choose a SDH and couple your probe above it

◆ Use a guide system to keep the probe from skewing side to side.

95

Set Section

◆ Choose whether to calibrate the whole angular sweep in one step or break it up into separate calibrations- if your calibration block has adequate spacing between SDHs you can usually do the whole range.

96

Set Gate A on Echo A

Set the gate to encompass the SDH reflection. Adjust the start/width/threshold of the gate.

Move the probe forward and backward to ensure the gate covers the reflector through all the angles and is not on any other reflectors that may inhibit the calibration

97

Set Compensation Gain

◆ Allows you to adjust the gain as needed to ensure the reflector is seen properly throughout all the angles

◆ In most cases no adjustment or an adjustment of the overall gain (if over reference level FSH%) is needed.

98

Calibrate and Accept

◆ Applying even pressure and not skewing right or left, move the probe forward and backwards to build the green line as the reflector is seen by the angles.

◆ Ensure the green line is on-screen across the whole screen-not to low or over the tolerance lines.
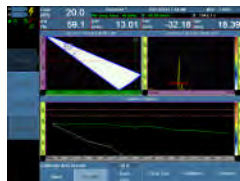
99

Calibrate and Accept

◆ Press Calibrate

◆ Verify the calibration by repeating the forward and backward movement of the probe

◆ The green line should fall within the defined tolerance lines across all the angles.

◆ Accept or Recalibrate as needed.

100

To Verify Sensitivity Calibration

◆ To verify sensitivity go to Display menu
◆ Select properties
◆ Change source to Highest

Run the probe back and forth and observe FSH in the A% reading field as the data cursor tracks the highest amplitude signal.

101

Adding a TCG to a Sectorial Calibration 2.0

TCG

◆ TCG equalizes the sensitivity for a reference reflector through time/depth to compensate for attenuation during beam travel.
◆ In phased array on the OmniScan we perform TCG calibration across all the angles.
◆ TCG equalizes the A-scan % FSH of a reflector as well as its representation in the amplitude based color coded imaging selections.
◆ When allowed TCG is almost always a better choice than DAC in phased array.

103

Using Wizard for TCG

◆ Enter calibration menu, select TCG-start

◆ Set reference amplitude and tolerance
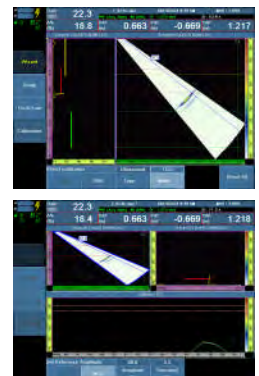
104

Set Section

◆ Set Section- choose to add TCG to the whole angular range or to break the calibration up into sections- in most cases you can do the whole range in one step.
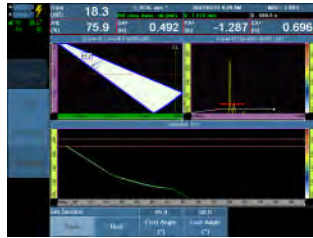
105

Set Gate A on Echo

◆ Choose the first reflector to begin your TCG.
◆ Couple the probe over this reflector and adjust the gate to encompass this reflector. Make sure no other reflector will affect the calibration.
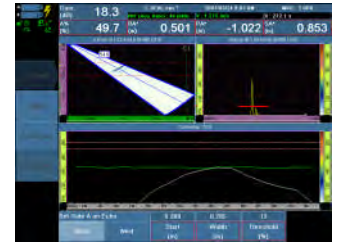
106

Using Wizard for TCG

◆ Run the probe over first reflector building a green line across the screen.
◆ Keep constant pressure and even coupling and avoid skewing right or left.
◆ Adjust gain as needed to keep line on screen and below red tolerance lines

Add point
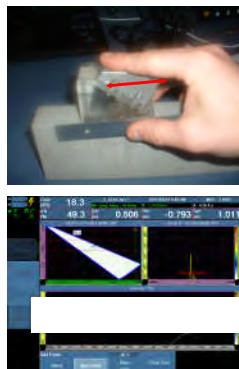
107

Accept or Cancel Point

Rerun the probe through the angular range.

Verify the green line is built within the tolerance lines across the whole sweep.

Cancel point if bad, continue to next deepest point if good. (Next Point)

108

Using Wizard for TCG

- Move to second deepest reflector
- Set Section for this point.
- Set gate for this reflector
- Repeat calibration process. Add point.
- Verify point

109

Next Point/Accept TCG

- Repeat the aforementioned steps until you have built the TCG through your inspection range
- When you complete the last point Accept the TCG.
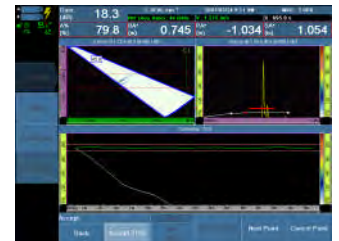
110

Verify TCG

- Set A% and DA readings
- Set display-properties-overlay-Source to Highest to track highest reflector
- Slowly move the probe forward and backwards over reflectors while observing these readings to ensure within tolerances.
- For the tracking Highest feature to work the reflector must fall within the A-gate

111

Setting up Mini Encoder- The Basics for a One Line Scan with 2.0 SW

Getting Started

- Almost all the parameters to set up the encoder can be found under two menus-Scan Menu, and Wizard- Calibration-encoder Menu.
- The encoder should be attached to the wedge using the brackets. Align the wheel in the direction you want to encode- the scan axis-direction probe will move.
- Make sure there is some tension on the wheel when you press down to ensure adequate pressure to avoid slipping.
- Insert the encoder cable into the encoder slot on top of the OmniScan being conscious of removed pin and its location.
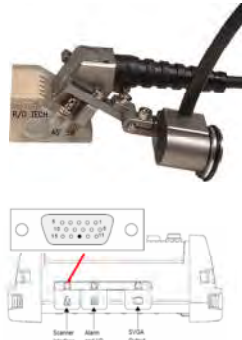
113

Change Scan- Inspection Menu parameters

Type- one line scan
Scan-Encoder 1
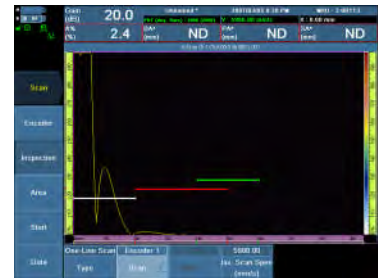
114

Select Encoder and Polarity-Scan/Encoder Menu

Select encoder 1.
Check polarity by looking at ax
movement in right corner while
moving encoder in intended
direction. If the numbers are
moving in a positive direction
polarity is correct, if not
change to inverse. Input encod
resolution if known.

115

Set Scan Length-Where to Start and End- Scan/Area Menu

Also set resolution in scan
axis.

116

Set Overwrite Parameters-Scan/Data Menu
What would you like the OmniScan to record when the encoder goes over an area it has already covered?

Can be last seen data, highest amplitude in the A gate, or the minimum or maximum thickness when doing thickness inspections
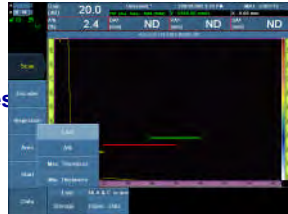
117

Calibrating the Encoder

◆ After the scan parameters are set the encoder will need to be calibrated if the encoder resolution is unknown.

◆ Needed items- small rule or distance reference, good surface to calibrate on.

118

Calibration-Wizard-Calibration Menu-choose Type-Encoder-Start

119

Setting Origin

x axis 0.00

After positioning encoder at a 0 position hit next

Start your 0 point at a reference point on the wedge.

120

Set Distance to Travel

Input the distance you plan on moving the encoder.

Move this Distance

Move the distance you input and hold

Push Calibrate and Verify

When you push calibrate the axis value will change to your set parameter

Carefully move the probe back to the 0 point and verify x axis reading is at 0.

Accept or Restart

STANDARD GUIDE FOR EVALUATING PERFORMANCE CHARACTERISTICS OF PHASED-ARRAY ULTRASONIC EXAMINATION INSTRUMENTS AND SYSTEMS

SE-2491

(Identical with ASTM E 2491-06)

1   Scope

1.1 This guide describes procedures for evaluating some performance characteristics of phased-array ultrasonic examination instruments and systems.

1.2 Evaluation of these characteristics is intended to be used for comparing instruments and systems or, by periodic repetition, for detecting long-term changes in the characteristics of a given instrument or system that may be indicative of impending failure, and which, if beyond ̲̲̲̲̲̲̲ uire corrective maintenance. Instru- ̲̲̲̲̲̲̲measured in accordance with this guide are expressed in terms that relate to their potential usefulness for ultrasonic examinations. Other electronic instrument characteristics in phased-array units are similar to non-phased-array units and may be measured as described in E 1065 or E 1324.

1.3 Ultrasonic examination systems using pulsed-wave trains and A-scan presentation (rf or video) may be evaluated.

1.4 This guide establishes no performance limits for examination systems; if such acceptance criteria are required, these must be specified by the using parties. Where acceptance criteria are implied herein they are for example only and are ̲ ̲̲̲̲̲̲̲ restrictive limits imposed by cust ̲̲̲̲̲̲̲ controlling documents.

1.5 The specific parameters to be evaluated, conditions and frequency of test, and report data required, must also be determined by the user.

1.6 This guide may be used for the evaluation of a complete examination system, including search unit, instrument, interconnections, scanner fixtures and connected alarm and auxiliary devices, primarily in cases where such a system is used repetitively without change or substitution. This guide is not intended to be used as a substitute for calibration or standardization of an instrument or system to inspect any given material.

1.7 Required test apparatus includes selected test blocks and position encoders in addition to the instrument or system to be evaluated.

1.8 Precautions relating to the applicability of the procedures and interpretation of the results are included.

1.9 Alternate procedures, such as examples described in this document, or others, may only be used with customer approval.

1.10 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 *ASTM Standards:*

E 317 Practice for Evaluating Performance Characteristics of Ultrasonic Pulse-Echo Examination Instruments and Systems without the Use of Electronic Measurement Instruments

E 494 Practice for Measuring Ultrasonic Velocity in Materials

E 1065 Guide for Evaluating Characteristics of Ultrasonic Search Units

E 1316 Terminology for Nondestructive Examinations

E 1324 Guide for Measuring Some Electronic Characteristics of Ultrasonic Examination Instruments

3. Terminology

3.1 Refer to Terminology E 1316 for definitions of terms in this guide.

3.2 *Definitions:*

3.2.1 *angle corrected gain* — also called ACG. This is compensation for the variation in signal amplitudes received from fixed depth side-drilled holes (SDHs) during S-scan calibration. The compensation is typically performed electronically at multiple depths. Note that there are technical limits to ACG, that is, beyond a certain angular range, compensation is not possible.

3.2.2 *annular array probes* — phased-array probes that have the transducers configured as a set of concentric rings. They allow the beam to be focused to different depths along an axis. The surface area of the rings is in most cases constant, which implies a different width for each ring.

3.2.3 *array (phased)* — a patterned arrangement of elements. Typical arrangements include linear, annular, two dimensional matrix, and "rho-theta".

3.2.4 *electronic scan* — also termed an E-scan. The same focal law is multiplexed across a group of active elements; electronic raster scanning is performed at a constant angle and along the phased-array probe length. This is equivalent to a conventional ultrasonic probe performing a raster scan. Also called electronic scanning.

3.2.5 *focal law* — the entire set of hardware and fecting the acoustic sensitivity field arch unit, whether a pulse-echo or a pitch-catch configuration. Within focal laws, there are included delay laws in transmitter and delay laws in receiver, as well as apodization laws, and element activation laws.

3.2.6 *linear array probes* — probes made using a set of elements juxtaposed and aligned along a linear axis. They enable a beam to be moved, focused, and deflected along a single azimuthal plane.

3.2.7 *matrix array probes* — these probes have an active area divided in two dimensions in different elements. This division can, for example, be in the form of a checkerboard, or sectored rings. These probes allow the ultrasonic beam steering in more

3.2.8 *sectorial scan* — also termed an S-scan or azimuthal scan. This may refer to either the beam movement or the data display. As a data display it is a 2D view of all A-scans from a specific set of elements corrected for delay and refracted angle. When used to refer to the beam movement it refers to the set of focal laws that sweeps a defined range of angles using the same set of elements.

3.2.9 *S-scan* — (q.v. sectorial scan)

4. Summary of Guide

4.1 Phased-array instruments and systems have similar individual components as are found in traditional ultrasonic systems that are based on single channel or multiplexed pulse-echo units. These include pulsers, receivers, probes and interconnecting cables. The most significant difference is that phased-array systems form the transmitted ultrasonic pulse by constructive phase interference from the wavelets formed off the individually pulsed elements of the phased-array probes.

4.2 Each phased-array probe consists of a series of individually wired elements that are activated separately using aprogrammable time delay pattern. Varying the number of elements used and the delay time between the pulses to each element allows control of the beam. Depending on the probe design, it is possible to electronically vary the angle (incident or skew), or the focal distance, or the beam dimensions, or a combination of the three. In the receiving mode, acoustic energy is received by the elements and the signals undergo a summation process utilizing the same type of time delay process as was used during transmission.

4.3 The degree of beam steering available is dependent on several parameters including; number of elements, pitch of the element spacing, element dimensions, element array shape, resonant frequency of the elements, the material into which the beam is directed, the minimum delay possible between firing of adjacent pulsers and receivers and the pulser voltage characteristics.

4.4 Pulser and receiver parameters in phased-array systems are generally computer controlled and the received signals are typically displayed on computer monitors via computer data acquisition systems and may be stored to computer files.

4.5 Although most systems use piezo-electric materials for the elements, electro-magnetic acoustic transducer (EMAT) devices have also been designed and built using phased-array instrumentation.

4.6 Most phased-array systems can use encoders for automated and semi-automated scanning.

4.7 Side-drilled holes used as targets in this document should have diameters less than the wavelength of the pulse being assessed and long enough to avoid end effects from causing interfering signals. This will typically be accomplished when the hole diameter is between about 1.5 mm and 2.5 mm and 20 mm to 25 mm in length.

5. Significance and Use

5.1 This guide is intended to evaluate performance assessment of combinations of phased-array probes and instruments. It is not intended to define performance and

acceptance criteria, but rather to provide data from which such criteria may be established.

5.2 Recommended procedures described in this guide are intended to provide performance-related measurements that can be reproduced under the specified test conditions using simple targets and the phased-array test system itself. It is intended for phased-array flaw detection instruments operating in the nominal frequency range of 1 MHz to 20 MHz, but the procedures are applicable to measurements on instruments utilizing significantly higher frequency components.

5.3 This guide is not intended for service calibration, or maintenance of circuitry for which the manufacturer's instructions are available.

5.4 Implementation of specific assessments may require more detailed procedural instructions in a format of the using facility.

5.5 The measurement data obtained may be employed by users of this guide to specify, describe, or provide a

performance criteria for procurement and quality assurance, or service evaluation of the operating characteristics of phased-array systems.

5.6 Not all assessments described in this guide are applicable to all systems. All or portions of the guide may be used as determined by the user.

6. Procedure

6.1 Procedures for assessment of several parameters in phased-array systems are described in Annexes A1 to A7.

6.1.1 These include; determination of beam profile, beam steering capability, element activity, focusing capability, software calculations (controls and display of received signals), compensation for wedge attenuation, receiver gain linearity.

7. Keywords

7.1 characterization; focal point; phased-array; phased-array probe; sound beam profile; ultrasound

ANNEXES

(Mandatory Information)

A1. DETERMINATION OF PHASED-ARRAY BEAM PROFILE

A1.1 Introduction

A1.1.1 This annex describes procedures to determine beam profiles of phased-array probes. Either immersion or contact probe applications can be addressed using these procedures. However, it should be cautioned that assess-

ments of contact probes may suffer from variability greater than imposed tolerances if proper precautions are not taken to ensure constant coupling conditions.

A1.2 Test Setup

A1.2.1 For single focal laws where the beam is fixed (that is, not used in an electronic or sectorial scan mode) and the probe is used in an immersion setup, the ball-target or hydrophone options described in E 1065 may be used. For phased-array probes used in a dynamic fashion where several focal laws are used to produce sectorial or electronic scanning it may be possible to make beam-profile assessments with no or little mechanical motion. Where mechanical motion is used it shall be encoded to relate signal time and amplitude to distance moved. E   e verified to be within tolerances a   urements made. Descriptions made for electronic scan and sectorial scan beam profile assessments will be made for contact probes; however, when assessment in water is required the machined targets may be replaced with rods or balls as appropriate.

A1.2.2 *Linear-Array Probes* — Linear-array probes have an active plane and an inactive or passive plane. Assessment of the beam in the active plane should be made by use of an electronic scan sequence for probes with sufficient number of elements to electronically advance the beam past the targets of interest. For phased-array probes using a large portion of the available elements to form the beam the number of remaining elements for the electronic raster may be too small to allow thebeam to pass over the target. In this case it wil   encoded mechanical motion and assess each focal law along the active plane separately.

