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Phased Array Testing

Basic Theory for Industrial Applications

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Phased Array Testing: Basic Theory for Industrial Applications

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Preface

As industrial ultrasonic testing moved into the twenty-first century, probably the most important development in the field was the increasing availability and acceptance of portable phased array imaging instruments. Phased array testing is grounded in the same basic wave physics that supports the conventional flaw detectors and thickness gages that have been in commercial use for more than fifty years. However, the increased capability offered by phased array testing frequently requires a higher level of skill and understanding on the part of inspectors using phased array testing. Thus, the introduction of new phased array instruments calls for the development of new training resources as well.

Olympus is proud to introduce this new *Phased Array Testing* field guide as a convenient resource for customers and anyone else interested in phased array technology. It is designed to be an easy-to-follow introduction to ultrasonic phased array testing, both for newcomers and for more experienced users who wish to review basic principles. This guide begins by explaining what phased array testing is and how it works, then outlines some considerations for selecting probes and instruments, and concludes with further reference information and a "Phased Array Glossary."

About This Guide

This guide is divided into the following sections:

Chapter 1, "Introduction." This chapter provides a brief history of conventional ultrasonic and phased array testing. It also lists the advantages of phased array testing as compared with conventional ultrasonics.

Chapter 2, "Phased Array Probes." This chapter describes how ultrasonic transducers and phased array probes are constructed, and explains their characteristics. In addition, the reader learns about focal law sequencing, beam shaping and steering, and transducer focusing.

Chapter 3, "Basics of Phased Array Imaging." This chapter explains the various image formats available for presenting inspection data through easy-to-understand illustrations from both conventional and phased array instruments, including: A-scans, B-scans, C-scans, linear scans and sectorial scans.

Chapter 4, "Phased Array Instrumentation." This chapter includes a brief overview of commercially available instrument categories. It also describes important specifications and features to be considered when selecting both conventional and phased array instrumentation.

Chapter 5, "Phased Array Test Setup and Display Format." This chapter provides further help with interpreting displays and making measurements.

Appendixes. These sections include a variety of reference information, including useful ultrasonic formulas, material velocity and acoustic impedance information, unit conversion, sources for further training and reference, and the types of equipment available that utilize these technologies.

"Phased Array Glossary." This final section presents a convenient list of definitions for terms used in conventional and phased array ultrasonic testing.

We hope that this guide will be helpful to you in carrying out phased array ultrasonic inspections. Comments and suggestions are welcome, and may be sent to: info@olympusndt.com.

About Olympus

Olympus Corporation is an international company operating in industrial, medical, and consumer markets, specializing in optics, electronics, and precision engineering. Olympus instruments contribute to the quality of products and add to the safety of infrastructure and facilities.

Olympus is a world-leading manufacturer of innovative nondestructive testing and measurement instruments that are used in industrial and research applications ranging from aerospace, power generation, petrochemical, civil infrastructure, and automotive to consumer products. Leading-edge testing technologies include ultrasound, ultrasound phased array, eddy current, eddy current array, microscopy, optical metrology, and X-ray fluorescence. Its products include flaw detectors, thickness gages, industrial NDT systems and scanners, videoscopes, borescopes, high-speed video cameras, microscopes, probes, and various accessories.

Olympus NDT is based in Waltham, Massachusetts, USA, and has sales and service centers in all principal industrial locations worldwide. Visit www.olympus-ims.com for applications and sales assistance.

A Note on Terminology

Because widespread use of phased array testing is relatively new in ultrasonic NDT, some terminology is still evolving. There are cases in which specific industries, such as nuclear power, standards organizations, such as ASME, and manufacturers of phased array equipment use different terms for the same activity. The main differences include the many terms used for *S-scan*, and the use of the term *linear scan*. The “Phased Array Glossary” presented at the end of this guide can be referenced for further explanation. The terminology used in this guide is intended to be consistent with that incorporated in Olympus NDT phased array instruments such as the OmniScan and EPOCH 1000.