A1.2.3 Side-drilled holes should be arranged at various depths in a flaw-free sample of the test material in which focal laws have been programmed for. Using the linear scan feature of the phased-array system the beam is passed over the targets at the various depths of interest. The electronic scan is illustrated schematically in Fig. A1.1.

A1.2.4 Data collection of the entire waveform over the range of interest shall be made. The display shall represent amplitude as a color or grayscale. Time or equivalent distance in the test material shall be presented along one axis and distance displaced along the other axis. This is a typical B-scan as illustrated in Fig. A1.2.

A1.2.5 Data display for an electronic scan using a phased-array probe mounted on a wedge can be similarly made using simple orthogonal representation of time versus displacement or it can be angle corrected as illustrated in Fig. A1.3.

A1.2.6 Resolution along the displacement axis will be a function of the step size of the electronic scan or, if the scan uses an encoded mechanical fixture the resolution will be dependent on the encoder step-size used for sampling.

A1.2.7 Resolution along the beam axis will be a function of the intervals between the target paths. For highly focused beams it may be desirable to have small differences between the sound paths to the target paths (for example, 1 mm or 2 mm).

A1.2.8 Beam profiling in the passive plane can also be made. The passive plane in a linear-array probe is perpendicular to the active plane and refers to the plane in which no beam steering is possible by phasing effects. Beam profiling in the passive direction will require mechanical scanning.

A1.2.9 Waveform collection of signals using a combination of electronic scanning in the active plane and encoded mechanical motion in the passive plane provides data that can be projection-corrected to provide beam dimensions in the passive plane. Figure A1.4 illustrates a method for beam assessment in the passive plane. This technique uses a corner reflection from an end-drilled hole at depths established by a series of steps.

A1.2.10 Figure A1.5 illustrates an alternative to the stepped intervals shown in Fig. A1.4. A through hole may be arranged perpendicular to the required refracted angle to provide a continuous transition of path length to the target.

A1.2.11 A projected C-scan can be used to size the beam based on either color or grayscale indicating amplitude drop or a computer display that plots amplitude with respect to displacement. The projected C-scan option is schematically represented in Fig. A1.6.

FIG. A1.1 ELECTRONIC SCAN OF SIDE-DRILLED HOLES
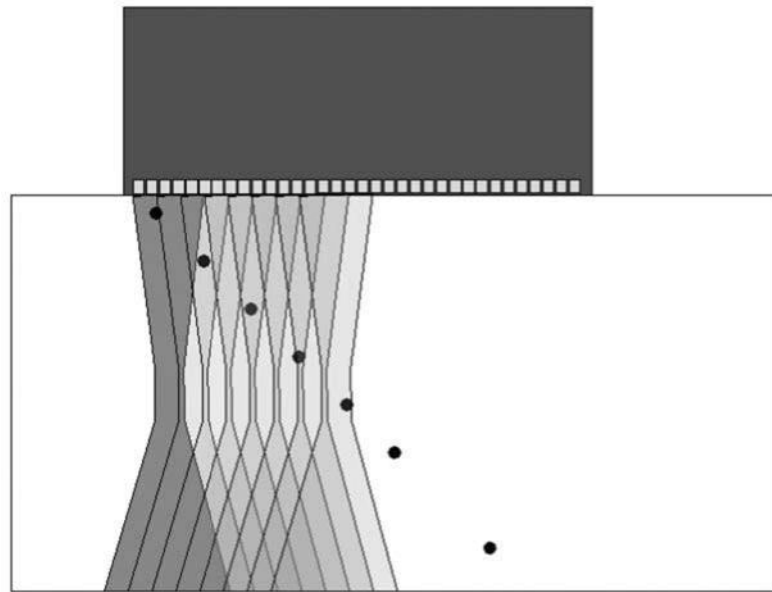
FIG. A1.2 B-SCAN DISPLAY OF ELECTRONIC SCAN REPRESENTED IN FIG. A1.1 (DEPTH IS IN THE VERTICAL AXIS AND ELECTRONIC-SCAN DISTANCE IS REPRESENTED ALONG THE HORIZONTAL AXIS)
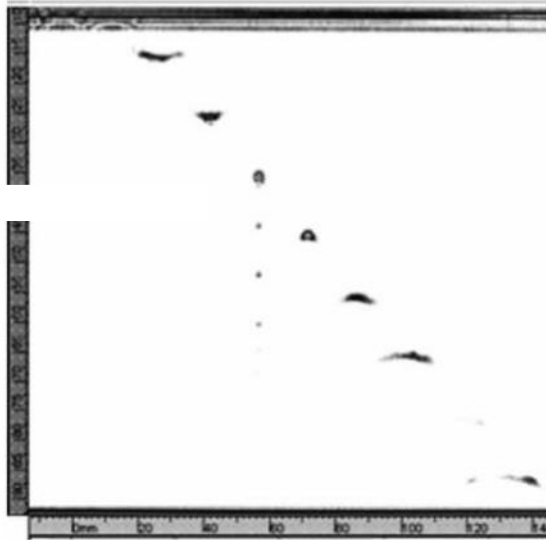
A2. DETERMINATION OF PHASED-ARRAY BEAM STEERIN

A2.1 Introduction

A2.1.1 This annex describes procedures to determine practical limits for beam steering capabilities of a phased-array probe and as such applies to the active plane(s) only. Either immersion or contact probe applications can be addressed using these procedures. However, it should be cautioned that assessments of contact probes may suffer from variability greater than imposed tolerances if proper precautions are not taken to ensure constant coupling conditions.

A2.1.2 Recommended limits to establish the working range of angular sweep of a phased-array probe relate to the divergence of the beam of each element in the probe array. When used in pulse-echo mode the steering limit is considered to be within the 6-dB divergence envelope of the individual elements. It is therefore possible to calculate a theoretical limit based on nominal frequency and manufacturer provided information on the element dimensions. However, several parameters can affect the theoretical calculations. These are primarily related to the nominal frequency of the probe. Some parameters affecting actual frequency include; pulse length, damping, use of a delay-line or refracting wedge and variations in manufacturing processes on thickness lapping and matching layers.

A2.1.3 For the purposes of this procedure, assessment of beam steering capability will be based on a comparison of signal to noise ratios at varying angular displacements. Beam steering capability will also be affected by project requirements of the beam. Applications where focusing is necessary may not achieve the same limits as applications where the beam is not focused as well as steered.

A2.1.4 Steering capability may be specific to a sound path distance, aperture and material.

A2.2 Test Set-Up — Configure the probe focal laws for the conditions of the test. This will include immersion

FIG. A1.3 ANGLE-CORRECTED B-SCAN OF A PHASED-ARRAY BEAM (IN SHEAR WAVE MODE) FROM A SIDE-DRILLED HOLE (OFF-AXIS LOBE EFFECTS CAN BE SEEN IN THE DISPLAY)
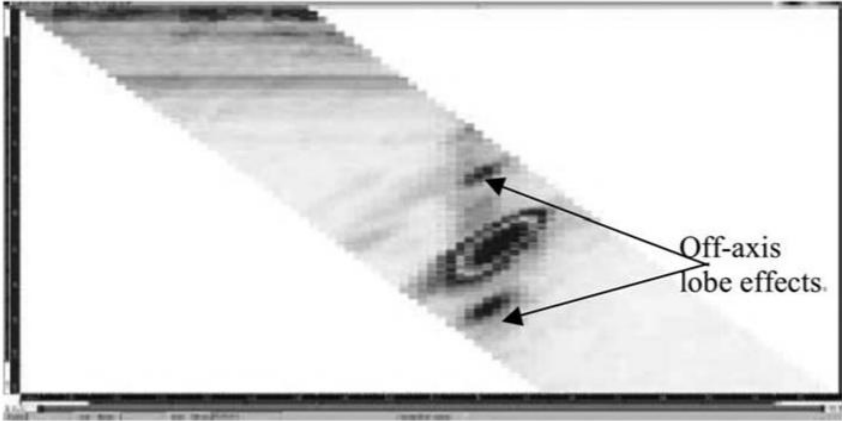
FIG. A1.4 SCANNING END-DRILLED HOLES TO OBTAIN BEAM DIMENSIONS IN PASSIVE PLANE
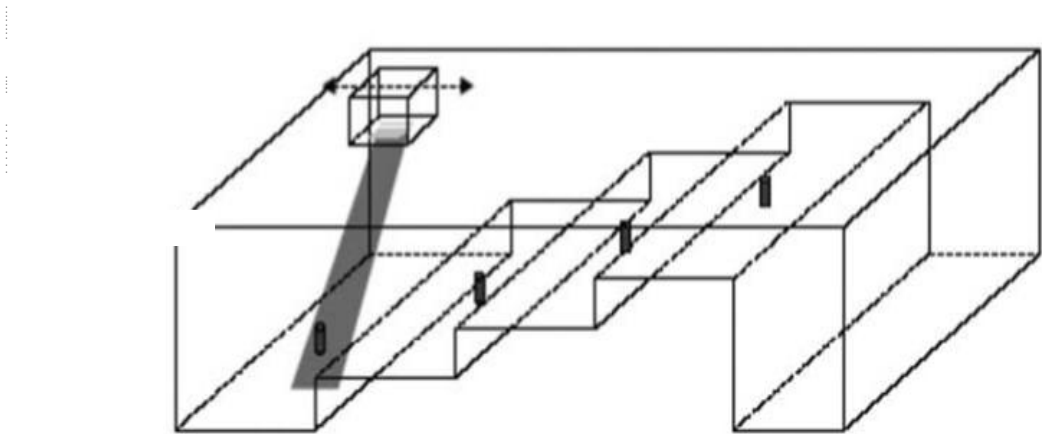
FIG. A1.5 REPRESENTATION OF AN INCLINED HOLE FOR BEAM CHARACTERIZATION IN THE PASSIVE PLANE
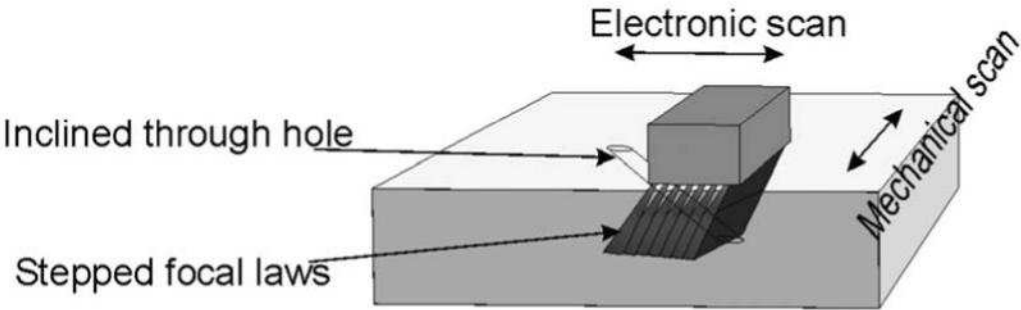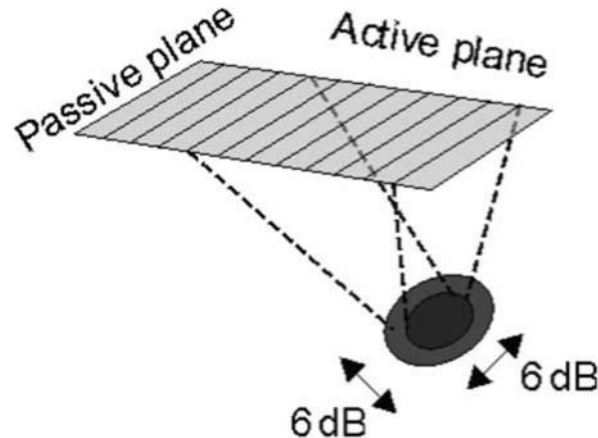
or contact, refracting wedge or delay-line, unfocused or a defined focal distance and the test material to be used.

A2.2.1 Prepare a series of side-drilled holes in the material to be used for the application at the distance or distances to be used in the application. The side-drilled-hole pattern should be as illustrated in Fig. A2.1. Holes indicated in Fig. A2.1 are at 5 deg intervals at a 25-mm and 50-mm distance from a center where the probe is located.

A2.2.2 Similar assessments are possible for different applications. When a set of focal laws is arranged to provide ⬚⬚⬚⬚⬚⬚⬚⬚⬚⬚ nstead of a sound path distance, the ⬚⬚⬚⬚⬚⬚⬚ be used to assess the steering limits of the beam. The block used for assessment would be arranged with side-drilled holes in the plane of interest. Such a plane-specific block is illustrated in Fig. A2.2 where a series of holes is made in a vertical and horizontal plane at a specified distance from the nominal exit point. Side-drilled holes may be arranged in other planes (angles) of interest.

A2.2.3 Assessments are made placing the probe such that the center of beam ray enters the block at the indicated centerline. For analysis of a probe where all the elements in a single plane are used without a delay line or refracting wedge the midpoint of the element array shall be aligned with the centerline. For focal laws using only a portion of the total available elem⬚⬚⬚⬚⬚⬚⬚⬚⬚⬚⬚⬚⬚⬚he element aperture shall be aligne⬚⬚⬚⬚⬚⬚⬚⬚⬚⬚⬚ When delay lines, refracting wedges or immersion methods are used corrections will be required to compensate for movement of the "apparent" exit point along the block entry surface. When a probe is used in direct contact with a verification block as illustrated in Fig. A2.2 the lack of symmetry either side of the centerline prevents both positive and negative sweep angles being assessed simultaneously. To assess the

sweep limit in the two directions when using this style of block requires that the probe be assessed in one direction first and then rotated 180 deg and the opposite sweep assessed.

A2.2.4 Angular steps between A-scan samples will have an effect on the perceived sweep limits. A maximum of 1 deg between S-scan samples is recommended for steering assessment. Angular steps are limited by the system timing-delay capabilities between pulses and element pitch characteristics. Most of the targets illustrated in Fig. A2.1 and Fig. A2.2 are separated by 5 deg; however, greater or lesser intervals may be used depending on the required resolution.

A2.2.5 Assessment of steering limits shall be made using the dB difference between the maximum and minimum signal amplitudes between two adjacent side-drilled holes. For example, when a phased-array probe is configured to sweep +45 deg on a block such as illustrated in Fig. A2.1, the higher of the pair of the SDHs which achieves a 6-dB separation shall be considered the maximum steering capability of the probe configuration.

A2.2.6 Acceptable limits of steering may be indicated by the maximum and minimum angles that can achieve a prespecified separation between adjacent holes. Depending on the application a 6dB or 20 dB (or some other value) may be specified as the required separation.

A2.2.7 Steering capabilities may be used as a prerequisite; for example, a phased-array system is required to achieve a minimum steering capability for 5 deg resolution of 2-mm diameter side-drilled holes of plus and minus 20 deg from a nominal mid-angle. Conversely, a system may be limited to S-scans not exceeding the angles assessed to achieve a specified signal separation, for example, −20 dB between 2-mm diameter SDHs separated by 5 deg.

FIG. A2.1 BEAM STEERING ASSESSMENT BLOCK—CONSTANT SOUND PATH
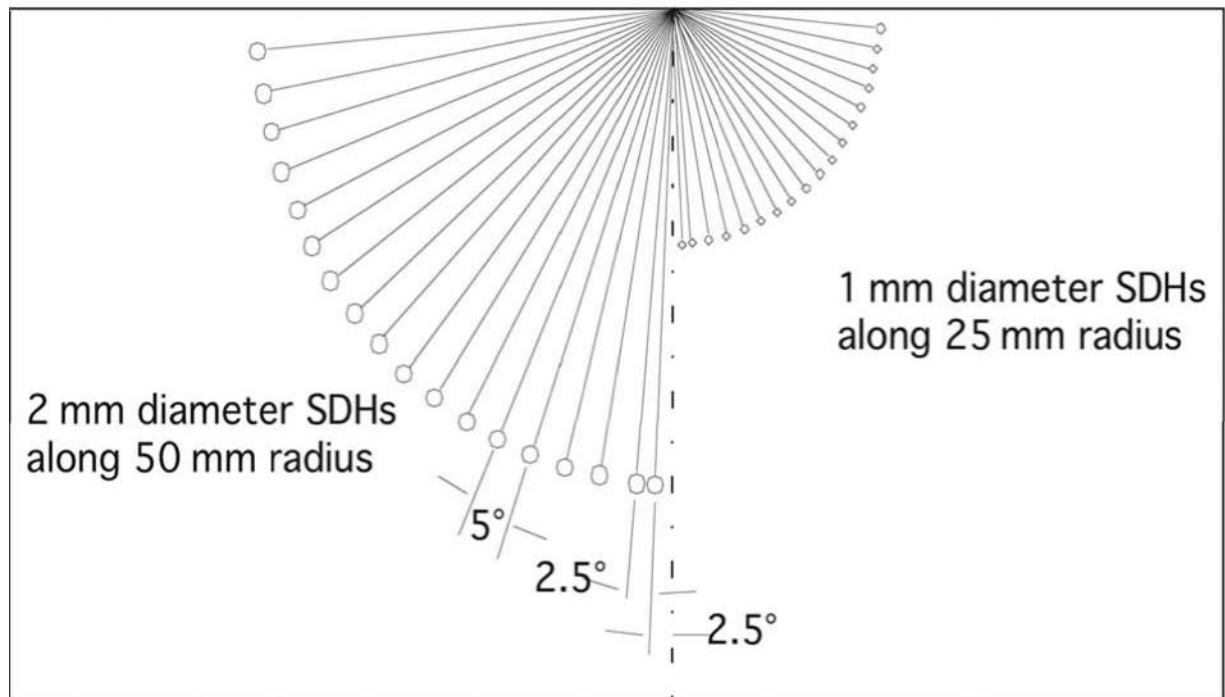
A2.3 An alternative assessment may use a single SDH at a specified depth or sound path distance. Displaying the   and minimum angles used would as   bility by observing the S/N ratio at the peaked response. Steering limit would be a pre-defined S/N ratio being achieved. Caution must be taken when using this method so as to not peak on grating lobe signals. This method will also require confirmation that the SDH is positioned at the calculated refracted angle.