- The term *linear scan* is used to describe the scan format in which the active beam aperture is electronically moved across the length of a linear array probe, either at normal incidence or a fixed angle. This format is alternately known as an “E-scan” in certain ASME and IIW documents.
- A probe that has been programmed to generate a linear scan in the forward direction may also be mechanically moved along the length of a weld or similar test piece, generating an *encoded linear scan*. This format is known as a “one-line scan” or “C-scan.”
- The term *S-scan* is used to describe the scan format in which the beam angle is electronically swept through a selected range. This format is also known as a “sectorial,” “sector,” “azimuthal,” or “swept angle” scan. Alternately, in some instruments the term *S-scan* has been applied to any stacked A-scan display, including linear scans.
- Time-Varied Gain (TVG) is also known as Time-Corrected Gain (TCG).

Activity	Nuclear	ASME
Mechanical scan along weld (encoded)	One-line scan	Linear scan
Electronic scan at fixed angle	Linear scan	E-scan
S-scan	Sector scan, sectorial scan, or S-scan	S-scan—also sectorial scan, sector scan, or swept angle scan
C-scan	One-line scan, or multiple line scans	C-scan

In this guide, we will use *S-scan* for “swept angle scan,” *linear scan* for “swept aperture scan,” and *C-scan* or *one-line scan* for any “encoded scan.”

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).

1. As a global company, Olympus NDT has chosen to use the ISO terms for equipment; for example, an array is specifically called a “probe” in this guide, not a “transducer.”

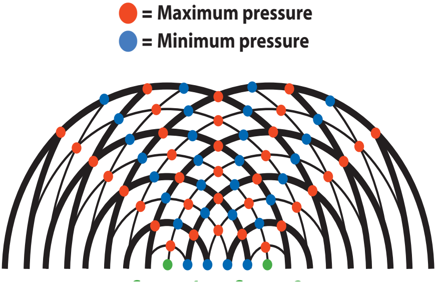


Figure 1-1 Two-point source interference pattern

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 thicknesses and geometries encountered 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

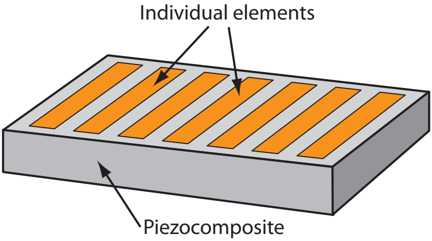


Figure 1-4 Typical multielement construction

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 returning echoes are received by the various 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.

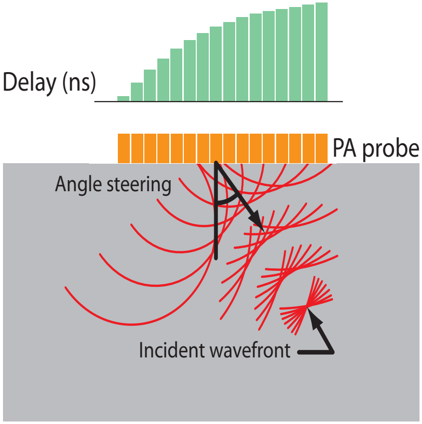


Figure 1-5 Example of an angle beam generated by a flat probe by means of the variable delay

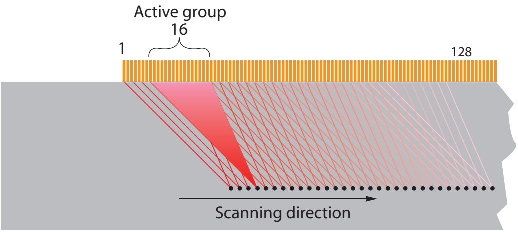


Figure 1-6 Example of focused angle beam linear scan

1.4 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.

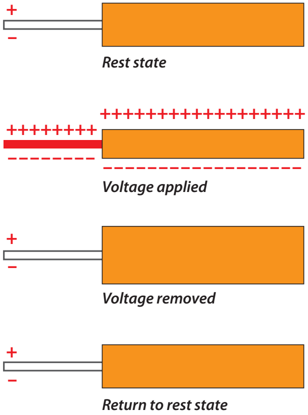


Figure 2-1 Principle of the piezoelectric transducer element

All transducers of the kind most commonly used for ultrasonic NDT have the following fundamental functional properties:

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.