A3. DETERMINATION OF PHASED-ARRAY ELEMENT ACTIVITY

A3.1 Introduction

A3.1.1 This assessment is used to determine that all elements of the phased-array probe are active and of uniform acoustic energy. Be   peration in a timed sequence, each of the elements is addressed by a separate pulser and receiver, a method must be used that ensures the electronic performance of the phased-array instrument is identical from element to element and any differences are attributable to the probe itself. To ensure that any variation of element performance is due only to probe construction, a single pulser-receiver channel is selected to address each element.

A3.2 Test Set-Up

A3.2.1 Connect the phased-array probe to be tested to the phased-array ultrasonic instrument and remove any delay line or refracting wedge from the probe.

A3.2.2 Acoustically couple the probe to the 25-mm thickness of an IIW (International Institute of Welding) block with a uniform layer of couplant. This may be accomplished by a contact-gap technique such that the probe-to-block interface is under water (to ensure uniform coupling). Alternatively an immersion method using a fixed water path may be used and the water-steel interface signal monitored instead of the steel wall thickness.

A3.2.3 Configure an electronic scan consisting of one element that is stepped along one element at a time for the total number of elements in the array. (This should ensure that the pulser-receiver number 1 is used in each focal law or if the channel is selectable it should be the same channel used for each element). Set the pulser parameters to optimize the response for the nominal frequency of the probe array and establish a pulse-echo response from the block backwall or waterpath to 80% display height for each element in the probe.

A3.2.4 Observe the A-scan display for each element in the array and record the receiver gain required to achieve

FIG. A2.2 BEAM STEERING ASSESSMENT BLOCK—SINGLE PLANE

Vertical plane 50 mm from exit point

85°
80°
75°
70°
65°
60°
55°

50°

45°

40°

35°

30°

5 10 20 30° 40°   50° 55° 60°

Horizontal plane 25 mm from exit
plane

Block dimensions 150 mm by 100 mm by 25 mm
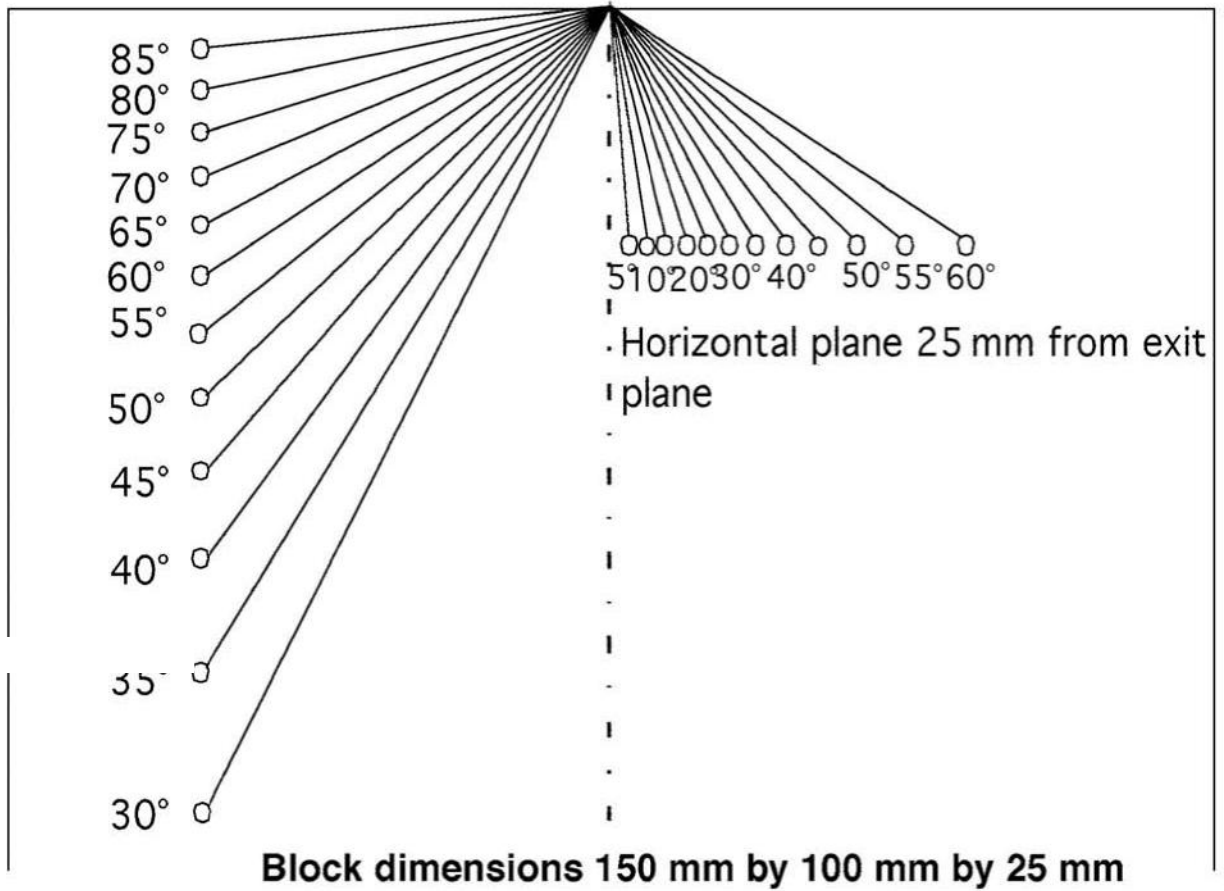
TABLE A3.1
PROBE ELEMENT ACTIVITY CHART: ENTER RECEIVER GAIN FOR 80% FSH

Element	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Gain																
Active ([sqcap]) Inactive (x)																

the 80% signal amplitude for each element. Results may be recorded on a table similar to that in Table A3.1.

A3.2.5 Note and record any elements that do not provide a backwall or waterpath signal (inactive elements). Results may be recorded on a table similar to that in Table A3.1.

A3.2.6 If a prepackaged program is available for checking element activity, this can be used as an alternative.

A3.2.7 Data collected is used to assess probe uniformity and functionality. Comparison to previous assessments is made using the same instrument settings (including gain) that were saved to file. The receiver gain to provide an 80% response should be within a range of ±2 dB of any previous assessments and within ±2 dB of each other.

A3.2.8 The total number of inactive elements and number of adjacent inactive elements in a probe should be agreed upon and identified in a written procedure. This number may be different for baseline and in-service verific   ay probes may have several hundred elements and even new phased-array probes may be found to have inactive elements as a result of manufacturing difficulties ensuring the electrical connections to elements with dimensions on the order of a fraction of a millimetre.

A3.2.9 The number of inactive elements allowed should be based on performance of other capabilities such as focusing and steering limits of the focal laws being used. No simple rule for the number of inactive elements can be made for all phased-array probes. Typically, if more than 25% of the elements in a probe are inactive, sensitivity and steering capabilities may be compromised. Similarly, the number of adjacent elements allowed to be inactive should be determined by the steering and electronic raster resolution required by the

A3.2.10 Stability of coupling is essential for the comparison assessment. If using a contact method and the assessment of elements produces signals outside the ±2 dB range the coupling should be checked and the test run again. If still outside the acceptable range the probe should be removed from service and corrected prior to further use. The test using a fixed water path to a water/steel interface will reduce coupling variations.

A3.2.11 Prior to removing the probe from service the cable used for the test should be exchanged with another cable, when possible, to verify that the inactive elements are not due to a bad cable.

A3.2.12 Cable continuity adapters can be made that allow the multi-strand connectors to be tested independently. These adaptors can be connected to the phased-array instrument directly to verify that all output channels are active or they can be connected to the probe-end of the cable to indicate the continuity of the individual co-axial connectors in the interconnecting cable. Figure A3.1 illustrates an example of a display used to identify inactive channels in a phased-array instrument or cable.

A4. ASSESSMENT OF PHASED-ARRAY FOCUSING ABILITY

A4.1 Introduction

A4.1.1 Focusing of ultrasonic beams is based on well known principles. However, unlike single element probes, phased-array systems can be configured to focus over a range of sound paths and in both transmit and receive modes. Effectiveness of the focusing algorithms can be assessed by determining the beam response dimensions. This is similar to the beam profiling described in Annex A1. Limits of focusing are intrinsic in the probe parameters and subject to the minimum timing-delay capabilities of the phased-array ultrasonic instrument.

A4.2 Test Set-Up

A4.2.1 Configure the phased-array system for the focusing focal laws to be assessed and acoustically couple the phased-array probe to a block with inclined side-drilled holes as illustrated in Fig. A1.1. Compression modes with or without a delay-line and shear modes using a refracting wedge can be assessed by this method.

A4.2.2 Focusing at a single refracted angle is assessed by this method. Where several angles are used it will be necessary to assess the focusing ability for each angle separately.

A4.2.3 Using either an electronic scan or encoded mechanical scan in the plane of interest, the full waveforms are collected and displayed in a depth corrected B-scan projection image as illustrated in Fig. A4.1.

FIG. A3.1 CONTINUITY DISPLAY FOR PHASED-ARRAY INSTRUMENT OR CABLE
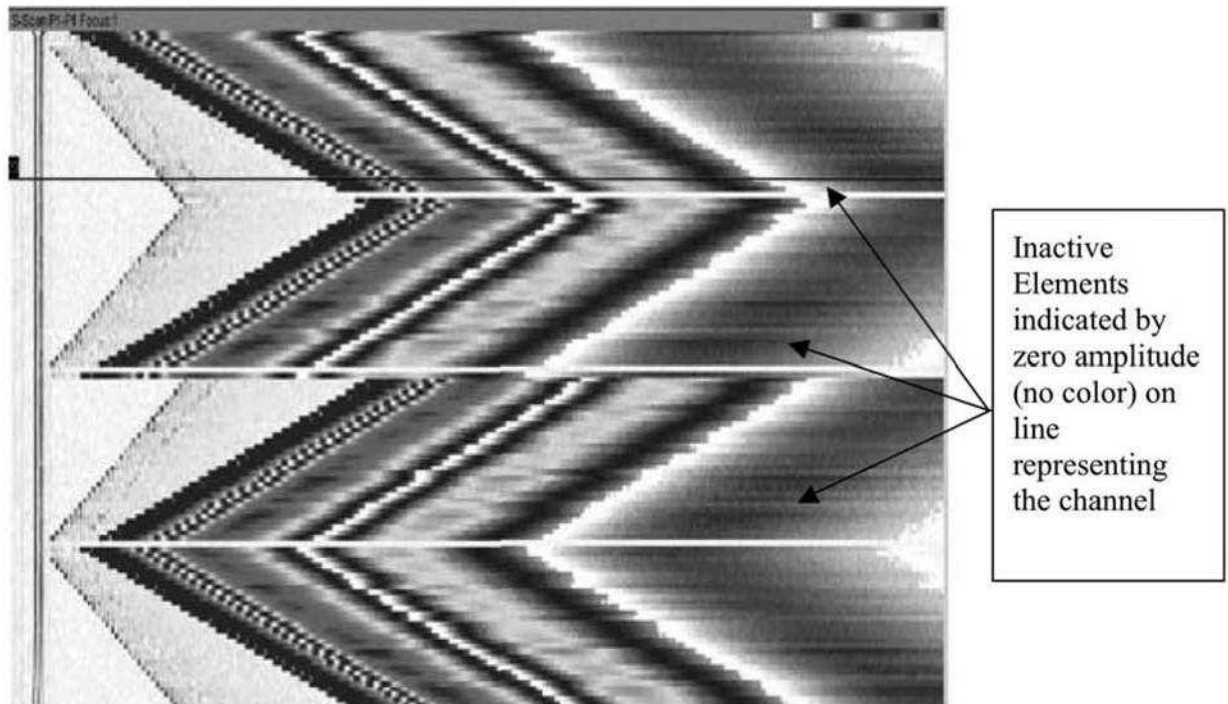
FIG. A4.1 B-SCAN PROJECTED IMAGE OF DYNAMIC DEPTH FOCUSING ALGORITHM
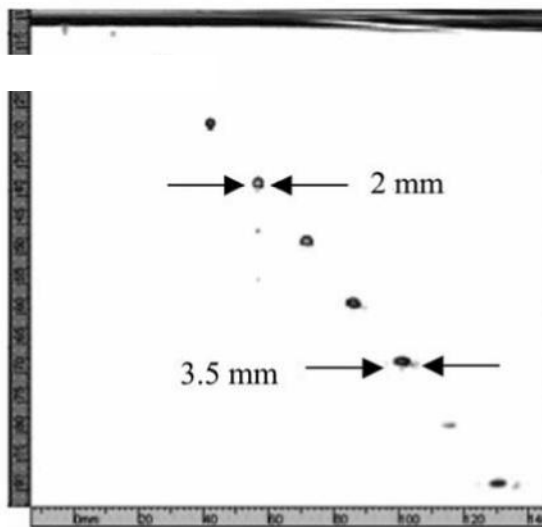
A4.2.4 Effectiveness of the focusing algorithm is assessed by sizing the diameter of the projected image based on a dB drop from maximum amplitude and comparing that dimension to the actual machined diameter of the side-drilled hole.

A4.2.5 Working range of the focusing algorithm may be determined by agreement as to the maximum dimension of the oversizing of the side-drilled hole diameter. For example, if 2-mm diameter SDHs are used and the 6-dB drop is used to gauge diameter from the B-scan, the working range can be defined as the depth or sound-path distance that the B-scan can maintain the 6-dB dimension to less than twice the actual diameter.

A4.2.6 Practical limits for hole diameters and focal spot sizes are required. Practical focal spots for focused beams cannot be made smaller that about 1.5 times the wavelength used. For a 5-MHz compression wave in steel this is about 1.7 mm. The focal spot size is also a function of sound path; the deeper the holes, the weaker the focusing.

A4.2.7 In order that the diameter assessment be meaningful, the sample interval must be small compared to the target assessed. It is recommended that at least four samples per hole diameter be used. For example, for a 2-mm diameter SDH target the sample interval of a mechanized encoded scan should be 0.5 mm or for an electronic scan the step between each focal law should not exceed 0.5 mm (this will be limited by the element pitch of the probe).

A5. ASSESSMENT OF PHASED-ARRAY COMPUTER CONTROL OF PARAMETERS AND DATA DISPLAY

A5.1 Introduction

A5.1.1 Phased-array beam control is based on the Fermat principles which implies that sound follows the

path of least time. This principle is used in ray-tracing of sound paths of transmitted wavefronts from the elements of a phased-array probe to calculate the delays required in the timing electronics to direct a beam to a specified location. Using the Fermat Principle, refracted angles and focal positions are calculated by entering the acoustic velocities of the materials through which the sound propagates. If the material acoustic velocities are accurate then the calculated position of the beam will also be accurate. Accuracy of the calculations is therefore a function of several variables including; acoustic velocity of the materials used, dimensions of the probe components (element size, dominant frequency, divergence, travel distance in the delay line or wedge) and pulser timing accuracy to affect the necessary phase interference patterns. If all the variables are accurately entered in the appropriate equations the beam should be accurately positioned. In a computer controlled system the only evidence available to the operator is the data display. This provides a coordinate system that positions the response from a target in two or three dimensions. Relating the theoretical plotted position on the display to actual known positions of specific targets is the only effective method of assessing the validity of the combination of variables and the computer algorithms for the display.

A5.2 Test Set-Up

A5.2.1 Using a contact linear phased-array probe, nominally 5 MHz and having at least 16 elements with a pitch not greater than 1 mm, configure the software for two separate S-scans, one at ±30 deg with a focal distance o   t is, focused at a sound path of 2   er at ±30 deg with a focal distance of 50 mm in steel (that is, focused at a sound path of 50 mm in steel). For both sets of focal laws program an angular step interval of 0.5 deg and all focal laws shall use 16 adjacent elements.

A5.2.2 Ensure that the digitizing frequency for data collection is at least 80 MHz.

A5.2.3 Prepare a series of side-drilled holes in a steel block that has acoustic velocity determined in accordance with E 494. This velocity value will be used in the focal laws.

A5.2.4 Acoustically couple and align the probe on the block illustrated in Fig. A2.1 such that the centre of the element array aligns   the hole pattern.

A5.2.5 Scan and save the S-scan for the 25-mm focal distance.

A5.2.6 Scan and save the S-scan for the 50-mm focal distance.