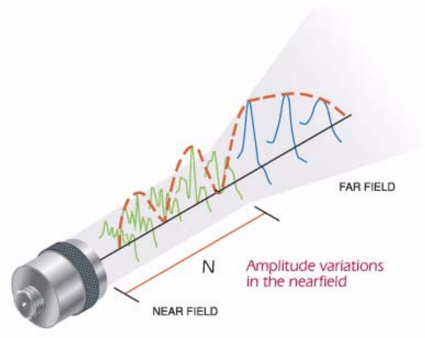


Figure 2-4 The sound field of a transducer

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:

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

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 = $\frac{c}{f}$

The aspect ratio constant is as shown in Table 2-1. It is based on the ratio between the short and long dimensions 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:

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

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 longer than the near-field distance, the beam also increases in diameter, diverging like the beam of a spotlight (see Figure 2-5).

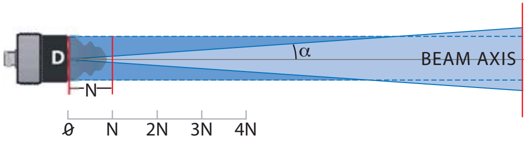


Figure 2-5 Beam spread

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:

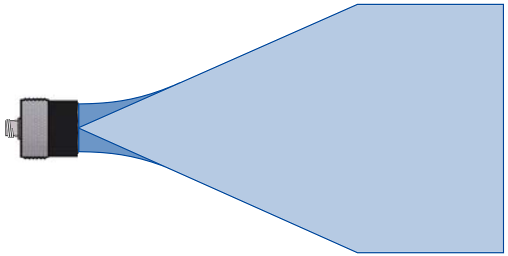
$$\alpha = \sin^{-1}\left(\frac{0.514c}{fD}\right)$$

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:

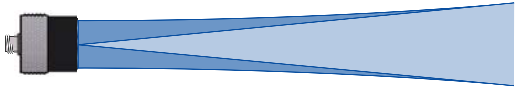
$$\alpha = \sin^{-1}\left(\frac{0.44c}{fL}\right) \quad \text{or} \quad \alpha = \sin^{-1}\left(\frac{0.44\lambda}{L}\right)$$

The following graphics show some generalized changes in beam spreading with changes in transducer diameter 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

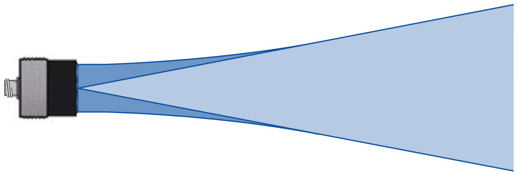
Figure 2-6 Beam spreading with a 3 mm element



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

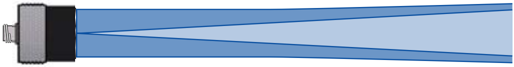


Figure 2-9 Beam spreading with a 10 MHz element

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 is related to the relative acoustic impedances of the two materials, with acoustic impedance in turn being defined as material density multiplied by speed of sound. The reflection coefficient at a planar boundary (the percentage of sound energy that is reflected back to the source) 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.

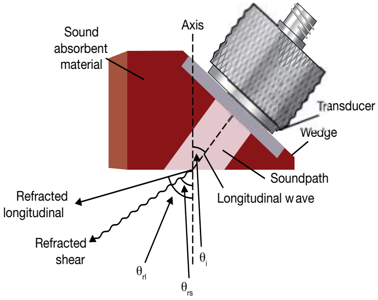


Figure 2-10 Sound wave refraction and mode conversion

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

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)

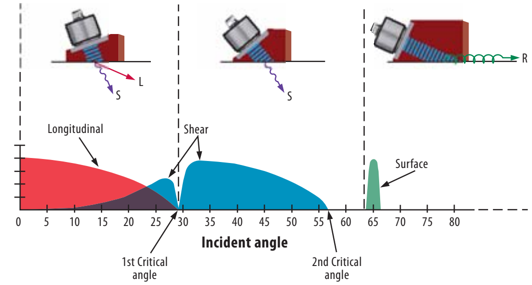


Figure 2-11 Relative amplitude of wave modes

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, most commonly from a longitudinal wave mode to a shear wave mode. This is the basis of widely used angle beam inspection techniques. As the incident angle in the first (slower) medium (such as a wedge or water) increases, the angle of the refracted longitudinal wave in the second (faster) material such as metal 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.

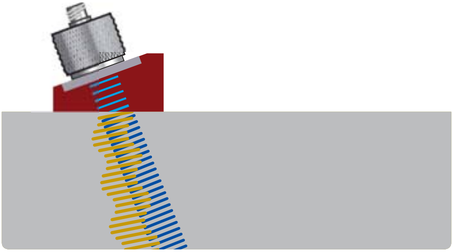


Figure 2-12 Incident angle: 10°. Strong longitudinal wave and weak shear wave.

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.

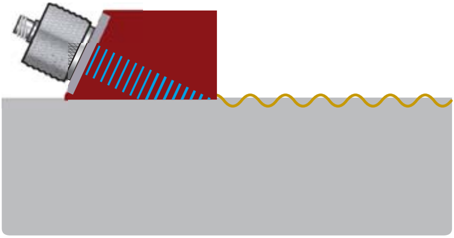


Figure 2-14 Incident angle: 65°. Beyond the second critical angle, the shear wave no longer exists, and all refracted energy is contained in a surface wave.

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 individual elements in one package (see Figure 2-16). While the elements in reality are much smaller than conventional 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).

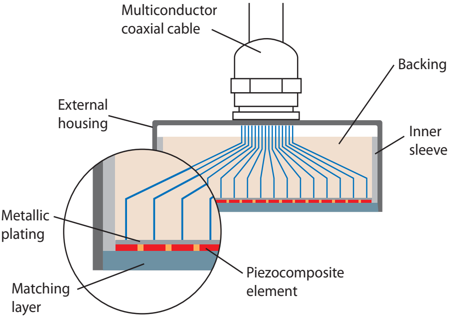


Figure 2-17 Phased array probe cross-section

Phased array probes are functionally categorized according to the following basic parameters:

Type. Most phased array probes are of the angle 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:

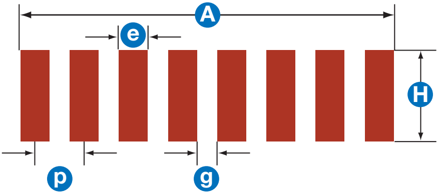


Figure 2-18 Dimensional parameters of a phased array probe

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 Phased Array Wedges

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 2-19.

Figure 2-19 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 2-20).

Figure 2-20 A zero-degree wedge

2.5 Phased Pulsing

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 2-21a). 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 2-21c). At phase angles between 0 degrees and 180 degrees, there is a range of intermediate stages between full addition and full cancellation (see Figure 2-21b). **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.

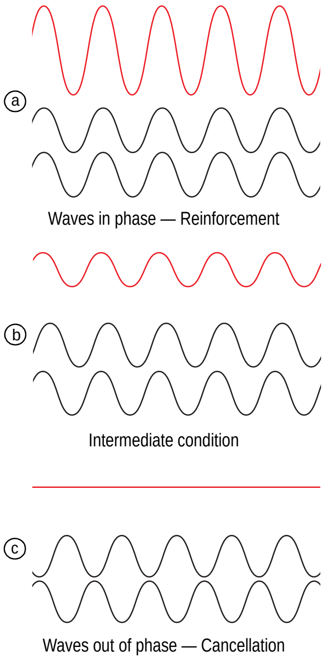


Figure 2-21 Phasing effects: combination and cancellation

In conventional transducers, constructive and destructive interference effects create the near-field and far-field zones and the various pressure gradients therein. Additionally, a conventional 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 2-22). 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.