A5.2.7 Using the computer display coordinate cursors assess and record the depths, off-sets from the center-line and angles to the side-drilled holes in a tabular form.

For the side-drilled holes at 50-mm radius use the results of the focal laws configured for 50-mm focus and for the holes at 25-mm radius use the focal laws configured for 25 mm.

A5.2.8 Compare the values assessed using the software to the physical positions of the holes in the block. Sound path distances indicated on the computer display should indicate hole positions within ±0.5 mm. Depth and off-set positions of holes should be within ±0.5 mm and all angles to the holes should be within ±1.0 deg.

A6. ASSESSMENT OF PHASED-ARRAY WEDGE ATTENUATION AND DELAY COMPENSATIONS

A6.1 Introduction

A6.1.1 When an electronic or sectorial scan is used the variations between the electronics of each pulser and receiver and variations between probe elements may result in small gain variations from one focal law to the next. Also, the efficiency of generation varies with angle, and declines away from the "natural" angle of the wedge. When a delay line or refracting wedge is used, variations in path distances within the wedge will result in some focal laws requiring more or less amplifier gain. A method of compensating for gain variations so as to "normalize" the set of focal laws in an electronic or S-scan is required.

A6.1.2 When a phased-array probe is used on a delay line or refracting wedge, calculations for beam steering and projection displays rely on the Fermat principle. This requires that the operator identify the position in space of the probe elements. This ensures that the path lengths to the wedge-steel interface are accurately known. It is necessary to verify that the coordinates used by the operator provide correct depth calculations. This ensures that the display software correctly positions indications detected.

A6.1.3 Compensation for attenuation variations and delay times may be made one focal law at a time or software can be configured to make the compensations dynamically. a tabular form. For the side-drilled holes at 50-mm radius use the results of the focal laws configured for 50-mm focus and for the holes at 25-mm radius use the focal laws configured for 25 mm.

A6.2 Wedge-Attenuation Compensation

A6.2.1 This guide applies to assessments of wedge-attenuation compensations for E-scan or electronic raster scans where 1D linear array probes are used.

A6.2.2 Configure the phased-array system for the focal laws to be used in the electronic raster scan application.

A6.2.3 Acoustically couple the phased-array probe to the block with a side-drilled hole at a known depth. The

1.5-mm diameter SDH in the IIW block is a convenient target for this purpose.

A6.2.4 Select the A-scan display for the first focal law configured and move the probe forward and backward to locate the maximum amplitude signal from the SDH.

A6.2.5 Adjust the response from the SDH to 80% full screen height (FSH) and save the parameters in the focal law file.

A6.2.6 Repeat the process of maximizing the signal from the SDH and setting it to 80% FSH for each focal law and saving the set-up file after each focal law is completed.

A6.2.7 Alternatively, this process may be computerized so that a dynamic assessment of sensitivity adjustment is calculated by the computer. A dynamic assessment would simply require the operator to move the probe back and forth over the SDH ensuring that all the focal laws used have the SDH target move through the beam. Wedge attenuation corrections would then be calculated by the phased-array system to ensure that the amplitude of the SDH detected by each focal law would be adjusted to the same amplitude.

A6.2.8 Assessment of wedge-attenuation compensation requires a constant steel path to ensure that only the effect wedge variations are assessed. For S-scans where 1D linear array probes are used, a single SDH results in a changing steel path for each angle making it unsuitable for this task. A recommended target is a radius similar to that of the 100-mm radius of the IIW block. For S-scans are used replacing the SDH with a the radius for S-scan configurations also provides correction for echotransmittance effects intrinsic in angle variation.

NOTE 6.1 — If appropriate compensation cannot be achieved, for example, if the angular range is so large that the signal amplitude cannot effectively be compensated, then the range must be reduced until it is possible to compensate.

A6.2.9 Probe motion for the various wedge and scan-type configurations are illustrated in Fig. A6.1.

A6.3 Wedge-Delay Compensation

A6.3.1 When an angled refracting wedge is used for E-scans or S-scans, or when a fixed thickness delay line is used for S-scans, the sound path in the wedge material varies from one focal law to the next. Compensation for this delay time differen   ensure that indications detected are correctly positioned in the projection scan displays, that is, depth and angle within the test piece are correctly plotted.

A6.3.2 Configure the phased-array system for the focal laws to be used in the S-scan or electronic raster scan application.

A6.3.3 Acoustically couple the phased-array probe to a block with known radius of curvature. The 50-mm or

100-mm radius of the IIW block is a convenient target for this purpose.

A6.3.4 Select the A-scan display for the first focal law configured and move the probe forward and backward to locate the maximum amplitude signal from the radius selected.

A6.3.5 Adjust the delay settings to indicate the sound path in the metal to correctly indicate the radius used and save the focal law parameters.

A6.3.6 Repeat the maximization of the radius response for each focal law in the scan set and save the parameter setting after each delay has been adjusted.

A6.3.7 Alternatively, this process may be computerized so that a dynamic assessment of delay adjustment is calculated by the computer. A dynamic assessment would simply require that the operator move the probe back and forth over the center of the radius assuring that all the focal laws used have the center of beam ray peak on the radius appropriate for their angle.

A6.3.8 Small angle compression wave focal laws may require a custom block to carry out this compensation.

A6.3.9 Probe motion for the various wedge and scan type configurations are illustrated in Fig. A6.2.

A7. ASSESSMENT OF PHASED-ARRAY INSTRUMENT LINEARITIES

A7.1 Introduction

A7.1.1 The individual pulser and receiver components of phased-array ultrasonic instruments operate essentially the same as any single channel ultrasonic instrument. Conformance to linearity requirements as described in E 317 may be carried out. However, due to the digital-control nature of all phased-array instruments and the fact that multiple pulsers and receivers are used, it is required that phased-array instruments be assessed for linearity differently than traditional single-channel units.

A7.2 Test Set-Up

A7.2.1 The phased-array instrument is configured to display an A-scan presentation.

A7.2.2 Adjust the time-base of the A-scan to a suitable range to display the pulse-echo signals selected for the linearity verifications. A linearity block similar to that described in E 317 is selected to provide signals to assess linearity aspects of the instrument. Such a block is shown in Fig. A7.1 with a single element probe mounted on it.

A7.2.3 Pulser parameters are selected for the frequency and bandpass filter to optimize the response from the pulse-echo (single element) probe used for the linearity verifications.

FIG. A6.1 SCAN MOTION MAXIMIZING RESPONSE FROM SDH TO COMPENSATE FOR WEDGE ATTENUATION

Sensitivity adjustment for 0° with delay line

Sensitivity adjustment for electronic scan with refracting wedge

Sensitivity adjustment for S-scan with refracting wedge
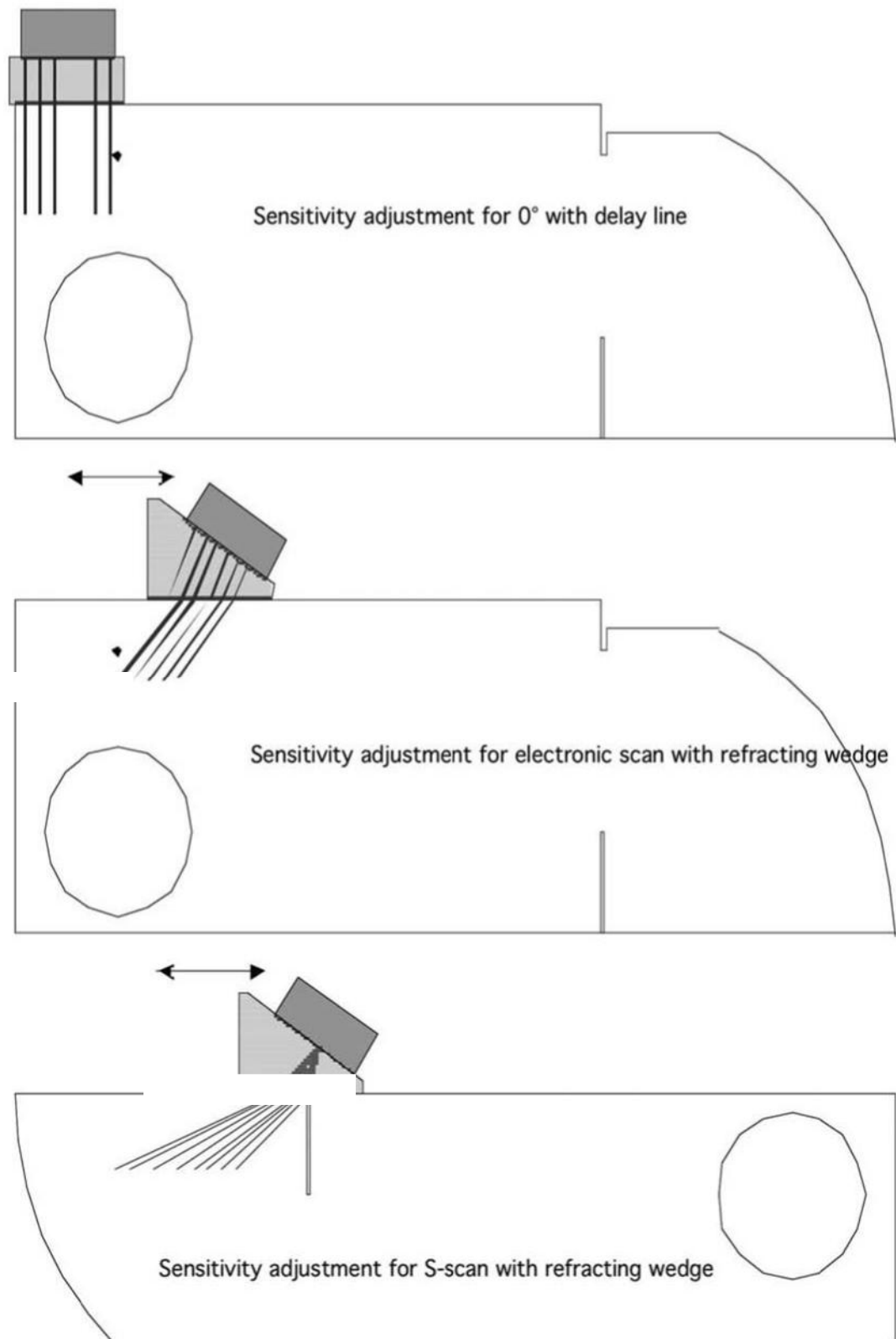
FIG. A6.2 DELAY ADJUSTMENT SCANS USING CURVED SURFACES

Delay adjustment movement for S-scan with refracting wedge

Delay adjustmentmovement for electronic scan with refracting wedge
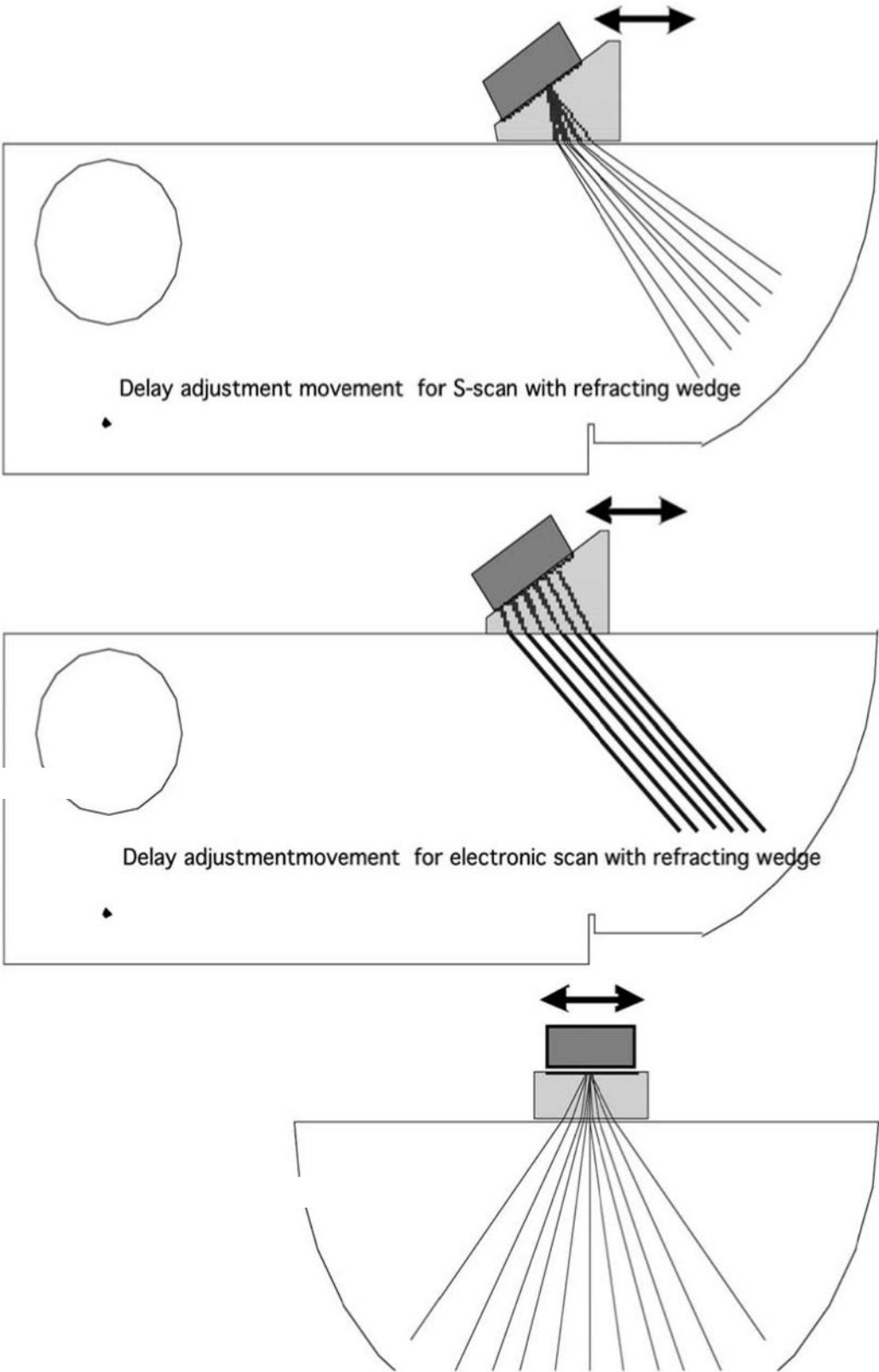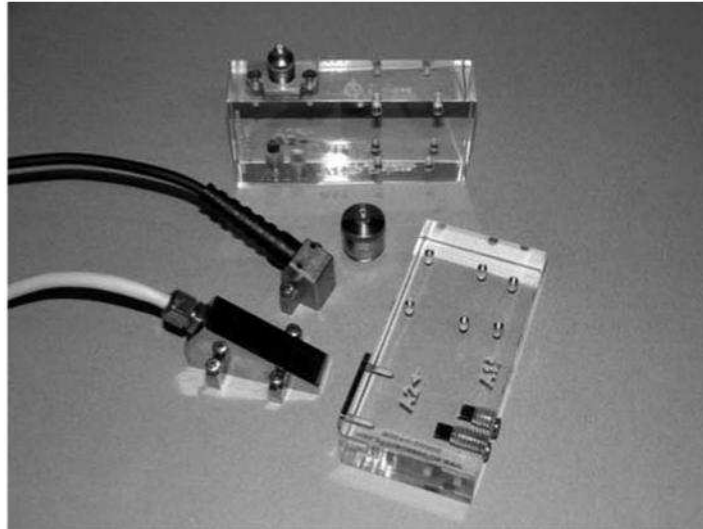
A7.2.4 The receiver gain is set to display non-saturating signals of interest for display height and amplitude control linearity assessments.

A7.3 Display Height Linearity

A7.3.1 With the phased-array instrument connected to a probe (shear or longitudinal) and coupled to any block that will produce two signals as shown in Fig. A7.2 adjust the probe such that the amplitude of the two signals are at 80% and 40% of the display screen height. If the phased-array instrument has provision to address a single element p   e then the two flat bottom holes w   impedance inserts in the custom linearity block shown in Fig. A7.1 provides such signals.

A7.3.2 Increase the gain using the receiver gain adjustment to obtain 100% of full screen height of the larger response. The height of the lower response is recorded at this gain setting as a percentage of full screen height.

NOTE A7.1 — For 8-bit digitization systems this value should be 99%, as 100% would provide a saturation signal.

A7.3.3 The height of the higher response is reduced in 10% steps to 10% of full screen height and the height of the second response is recorded for each step.

A7.3.4 Return the larger signal to 80% to ensure that the smaller signal has   inal 40% level due to coupling vari   variation of the second signal is greater than 41% or less than 39% FSH.

A7.3.5 For an acceptable tolerance, the responses from the two reflectors should bear a 2-to-1 relationship to within ±3% of full screen height throughout the range 10% to 100% (99% if 100% is saturation) of full screen height.

A7.3.6 The results are recorded on an instrument linearity form.

A7.4 Amplitude Control Linearity

A7.4.1 A $_{1664}$ phased-array instrument has 16 pulsers and receivers that are used to address up to 64 elements. Each of the pulser-receiver components is checked to determine the linearity of the instrument amplification capabilities.

A7.4.2 Select a flat (normal incidence) linear array phased-array probe having at least as many elements as the phased-array ultrasonic instrument has pulsers.

A7.4.3 Using this probe, configure the phased-array ultrasonic instrument to have an electronic raster scan. Each focal law will consist of one element and the scan will start at element number 1 and end at the element number that corresponds to the number of pulsers in the phased-array instrument.

A7.4.4 Couple the probe to a suitable surface to obtain a pulse-echo response from each focal law. The backwall echo from the 25-mm thickness of the IIW block or the backwall from the 20-mm thickness of the custom linearity block illustrated in Fig. A7.1 provides a suitable target option. Alternatively, immersion testing can be used.

A7.4.5 Select Channel 1 of the pulser-receivers of the phased-array instrument. Using the A-scan display, monitor the response from the selected target. Adjust the gain to bring the signal to 40% screen height. This is illustrated in Fig. A7.3.

A7.4.6 Add gain to the receiver in the increments of 1 dB, then 2 dB, then 4 dB and then 6 dB. Remove the gain added after each increment to ensure that the signal has returned to 40% display height. Record the actual height of the signal as a percentage of the display height.

FIG. A7.2 DISPLAY HEIGHT LINEARITY
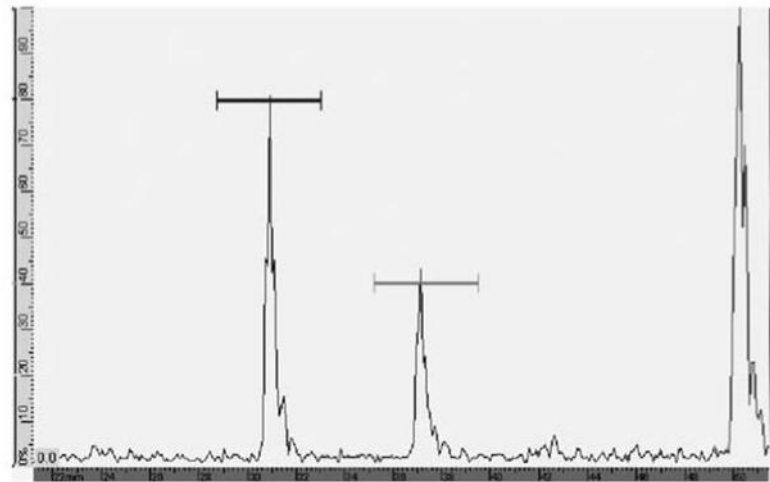
FIG. A7.3 A-SCAN DISPLAY OF BACKWALL ECHO ON CHANNEL 1 OF A PHASED-ARRAY INSTRUMENT
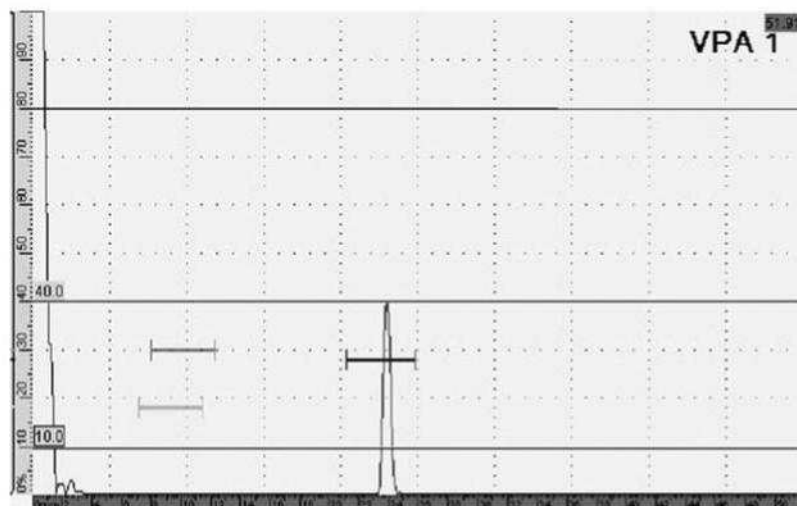
A7.4.7 Adjust the signal to 100% display height, remove 6-dB gain and record the actual height of the signal as a percentage of the display height.

A7.4.8 Signal amplitudes should fall within a range of ±3% of the display height required in the allowed height range of Table A7.1.

A7.4.9 Repeat the   to A7.4.7 for all other pulser-rece

A7.4.10 For instruments having 10- or 12-bit amplitude digitization and configured to read amplitudes in a gated region to amplitudes greater than can be seen on the display, a larger range of check points can be used. For these instruments the gated output instead of the A-scan display would be verified for linearity.

NOTE A7.2 — An example of amplitudes greater than 100% display height is seen in Fig. A7.4 where gate A% indicates a 200% signal and gate B% indicates 176%.

A7.5 Time-Base Linearity (Horizontal Linearity)

A7.5.1 Configure the phased-array instrument to display an A-scan presentation.

A7.5.2 Select any compression wave probe and configure the phased-array instrument to display a range suitable to obtain at least ten multiple back reflections from a block of a known thickness. The 25-mm wall thickness of the IIW block is a convenient option for this test.

A7.5.3 Set the phased-array instrument analog-to-digital conversion rate to at least 80 MHz.

TABLE A7.1
LINEARITY VERIFICATION REPORT FORM

Location::			Date:		
Operation:			Signature:		
Instrument:			Couplant:		
Pulser Voltage (V):		Pulse Duration (ns):	Receiver (band):		Receiver smoothing:
Digitization Frequency (MHz):			Averaging:		
Display Height Linearity			Amplitude Control Linearity		
Large (%)	Small Allowed Range	Small Actual (%)	Ind. Height	dB	Allowed Range
100	47–53		40	+1	42–47
90	42–48		40	+2	48–52
80	40	40	40	+4	60–66
70	32–38		40	+6	77–83
60	27–33		40	−6	47–53
50	22–28				
40	17–23				
30	12–18				
20	7–13				
10	2–8				
Amplitude Control Linearity Channel Results: (Note any channels that do not fall in the allowed range)					
Channel (Add more if required for 32 or 64 pulser-receiver units)					

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

5-mm IIW blocks)										
Multiple	1	2	3	4	5	6	7	8	9	10
Thickness	25	50	75	100	125	150	175	200	225	250
Measured Interval										
Allowed deviation ±0.5 mm (Yes/No)										

FIG. A7.4 HORIZONTAL LINEARITY A-SCAN
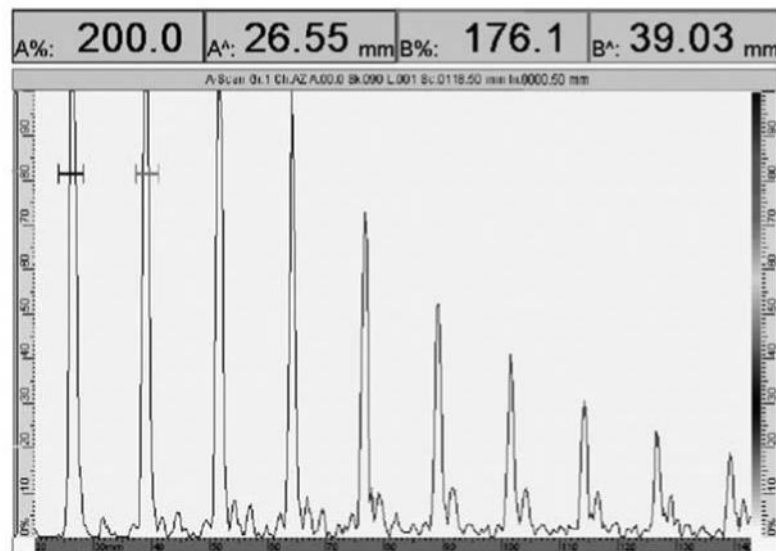
A7.5.4 With the probe coupled to the block and the A-scan displaying 10 clearly defined multiples as illustrated in Fig. A7.4, the display software is used to assess the interval between adjacent backwall signals.

A7.5.5 Acoustic velocity of the test block, determined using the methods described in E 494, is entered into the display software and the display configured to read out in distance (thickness).

A7.5.6 Using the reference and measurement cursors between each multiple and record 10 multiples.

A7.5.7 Acceptable linearity may be established by an error tolerance based on the analog-to-digital conversion rate converted to a distance equivalent. For example, at 100 MHz each sample of the timebase is 10 ns. For steel at 5900 m/s each sample along the timebase (10 ns) in pulse-echo mode represents 30 m. A tolerance of ±3 timing samples should be achievable by most analog-to-digital systems. Some allowance should be made for velocity determination error (~1%). Typically the errors on the multiples should not exceed ±0.5 mm for a steel plate.

A7.5.8 A sample recording table for the linearity checks is indicated in Table A7.1.

Approval Date: October 11, 2005

*The ASME Boiler and Pressure Vessel Standards Committee took action to
eliminate Code Case expiration dates effective March 11, 2005. This means that
all Code Cases listed in this Supplement and beyond will remain available for
use until annulled by the ASME Boiler and Pressure Vessel Standards Committee.*

Case 2235-9
Use of Ultrasonic Examination in Lieu of Radiography
Section I; Section VIII, Divisions 1 and 2; and
Section XII

Inquiry: Under what conditions and limitations may an
ultrasonic examination be used in lieu of radiography, when
radiography is required in accordance with Section I, para.
PW-11; Section VIII, Division 1, para. UW-11(a); Section
VIII, Division 2, Table AF-241.1; and Section
XII, TE-230.1?

Reply: It is the opinion of the Committee that all welds in
material $\frac{1}{2}$ in. (13 mm) or greater in thickness in
pressure vessels and power boilers may be examined
using the ultrasonic (UT) method in lieu of the radiogra-
phy (RT) method, provided that all of the following
requirements are met:

(a) The ultrasonic examination area shall include the
volume of the weld, plus 2 in. (50 mm) on each side of the
weld for material thickness greater than 8 in. (200 mm).
For material thickness 8 in. (200 mm) or less, the ultrasonic
exa   e the volume of the weld, plus
the lesser of 1 in. (25 mm) or *t* on each side of the weld.
Alternatively, examination volume may be reduced to
include the actual heat affected zone (HAZ)
plus $\frac{1}{4}$ in. (6 mm) of base material beyond the heat∕
affected zone on each side of the weld, provided the
following requirements are met:

(1) The extent of the weld HAZ is measured and
documented during the weld qualification process.

(2) The ultrasonic (UT) transducer positioning and
scanning device is controlled using a reference mark (paint
or low stress stamp adjacent to the weld) to ensure
that the actual HAZ plus an additional $\frac{1}{4}$ in. (6 mm) of
base metal is examined.

(b) A documented examina   n
shall be provided showing tra   -
ment, and component coverage that provides a standard-
ized and repeatable methodology for weld acceptance.

The scan plan shall also include ultrasonic beam angle
used, beam directions with respect to weld centerline, and
vessel volume examined for each weld. The docu-
mentation shall be made available to the Owner/User upon
request.

(c) The ultrasonic examination shall be performed in
accordance with a written procedure conforming to the
requirements of Section V, Article 4.[1] The procedure shall
have been demonstrated to perform acceptably on a
qualification block(s). The qualification block(s) shall be
prepared by welding or the hot isostatic process (HIP) and
shall contain a minimum of three flaws, oriented to simulate
flaws parallel to the production weld's fusion
line as follows:

(1) one surface flaw on the side of the block repre-
senting the vessel OD surface

(2) one surface flaw on the side of the block repre-
senting the vessel ID surface

(3) one subsurface flaw

(4) If the block can be flipped during UT examina-
tion, then one flaw may represent both the ID and OD
surfaces. Thus only two flaws may be required.

Flaw size shall be no larger than the flaw in Table 1,
2, or 3 for the thickness to be examined. Acceptable
performance is defined as response from the maximum
allowable flaw and other flaws of interest demonstrated
to exceed the reference level. Alternatively, for tech- niques
that do not use amplitude recording levels, accept- able
performance is defined as demonstrating that all

---

[1] Sectorial scans (S-scans) with phased arrays may be used for the
examination of welds, provided they are demonstrated satisfactorily in
accordance with para. (c). S-scans provide a fan beam from a single
emission point, which covers part or all of the weld, depending on
transducer size, joint geometry, and section thickness. While S-scans can
demonstrate good detectability from side drilled holes, because they are
omnidirectional reflectors, the beams can be misoriented for planar
reflectors (e.g., lack of fusion and cracks). This is particularly true for
thicker sections, and it is recommended that multiple linear passes with S-
scans be utilized for components greater than 1 in. (25 mm) thick. An
adequate number of flaws should be used in the demonstration block to
ensure detectability for the entire weld volume.

TABLE 1
FLAW ACCEPTANCE CRITERIA FOR ½ in. (13 mm) TO LESS THAN 1 in. (25 mm) THICK WELD

	a/t	
Surface flaw	≤0.087	≤0.25 in. (6.4 mm)
Subsurface flaw	≤0.143	≤0.25 in. (6.4 mm)

GENERAL NOTES:
(a) t π the thickness of the weld excluding any allowable reinforcement. For a buttweld joining two members having different thickness at the weld, t is the thinner of these two thicknesses. If a full penetration weld includes a fillet weld, the thickness of the throat of the fillet weld shall be included in t.
(b) A subsurface indication shall be considered as a surface flaw if the separation (S in Fig. 1) of the indication from the nearest surface of the component is equal to or less than half the through dimension (2d in Fig. 1, sketch [b]) of the subsurface indication.

imaged flaws with recorded lengths, including the maximum allowable flaws, have an indicated length equal to or greater than the actual length of the flaws in the qualification block.

(d) The ultrasonic examination shall be performed using a device employing automatic computer based data acquisition. The initial straight beam material examination (T-472 of Section V, Article 4) for reflectors that could interfere with the angle beam examination shall be performed (1) manually, (2) as part of a previous manufacturing process, or (3) during the automatic UT examination provided detection of these reflectors is demonstrated [subpara. (c)].

(e) Data is recorded in unprocessed form. A complete data set with no gating, filtering, or thresholding for response from examination volume in para. (a) above shall be included in the data record.

(f) Personnel performing and evaluating UT examinations shall be qualified and certified in accordance with their employer's written practice. ASNT SNT-TC-1A or CP-189 shall be used as a guideline. Only Level II or III personnel shall analyze the data or interpret the results.

(g) Contractor qualification records of certified personnel shall be approved by the Certificate Holder and maintained by their employer.

(h) In addition, personnel who acquire and analyze UT data shall be trained using the equipment in (d) above, and participate in the demonstration of (c) above.

TABLE 2
FLAW ACCEPTANCE CRITERIA FOR 1 in. (25 mm) TO 12 in. (300 mm) THICK WELD

a/	1 in. (25 mm) ≤ t ≤ 2½ in. (64 mm) [Note (1)]		4 in. (100 mm) ≤ t ≤ 12 in. (300 mm) [Note (1)]	
	Surface Flaw, a/t	Subsurface Flaw, a/t	Surface Flaw, a/t	Subsurface Flaw, a/t
0.00	0.031	0.034	0.019	0.020
0.05	0.033	0.038	0.020	0.022
0.10	0.036	0.043	0.022	0.025
0.15	0.041	0.049	0.025	0.029
0.20	0.047	0.057	0.028	0.033
0.25	0.055	0.066	0.033	0.038
0.30	0.064	0.078	0.038	0.044
0.35	0.074	0.090	0.044	0.051
0.40	0.083	0.105	0.050	0.058
0.45	0.085	0.123	0.051	0.067
0.50	0.087	0.143	0.052	0.076

GENERAL NOTES:
(a) t π thickness of the weld excluding any allowable reinforcement. For a buttweld joining two members having different t   inner of these two thicknesses. If a full penetration weld includes a fillet weld, the thi   weld shall be included in t.
(b) A subsurface indication shall be considered as a surface flaw if separation (S in Fig. 1) of the indication from the nearest surface of the component is equal to or less than half the through thickness dimension (2d in Fig. 1, sketch [b]) of the subsurface indication.
(c) If the acceptance criteria in this table results in a flaw length, , less than 0.25 in. (6.4 mm), a value of 0.25 in. (6.4 mm) may be used.

NOTE:
(1) For intermediate flaw aspect ratio a/ and thickness t (2½ in. [64 mm] < t < 4 in. [100 mm]) linear interpolation is permissible.

TABLE 3
FLAW ACCEPTANCE CRITERIA FOR LARGER THAN 12 in. (300 mm) THICK WELD

Aspect Ratio, a/ℓ	Surface Flaw, a		Subsurface Flaw, a	
	in.	mm	in.	mm
0.00	0.228	5.79	0.240	6.10
0.05	0.240	6.10	0.264	6.71
0.10	0.264	6.71	0.300	7.62
0.15	0.300	7.62	0.348	8.84
0.20	0.336	8.53	0.396	10.1
0.25	0.396	10.1	0.456	11.6
0.30	0.456	11.6	0.528	13.4
0.35	0.528	13.4	0.612	15.5
0.40	0.612	15.5	0.696	17.7
0.45	0.618	15.7	0.804	20.4
0.50	0.624	15.9	0.912	23.6

GENERAL NOTES:

(a) For intermediate flaw aspect ratio, a/ℓ linear interpolation is permissible.

(b) t π the thickness of the weld excluding any allowable reinforcement. For a buttweld joining two members having different thickness at the weld, t is the thinner of these two thicknesses. If a full penetration weld includes a fillet weld, the thickness of the throat of the fillet weld shall be included in t.

(c) A subsurface indication shall be considered as a surface flaw if separation (S in Fig. 1) of the indication from the nearest surface of the component is equal to or less than half the through thickness dimension (2d in Fig. 1, sketch [b]) of the subsurface indication.

(i) Data analysis and acceptance criteria shall be as follows:

(1) Data Analysis Criteria. Reflectors exceeding the limits in either (a) or (b) below, as applicable, shall be investigated to determine whether the indication originates from a flow or is a geometric indication in accordan   w. When a reflector is determined to be a flaw, it shall be evaluated for acceptance in accordance with para. (i)(4), Flaw Evaluation and Acceptance Criteria.

(a) For amplitude-based techniques, the location, amplitude, and extent of all reflectors that produce a response greater than 20% of the reference level shall be investigated.

(b) For nonamplitude-based techniques, the location and extent of all images that have an indicated length greater than the limits in (1), (2), or (3) below, as applica- ble, shall be investigated.

(1) For welds in material equal to or less than $1\frac{1}{2}$ in. (38 mm) thick at the weld, images with indicated lengths greater than 0.150 in. (3.8 mm) shall be investigated.

(2) For welds in material greater than $1\frac{1}{2}$ in./ (38 mm) thick but less than 4 in. (100 mm) thick at the weld, images with indicated lengths greater than 0.200 in. (5 mm) shall be investigated.

(3) For welds in material greater than 4 in. (100 mm) thick at the weld, images with indicated lengths greater than $0.05t$ or 0.75 in. (19 mm), whichever is

smaller, shall be investigated (t π nominal material thickness adjacent to the weld).

(2) Geometric. Ultrasonic indications of geometric and metallurgical origin shall be classified as follows:

(a) Indications that are determined to originate from the surface configurations (such as weld reinforcement or root geometry) or variations in metallurgical structure of materials (such as cladding to base metal interface) may be classified as geometric indications, and

(1) need not be characterized or sized in accordance with (i)(3) below;

(2) need not be compared to allowable flaw acceptance criteria of Table 1, 2, or 3;

(3) the maximum indication amplitude and location shall be recorded, for example: internal attachments, 200% DAC maximum amplitude, one (1) in. (25 mm) above the weld centerline, on the inside surface, from 90 to 95 deg.

(b) The following steps shall be taken to classify an indication as geometric:

(1) Interpret the area containing the reflector in accordance with the applicable examination procedure;

(2) Plot and verify the reflector coordinates, provide a cross-sectional display showing the reflector position and surface discontinuity such as root or counterbore; and

(3) Review fabrication or weld prep drawings.

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(a)   **(b)**

Surface Indications

$S > a$

(c) Subsurface Indications
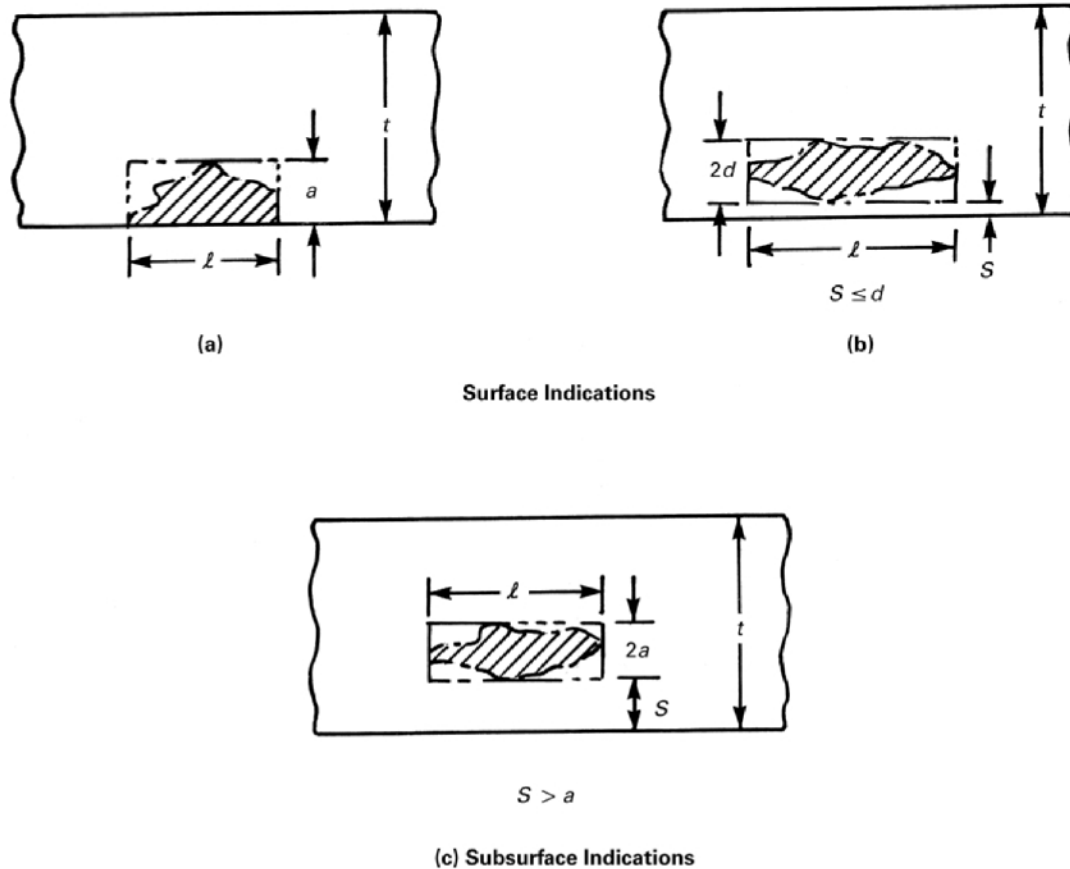
FIG. 1 SINGLE INDICATIONS

(c) Alternatively, other NDE methods or techniques may be applied to classify an indication as geometric (e.g., alternative UT beam angles, radiography, ID and/or OD profiling).

(3) Flaw Sizing. Flaws shall be sized in accordance with a procedure demonstrated to size similar flaws at similar material depths. Alternatively, a flaw may be sized by a supplemental manual technique so long as it has been qualified by the demonstration above. The dimensions of the flaw shall be determined by the rectangle that fully contains the area of the flaw. (Refer to Figs. 1-5.)

(a) The length (*l*) of the flaw shall be drawn parallel to the inside pressure-retaining surface of the component.

(b) The depth of the flaw to the inside pressure retaining surface and shall be denoted as "a" for a surface flaw or "2a" for a subsurface flaw.

(4) Flaw Evaluation and Acceptance Criteria. Flaws shall be evaluated for acceptance using the applicable criteria of Table 1, 2, or 3 and with the following additional requirements:

(a) Surface Connected Flaws. Flaws identified as surface flaws during the UT examination may or may not be surface connected. Therefore, unless the UT data analysis confirms that that flaw is not surface connected, it shall be considered surface connected or a flaw open to the surface, and is unacceptable unless a surface examination is performed in accordance with (1), (2), or (3) below. If the flaw is surface connected, the requirements above still apply; however, in no case shall the flaw exceed the acceptance criteria in the applicable Construction Code for the method employed.

Acceptable surface examination techniques are:

(1) Magnetic particle examination (MT) in accordance with Appendix 6 of Section VIII, Division 1; Appendix 9-1 of Section VIII, Division 2; Appendix A-260 of Section I as applicable; or Appendix V of Section XII, or

(2) Liquid penetrant examination (PT) in accordance with Appendix 8 of Section VIII, Division 1; Appendix 9-2 of Section VIII, Division 2; Appendix A-270 of Section I as applicable; or Appendix VI of Section XII, or
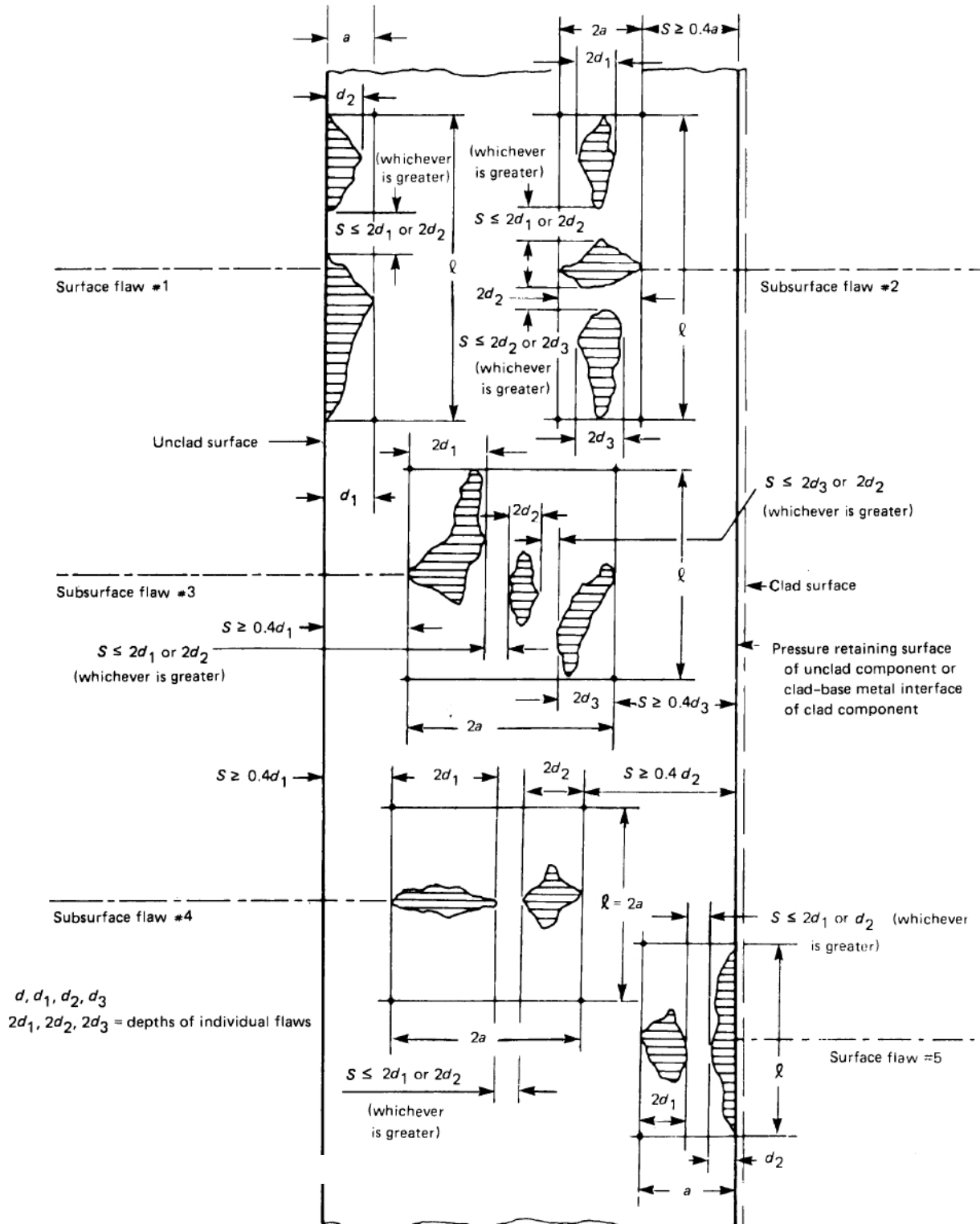
FIG. 2 MULTIPLE PLANAR FLAWS ORIENTED IN PLANE NORMAL TO PRESSURE RETAINING SURFACE
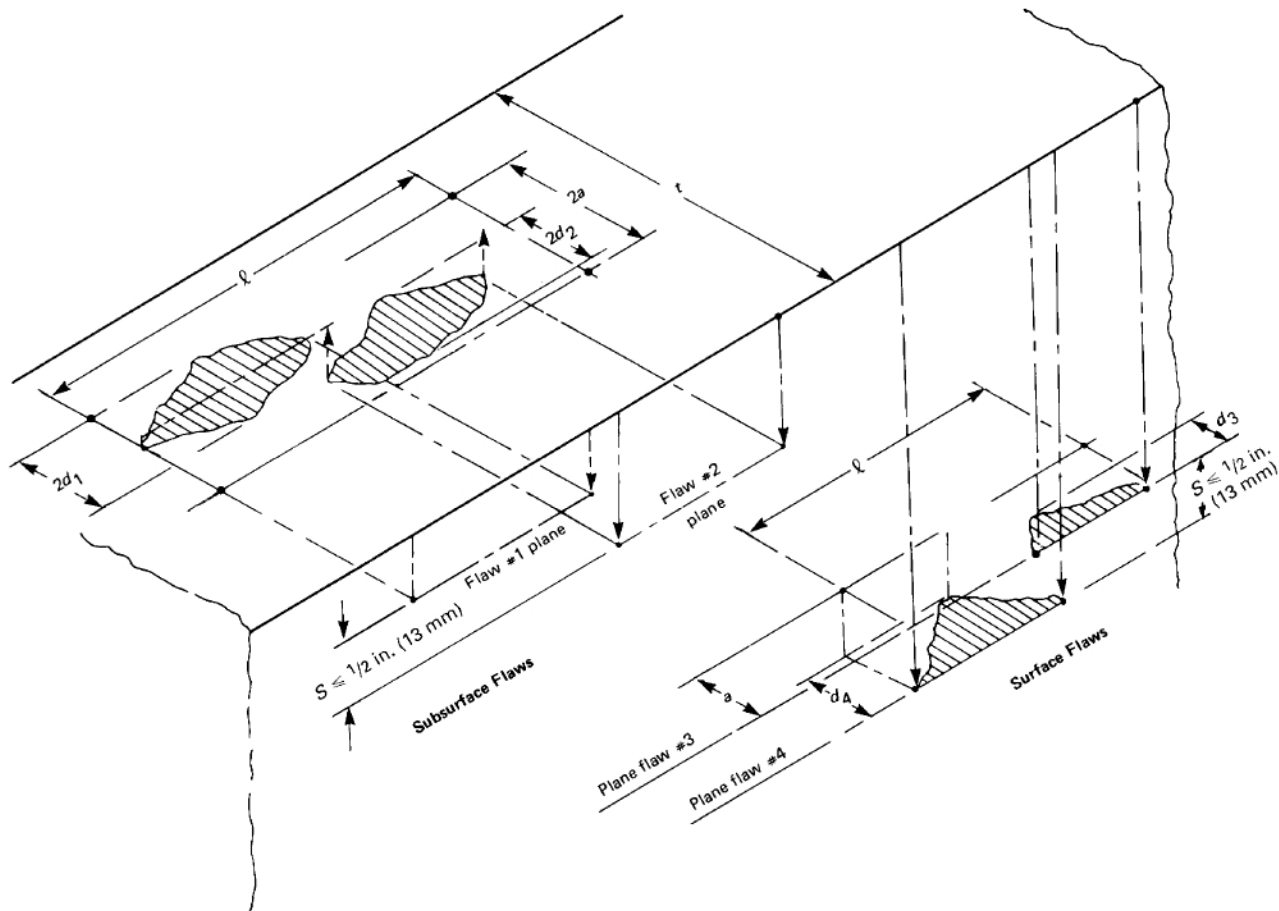
FIG. 3

(3) Eddy current examination (ET) in accordance with Supplement I of this Case. All relevant ET indications that are open to the surface are unacceptable regardless of length.

(b) Multiple Flaws

(1) Discontinuous flaws shall be considered a singular planar flaw if the distance between adjacent flaws is equal to or less than S as shown in Fig. 2.

(2) Discontinuous flaws that are oriented primarily in parallel planes shall be considered a singular planar flaw if the distance between the adjacent planes is equal to or less than $\frac{1}{2}$ in. (13 mm). (Refer to Fig. 3.)

(3) Discontinuous flaw nonaligned in the through-wall th component shall be considered a singular planar flaw if the distance between adjacent flaws is equal to or less than S as shown in Fig. 4.

(4) Discontinuous flaws that are coplanar in the through-wall direction within two parallel planes $\frac{1}{2}$ in. (13 mm) apart (i.e., normal to the pressure-retaining surface of the component) are unacceptable if the additive

flaw depth dimension of the flaws exceeds those shown in Fig. 5.

(c) Subsurface Flaws. Flaw length (l) shall not exceed $4t$.

(j) The final data package shall be reviewed by a UT Level III individual. The review shall include:

(1) the ultrasonic data record

(2) data interpretations

(3) flaw evaluations/characterizations performed by another qualified Level II or III individual. The data review may be performed by another individual from the same organization.

Alternatively, the review may be achieved by arranging for a data acquisition and initial interpretation by a Level II individual qualified in accordance with paras. (f) and (h) above, and a final interpretation and evaluation shall be performed by a Level III individual qualified similarly. The Level III individual shall have been qualified in accordance with para. (f) above, including a practical examination on flawed specimens.
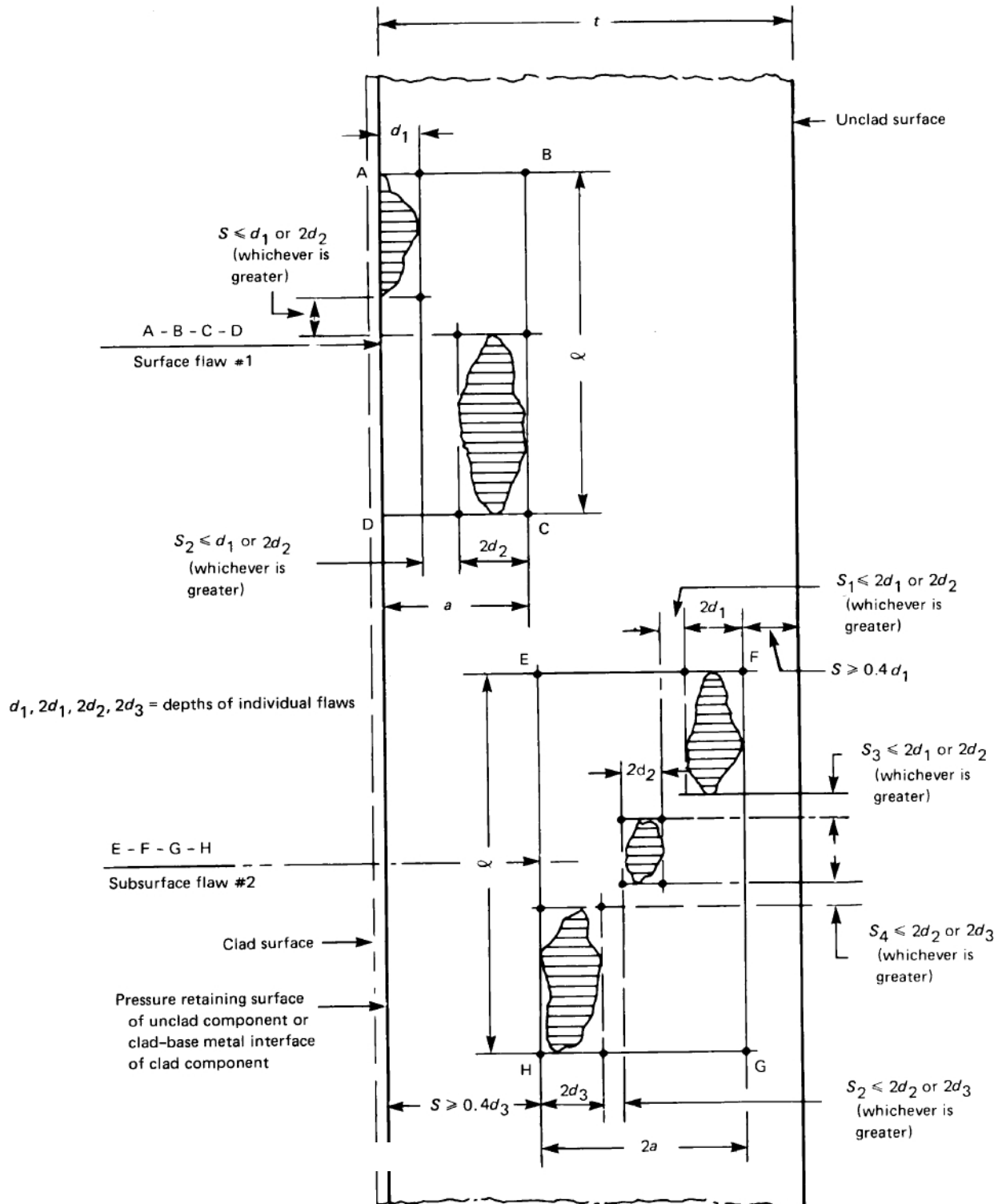
**FIG. 4 NONALIGNED COPLANAR FLAWS IN PLANE NORMAL TO PRESSURE RETAINING
SURFACE (ILLUSTRATIVE FLAW CONFIGURATIONS)**

Unclad surface

1/2 in. (13 mm)

a_1

a_2

Parallel planes bounding aligned flaws

Clad surface

Pressure retaining surface of unclad component or clad – base metal interface of clad component

Section T – T

Surface Flaws [Note (1)]

Subsurface Flaws

Surface and Subsurface Flaws [Note (3)]

GENERAL NOTE: The flaw depth dimensions a_s and a_e are the allowable flaw standards for surface and subsurface flaws, respectively.

NOTES:
(1) This illustration indicates two surface flaws. The first, a_1, is on the outer surface of the component, and the second, a_2, is on the inner surface:
   $(a_1 + a_2) \leq (a_s + a'_s)/2$ within planes A–A' and B–B'
(2) This illustration indicates two subsurface flaws:
   $(a_1 + a_2) \leq (a_e + a'_e)/2$ within planes C–C' and D–D'
(3) This illustration indicates two surface flaws and one subsurface flaw:
   (a) $(a_1 + a_3) \leq (a_s + a'_e)/2$ within planes E–E' and F–F'
   (b) $(a_1 + a_2) \leq (a_s + a_e + a'_s)/3$ within planes F–F' and G–G'
   (c) $(a_2 + a_3) \leq (a'_s + a_e)/2$ within planes G–G' and H–H'

FIG. 5 MULTIPLE ALIGNED PLANAR FLAWS

(k) The nameplate shall be marked under the Code Symbol stamp by applying UT, to indicate ultrasonic examination of welded seams required to be inspected in accordance with Section I; Section VIII, Division 1 or 2; or Section XII.

(l) This Case number shall be shown on the Manufacturer's Data Report, and the extent of the UT examination shall be noted.

SUPPLEMENT I: EDDY CURRENT SURFACE EXAMINATION PROCEDURE REQUIREMENTS

(a) Procedure Requirements. A written procedure shall be provided containing a statement of scope that specifically defines the limits of procedure applicability (e.g., material specification, grade, type, or class). The procedure shall reference a technique specification, delineating the essential variables, qualified in accordance with the requirements below.

(b) Procedure Specifications

(1) The eddy current procedure shall specify the following regarding data acquisition:

(a) instrument or system, including manufacturer's name and model

(b) size and type of probe, including manufacturer's name and part number

and length

(d) examination frequencies, or minimum and maximum range, as applicable

(e) coil excitation mode (e.g., absolute or differential)

(f) minimum data to be recorded

(g) method of data recording

(h) minimum digitizing rate (samples per inch) or maximum scanning speed (for analog systems), as applicable

(i) scan pattern, when applicable (e.g., helical pitch and direction, rectilinear rotation, length, scan index, or overlap)

(j) magnetic bias technique, when applicable

(k) material type

(l) coating type and thickness, when applicable

(2) The eddy current procedure shall define the following regarding data analysis:

(a) method of calibration (e.g., phase angle or amplitude adjustments)

(b) channel and frequencies used for analysis *(c)* extent or area of the component evaluated

(d) data review requirements (e.g., secondary data review, computer screening)

(e) reporting requirements (i.e., signal-to-noise threshold, voltage threshold, flaw depth threshold)

(f) methods of identifying flaw indications and distinguishing them from nonrelevant indications, such as indications from probe lift-off or conductivity and permeability changes in weld material

(g) manufacturer and model of eddy current data analysis equipment, as applicable

(h) manufacturer, title, and version of data analysis software, as applicable

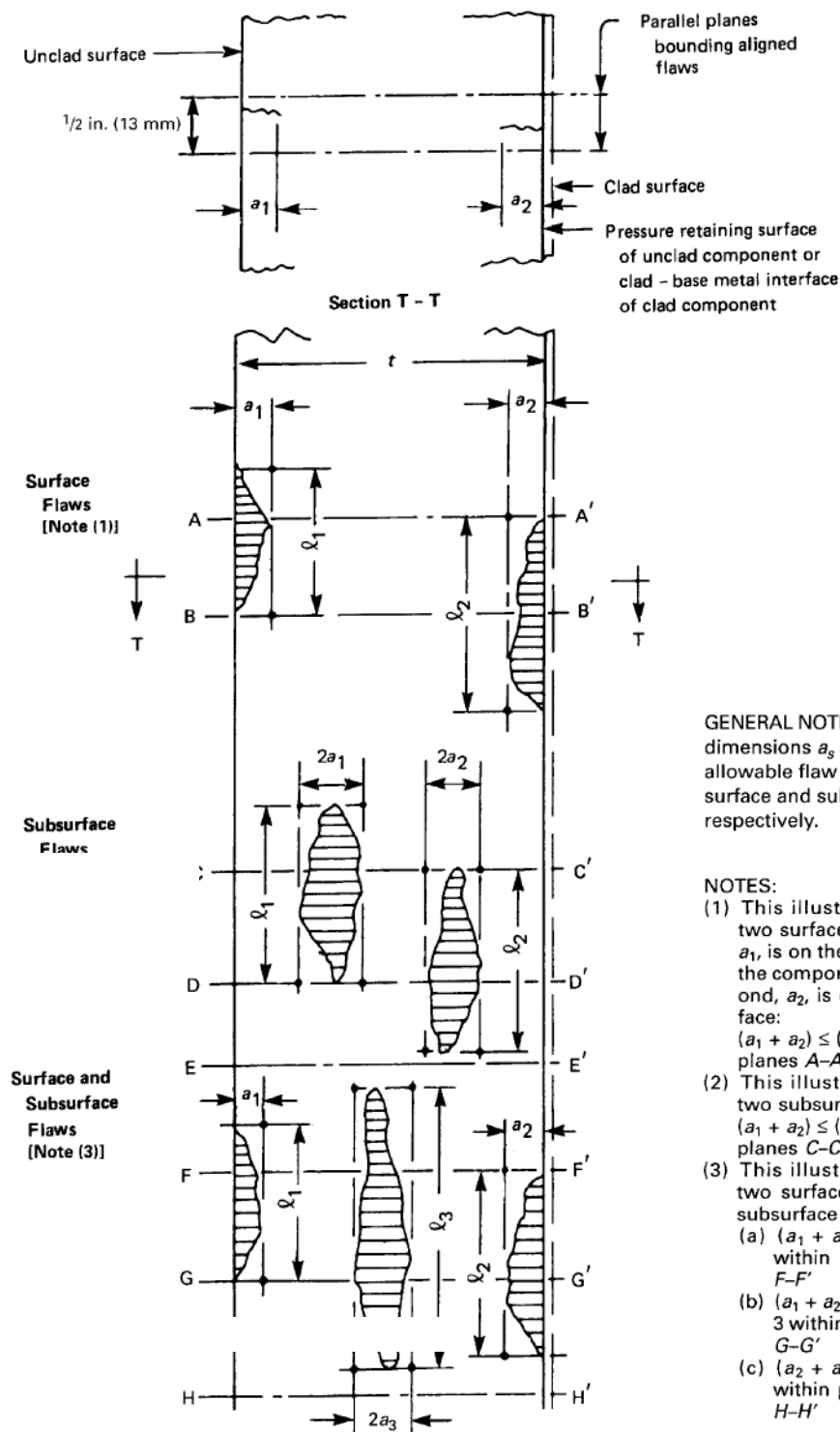*(3)* The procedure shall address requirements for system calibration. Calibration requirements include those actions required to ensure that the sensitivity and accuracy of the signal amplitude and time outputs of the examination system, whether displayed, recorded, or automatically processed, are repeatable and correct. Any process of calibrating the system is acceptable; a description of the calibration process shall be included in the procedure.

(4) Data acquisition and analysis procedures may be combined or separate, provided the above requirements are met.

(c) Personnel Requirements

(1) Personnel performing data acquisition shall have received specific training and shall be qualified by examination, in accordance with the employer's written practice, in the operation of the equipment, applicable techniques, and recording of examination results.

(2) Personnel performing analysis of data shall have received additional specific training in the data analysis techniques used in the procedure qualification and shall successfully complete the procedure qualification described below.

(3) American Society of Nondestructive Testing (ASNT) standards SNT-TC-1A or CP 189 shall be used as a guideline.

(4) Personnel qualifications may be combined provided all requirements are met.

(d) Procedure Qualification

(1) Data sets for detection and sizing shall meet requirements shown below.

(2) The eddy current procedure and equipment shall be considered qualified upon successful completion of the procedure qualification.

(3) Essential Variables. An essential variable is a procedure, software, or hardware item that, if changed, could result in erroneous examination results. Further, any item that could decrease the signal to noise ratio to less than 2:1 shall be considered an essential variable.

(4) Any two procedures with the same essential variables are considered equivalent. Equipment with essential variables that vary within the demonstrated ranges identified in the Data Acquisition Procedure Specification shall be considered equivalent. When the procedure allows more than one value or range for an essential variable, the qualification test shall be repeated at the minimum and maximum value for each essential variable with all other variables remaining at their nominal values. Changing essential variables may be accomplished during successive procedure qualifications involving different personnel; each data analyst need not demonstrate qualification over the entire range of every essential variable.

(e) Qualification Requirements

(1) Specimens to be used in the qualification test shall meet the requirements listed herein unless a set of test specimens is designed to accommodate specific limitations stated in the scope of the examination proce- dure (e.g., surface roughness or contour limitations). The same specimens may be used to demonstrate both detec- tion and sizing qualification. For examination of vessels with coated surfaces, Section V, Article 8 shall apply.

(2) Specimens shall be fabricated from the same base material nominal composition (UNS Number) and heat treatment (e.g., solution annealed, precipitation hard- ened, s   aged) as those to be examin

(3) Specimen surface roughness and contour shall be generally representative of the surface roughness and contour of the component surface to be examined. The examination surface curvature need not be simulated if the ratio of the component diameter to the coil diameter exceeds 20:1.

(4) Welding shall be performed with the same filler material AWS classification, and postweld heat treatment

(e.g., as welded, solution annealed, stress relieved) as the welds to be examined.

(5) Defect Conditions

(a) The qualification flaws shall be cracks or notches.

(b) The length of cracks or notches open to the surface shall not exceed 0.125 in. (3.2 mm).

(c) The maximum depth of a crack or compressed notch shall be 0.040 in. (1.02 mm).

(d) Machined notches shall have a maximum width of 0.010 in. (0.25 mm) and a maximum depth of 0.020 in. (0.51 mm).

(6) Demonstration Specimens. The demonstration specimen shall include one crack or notch at each of the following locations:

(a) on the weld

(b) in the heat affected zone

(c) at the fusion line of the weld

(d) in the base material

(7) Procedure Qualification Acceptance Criteria. All flaws in each of the four identified areas shall be detected with a minimum 2:1 signal-to-noise ratio at the maximum digitization rate (for digital systems) or maxi- mum scanning speed (for analog systems) permitted by the procedure.

(f) Evaluation of Eddy Current Results. Eddy current results are evaluated in accordance with the procedure described in para. (b)(2) above. For this Case, ET is used to simply confirm that a UT flaw is in fact, surface connected. If a UT flaw is determined by ET to be surface connected it shall comply with Acceptance Standards in para. (g) below.

(g) Acceptance Standards. These acceptance stan- dards apply unless other more restrictive standards are specified for specific materials or applications within the Construction Code. All surfaces examined shall be free of relevant ET surface flaw indications.

Appendix A: Constants and Useful Formula Tables

Table A-1 Main ultrasonic features and their definition or relationship

Feature	Definition / formula / units / remarks
Longitudinal (compression) velocity (Table A-2)	$v_L = \left[\dfrac{E(1-\mu)}{\rho(1+\mu)\,(1-2\mu)} \right]^{0.5}$ [m/s; mm/s; in./s] where: E = modulus of elasticity (Young's modulus) [N/m²] ρ = mass density [kg/m³] μ = Poisson's ratio, $\mu = \dfrac{(E-2G)}{2G}$ G = shear modulus [N/m²]
Transverse (shear) velocity (Table A-2)	$v_T = \left[\dfrac{E}{2\rho(1+\mu)} \right]^{0.5}$ [m/s; mm/s; in./s]
Rayleigh velocity	$v_R = \left[\dfrac{(0.87+1.12\mu)}{(1+\mu)} \right] v_T$ [m/s; mm/s; in./s]
Frequency	$f = \dfrac{n}{t}$; number of oscillations in a specific time interval; MHz = 10⁶ Hz = $\dfrac{10^6}{s}$; also: $f = \dfrac{c}{\lambda}$
Wavelength (Table A-3)	$\lambda = \dfrac{v}{f}$; also : $\lambda = \dfrac{PL}{CN}$ [mm/in.] PL = pulse length ($v \cdot \Delta\tau_{20dB}$)[mm/in.] CN = cycle number

Table A-1 Main ultrasonic features and their definition or relationship *(continued)*

Feature	its / remarks
Near-field Length (Circular) [see table A-4]	$N_0 = \dfrac{(D^2 - \lambda^2)}{4\lambda}$; $N_0 = \dfrac{D^2 f}{4v}$ [mm/in.] for $\dfrac{D}{\lambda} > 10$ D = active crystal diameter [mm/in.]
Near-field length (rectangular) [see Table A-5]	$N_{rectangular} = \dfrac{k_\square L^2 f}{4v}$ [mm/in.]
Near-field length (effective)	$N_{eff} = \left(\dfrac{D^2 f}{4v}\right) \cdot \left(\dfrac{\cos\beta}{\cos\alpha}\right)^2$ [mm/in.] for disc-shaped crystal; $N_{eff\,\square} = \dfrac{K_\square \left(\dfrac{L_{probe}\cos\beta}{\cos}\right)^2}{4v_{test\,piece}} - \dfrac{L_{wedge}v_{wedge}}{v_{test\,piece}}$ for rectangular probe on wedge; D = active crystal diameter [mm/in.] α = incident (wedge) angle [°] β = refracted angle in test piece [°] L = crystal length [mm/in.] L_{wedge} = UT path in wedge [mm/in.] v_{wedge} = velocity in the wedge [m/s; mm/μs; in./μs] $v_{testpiece}$ = velocity in the test piece [m/s; mm/μs; in./μs] k = near-field correction factor
Beam diameter (circular)	$\Phi_{AdB} = \dfrac{2k_{free\text{-}field}\,\lambda z}{D}$ [1] [mm/in.] z = UT path [mm/in.]; $\Phi_{(6dB)PE} = \dfrac{\lambda z}{D}$
Beam width (rectangular)	$\Phi_{-\Delta dB} = \dfrac{2k_{free\text{-}field}\,\lambda z}{w}$ [mm/in.] W = crystal width [mm/in.]

Table A-1 Main ultrasonic features and their definition or relationship *(continued)*

Featu...	...la / units / remarks
Beam length (rectangular)	$\Phi_{(-\Delta dB)L} = \dfrac{2k_{\text{free-field}} \cdot \lambda \cdot z}{L}$ [mm/in.]
Half-angle beam divergence (circular)	$\gamma_{\Delta dB} = a\sin\left(\dfrac{k_{\Delta dB}}{D} \cdot \lambda\right)$ [rad/°]; $\gamma_{(-3dB)\,\text{free field}} = \gamma_{(-6dB)\,\text{pulse-echo}} = \dfrac{0.5\lambda}{D}$ [rad/°]; $k_{\Delta dB}$ = half-angle beam divergence constant[1]
Half-angle beam divergence (rectangular)	$\gamma_{(-6dB)L} = a\sin(0.44\lambda/L)$ [rad/°] $\gamma_{(-6dB)W} = a\sin(0.44\lambda/W)$ [rad/°]
Acoustic impedance	$Z = v \cdot \rho$ [kg/m²s=Rayl] (generally 10^6 [MRayl]) [see Table A-2]
Reflection coefficient	$R = \dfrac{(Z_2 - Z_1)}{(Z_1 + Z_2)}$
Transmission coefficient	$T = \dfrac{2Z_2}{(Z_1 + Z_2)}$
Transmission loss	$\Delta G_{\text{transmission}} = -10\log_{10}\left[\dfrac{4Z_1\,Z_2}{(Z_1+Z_2)^2}\right]$ [dB]
Snell's law	$\dfrac{\sin\alpha}{\sin\beta} = \dfrac{v_1}{v_2}$

Table A-2 Acoustic properties of materials

MATERIAL	velocity		Shear velocity		Acoustic impedance
	in./µs	m/s	in./µs	m/s	kg/m²s × 10⁶
Acrylic resin (Perspex)	0.107	2,730	0.056	1,430	3.22
Aluminum	0.249	6,320	0.123	3,130	17.06
Beryllium	0.508	12,900	0.350	8,880	23.50
Brass, naval	0.174	4,430	0.083	2,120	37.30
Copper	0.183	4,660	0.089	2,260	41.61
Diamond	0.709	18,000	0.485	12,320	63.35
Glycerin	0.076	1,920	------	----	2.42
Inconel	0.229	5,820	0.119	3,020	49.47
Iron, cast (slow/soft)	0.138	3,500	0.087	2,200	25.00
Iron, cast (fast/hard)	0.220	5,600	0.126	3,200	40.00
Iron oxide (magnetite)	0.232	5,890	0.128	3,250	30.70
Lead	0.085	2,160	0.028	700	24.29
Lucite	0.106	2,680	0.050	1,260	3.16
Molybdenum	0.246	6,250	0.132	3,350	63.75
Motor oil (SAE 20 / 30)	0.069	1,740	------	-----	1.51
Nickel, pure	0.222	5,630	0.117	2,960	49.99
Polyamide (slow)	0.087	2,200	0.043	1,100	2.40
Polyamide (nylon, fast)	0.102	2,600	0.047	1,200	3.10
Polyethylene, high density (HDPE)	0.097	2,460	0.051	1,295	2.36
Polyethylene, low density (LDPE)	0.082	2,080	0.025	645	1.91
Polystyrene	0.092	2,340	0.046	1,160	2.47
Polyvinylchloride (PVC, hard)	0.094	2,395	0.042	1,060	3.35
Rexolite	0.092	2,330	0.045	1,155	2.47
Rubber (polybutadiene)	0.063	1,610	------	-----	2.43
Silicon	0.379	9,620	0.206	5,230	22.50
Silicone	0.058	1,485	------	-----	1.56
Steel, 1020	0.232	5,890	0.128	3,240	45.41
Steel, 4340	0.230	5,850	0.128	3,240	45.63
Steel, 302 austenitic stainless	0.223	5,660	0.123	3,120	45.45
Steel, 347 austenitic stainless	0.226	5,740	0.122	3,090	45.40
Tin	0.131	3,320	0.066	1,670	24.20
Titanium, Ti 150A	0.240	6,100	0.123	3,120	27.69
Tungsten	0.204	5,180	0.113	2,870	99.72
Water (20 °C)	0.058	1,480	------	-----	1.48
Zinc	0.164	4,170	0.095	2,410	29.61
Zirconium	0.183	4,650	0.089	2,250	30.13

Table A-3 Wavelength for the most commonly used and tested materials in industrial

Frequency [MHz]	Wavelength			
	L-waves		S-waves	
	[mm]	[in.]	[mm]	[in.]
Water [couplant]				
1	1.5	0.059	-	-2
	0.75	0.030	-	-4
	0.4	0.016	-	-5
	0.3	0.012	-	-
10	0.15	0.006	-	-
Glycerin (Hamikleer) [couplant]				
1	1.9	0.075	-	-2
	0.95	0.037	-	-4
	0.48	0.019	-	-5
	0.38	0.015	-	-
10	0.19	0.008	-	-
Plexiglas [wedge]				
1	2.7	0.106	-	-2
	1.35	0.053	-	-4
	0.75	0.030	-	-5
	0.54	0.021	-	-
10	0.27	0.011	-	-
Rexolite [wedge]				
1	2.3	0.091	-	-2
	1.15	0.045	-	-4
	0.58	0.023	-	-5
	0.46	0.018	-	-
10	0.23	0.009	-	-
Steel [test piece]				
1	5.9	0.232	3.2	0.1262
	3	0.118	1.6	0.0634
	1.5	0.059	0.8	0.0325
	1.2	0.047	0.6	0.024
10	0.6	0.024	0.3	0.012
Aluminum [test piece]				
1	6.1	0.240	3	0.1182
	3	0.118	1.5	0.0594
	1.5	0.059	0.8	0.0325
	1.2	0.047	0.6	0.024
10	0.6	0.024	0.3	0.012

Table A-4 Near-field length for circular crystal (in millimeters)

Frequency [MHz]	Crystal diameter [mm]					
	5	6	10	12	20	24
Water; LW; $v = 1.5$ mm/s						
1	4.2	6	17	24	68	96.2
	8.4	12	34	48	136	192
4	17	24	68	96	272	384
5	21	30	85	120	340	480
10	42	60	170	240	680	920
Steel; LW; $v = 5.9$ mm/s						
1	1	1.5	4	6	16	24.2
	2	3	8	12	32	48.4
	4	6	16	24	64	96.5
	5	7.	20	30	80	120
10	10	15	40	60	160	240
Steel; SW; $v = 3.2$ mm/s						
1	2	3	8	12	32	48.2
	4	6	16	24	64	96.4
	8	12	32	48	128	192
5	10	15	40	60	160	240
10	20	30	80	120	320	480
Copper; LW; $v = 4.7$ mm/s						
1	1.3	2	5	8	20	32.2
	2.6	4	10	16	40	64.4
	5	8	20	32	80	128
5	6.5	10	26	40	104	160
10	13	20	52	80	208	320
Aluminum; LW; $v = 6.3$ mm/s						
1	1	1.4	4	6	16	24.2
	2	3	8	12	32	48.4
	4	6	16	24	64	96.5
	5	7	20	30	80	120
10	10	14	40	60	160	240

Table A-5 Near-field length (mm × mm) and half-angle divergence beam at -6 dB [°] of rectangular crystals — shear waves in steel ($v = 3,250$ m/s)

Frequency [MHz]	6×6		8×9		16 × 16		20 × 22	
	N_0	γ	N_0	γ	N_0	γ	N_0	γ
1	N/A	N/A	8	10	32	5	45	42
	9.6	15	5	64	2.5	90	24	
	N/A	N/A	30	2.5	128	1.2	180	15
	20	2.5	40	2	160	1	225	0.8

Appendix B: Unit Conversion

This appendix provides the metric-US-customary conversions for units used in this guide.

Table B-1 Conversion from metric to US customary units

Measure	Metric unit	US customary unit
Length	1 mm	= 39.37 mils = 0.03937 in.
	1 cm	= 0.3937 in.
	1m	= 39.37 in. = 3.28 ft
Area	1 cm^2	= 0.155 in.^{2}
	1 m^2	= 10.7639 ft^2
Velocity	1 mm/μs	= 0.03937 in./μs
	1 m/s	= 3.28 ft/s = 196.85 ft/min
Mass	1g	= 0.03527 oz
	1 kg	= 35.2739 oz = 2.20462 lb
Mass density	1 kg/m^3	= 0.062428 lb/ft^3
Acoustic impedance	1 kg/m^{2}s	= 0.001423 lb/in.^{2}s = 0.204816 lb/ft^{2}s
Temperature	°C	= (5/9) × (°F - 32)
	(°C × 1.8) + 32	= °F

Phased Array Glossary

A-scan

An ultrasonic waveform plotted as amplitude with respect to time. It can be either rectified or unrectified (RF).

Angle-corrected gain (ACG)

This is the gain compensation applied to an S-scan to normalize reflected response from a specific target at each angle comprising the S-scan.

Apodization

A computer-controlled function that applies lower excitation voltage to the outside elements of an array in order to reduce the amplitude of unwanted side lobes.

Aperture

In phased array testing, the width of the element or group of elements pulsed simultaneously.

Azimuthal scan

An alternate term for *S-scan*. It is a two-dimensional view of all amplitude and time or depth data from all focal laws of a phased array probe, corrected for delay and refracted angle. In addition, an S-scan also refers to the action of sweeping the beam through a range of angles.

B-scan

A two-dimensional image of ultrasonic data plotted as reflector depth or distance with respect to beam position. B-scans can be either single value or cross-sectional.

B-scan, cross-sectional

A two-dimensional image of ultrasonic data based on full waveform storage at each data point, which can be plotted to show all reflectors in a cross-section rather than just the first or largest. This allows visualization of both near- and far-surface reflectors within the sample.

B-scan, single value

A two-dimensional image based on plotting the first or largest reflector within a gate. This format is commonly used in ultrasonic

flaw detectors and advanced thickness gages, and it shows one reflect

Bandwidth

The portion of the frequency response that falls within specified amplitude limits. In this context, it should be noted that typical NDT transducers do not generate sound waves at a single pure frequency, but rather over a range of frequencies centered at the nominal frequency designation. The industry standard is to specify this bandwidth at the -6 dB (or half amplitude) point. As a general rule, a broader bandwidth results in a better near-surface and axial resolution, while a narrow bandwidth results in a higher energy output and thus higher sensitivity.

Beam forming

In phased array testing, the generation of a sound beam at a particular position, angle, and/or focus through sequential pulsing of the elements of an array probe.

Beam spread

The angle of divergence from the centerline of a sound beam in its far field.

Beam steering

The capability to modify the refracted angle of the sound beam generated by a phased array probe.

Calibration, sensitivity

A procedure that electronically equalizes amplitude response across all beam components in a phased array scan. This typically compensates for both element-to-element sensitivity variations, and the varying energy transfer at different refracted angles.

Calibration, wedge delay

A procedure that electronically compensates for the different sound paths taken by different beam components in a wedge, used to normalize the measure sound path length to a reflector.

C-scan

A two-dimensional view of ultrasonic amplitude or time/depth data displayed as a top view of the test piece.

E-scan

Also termed an *Electronic-scan*, swept index point, or electronic raster scanning. In some industries, an E-scan is referred to as a "linear scan" or "linear electronic scan." The ability to move the acoustic beam along array without any mechanical movement. The equivalent focal law is multiplexed across a group of active elements; E-scans are performed at a constant angle and along the phased array probe length. For angle beam scans, the focal laws typically compensate for the change in wedge thickness.

Far field

The porti   st on-axis pressure
maximum   ar field.

Focal laws

The programmed pattern of time delays applied to pulsing and receiving from the individual elements of an array probe in order to steer and/or focus the resulting sound beam and echo response.

Focus

In ultrasonics, the point at which a sound beam converges to minimum diameter and maximum sound pressure, and beyond which the beam diverges.

Grating lobes

Spurious components of a sound beam diverging to the sides of the center of energy, caused by even sampling across the probe elements. Grating lobes occur only with phased array probes and are caused by ray components associated with the regular, periodic spacing of the small individual elements. See also "Side lobes."

Huygens' principle

A mathematical model of wave behavior that states that each point on an advancing wave front may be thought of as a point source that launches a new spherical wave, and that the resulting unified wave front is the sum of those individual spherical waves.

Linear scan

The ability to move the acoustic beam along the major axis of the array without any mechanical movement. The equivalent focal law is multiplexed across a group of active elements; linear scans are performed at a constant angle and along the phased array probe length. For angle beam scans, the focal laws typically compensate for the change in wedge thickness. In some industries this term is used to describe a one-line scan.

Near field

The portion of a sound beam between the transducer and the last on-axis sound pressure peak. Transducers can be focused only in the near field.

One-line scan

A single pass mechanical scan of a phased array probe parallel to a weld or region to be inspected. Typically done with a linear array probe to create a C-scan like image of amplitude or depth data as a function of electronic aperture positions versus mechanical positions.

Phased array

A multielement ultrasonic probe (typically with 16, 32, or 64 elements) used to generate steered beams by means of phased pulsing and receiving.

Phasing

The inte   he same frequency but
with dift   esult in either constructive or
destructive interference.

Pitch

The separation between individual elements in a phased array
probe.

Plane, active

The orientation parallel to the phased array probe axis consisting of
multiple elements.

Plane, passive

The orientation parallel to the individual element length or probe
width.

Plane, steering

The orientation in which the beam direction is varied for a phased
array probe.

Pulse duration

The time interval between the point at which the leading edge of a
waveform reaches a specified amplitude (typically -20 dB with
respect to peak) to the point at which the trailing edge of the
waveform reaches the same amplitude. A broader bandwidth
typically reduces the pulse duration, while a narrower bandwidth
increases it. Pulse duration is highly dependent on pulser settings.

Resolution, angular

In phased array systems, the angular resolution is the minimum
angular value between two A-scans where adjacent defects located at
the same depth are individually resolvable.

Resolution, axial

The minimum depth separation between two specified reflectors
that permits the discrete identification of each. A higher frequency
and/or a higher bandwidth generally increases axial separation.

Resolution, far-surface

The minimum distance from the back-wall surface at which a
specified reflector has an echo amplitude at least 6 dB greater than
the leading edge of the back-wall echo. More generally, the closest
distance from the back-wall surface at which a reflector can be
identified.

Resolution, lateral

In phased array systems, the minimum lateral separation between
two specified reflectors that permits the discrete identification of
each. This is related to both the design of the array probe and the
selected focal law programming.

Resolution, near-surface

The minimum distance from the sound entry surface at which a specified reflector has an echo amplitude at least 6 dB greater than the trailing edges of the excitation pulse, delay line, or wedge echo. More generally, the closest distance from the sound entry surface at which a reflector can be identified. The area above this point is known as the dead zone, and it generally increases as gain increases.

S-scan

Also termed a *sectorial scan*, *swept angle scan*, *angular electronic scanning*, or *azimuthal scan*. A two-dimensional view of all amplitude and time or depth data from all focal laws of a phased array probe corrected for the delay and the refracted angle. In addition, an S-scan also refers to the action of sweeping the beam through a range of angles.

Side lobes

Spurious components of a sound beam diverging to the sides of the center of energy, produced by acoustic pressure leaking from probe elements at different angles from the main lobe. Side lobes are generated by all types of ultrasonic transducers. See also "Grating lobes."

Virtual aperture

The combined width of a group of phased array elements that are pulsed simultaneously.