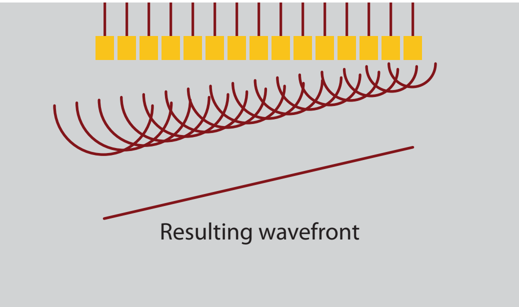


Figure 2-22 Angled waveform

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 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. 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.

2.6 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 decreases when frequency increases because material attenuation increases as frequency rises. Applications 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 2-23).

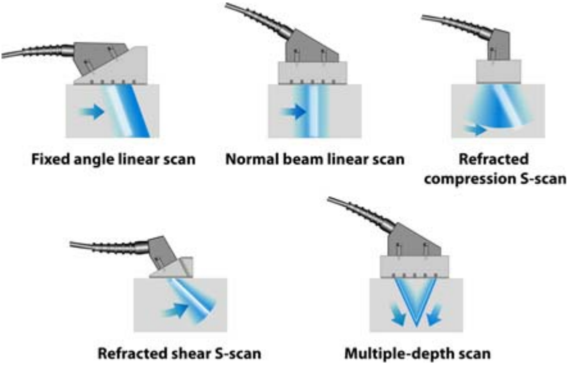


Figure 2-23 Focal law sequences

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 2-24).

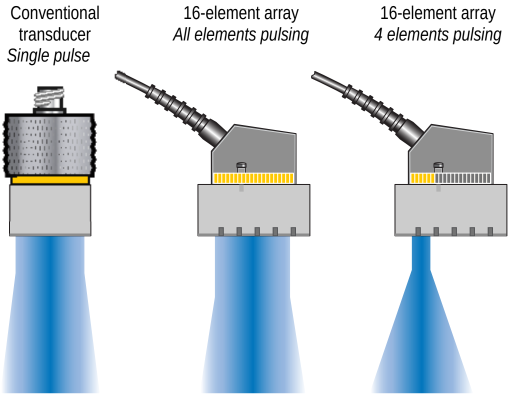


Figure 2-24 Effective aperture

For phased array probes, the maximum steering angle (at –6 dB) in a given case is derived from the beam spread equation. It can be easily seen that small elements have more beam spreading 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

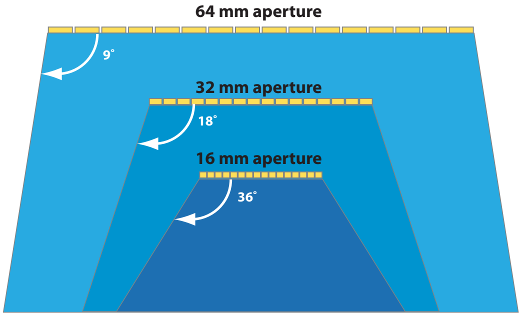


Figure 2-25 Beam steering limits: When the element number is constant, 16 as shown, the maximum beam steering angle increases as the aperture size decreases.

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 by a tapering cone (or wedge in the case of single-axis focusing) that converges to a focal point and then 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 = $\frac{c}{f}$

For the formula for square or rectangular elements, see pages 13-14.

2.7 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 2-26).

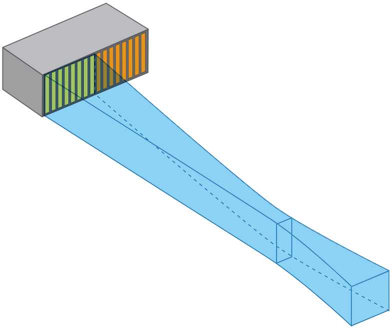


Figure 2-26 Focused sound beam

The depth at which the beam from a phased array focuses can be varied by changing the pulse delays. The near-field length in a given material defines the maximum depth at which 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:

$$-6\text{ dB beam diameter or width} = \frac{1.02\ \mathrm{F}c}{f\,\mathrm{D}}$$

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 2-27). Red areas correspond to the highest sound pressure, and blue areas to lower sound pressure.

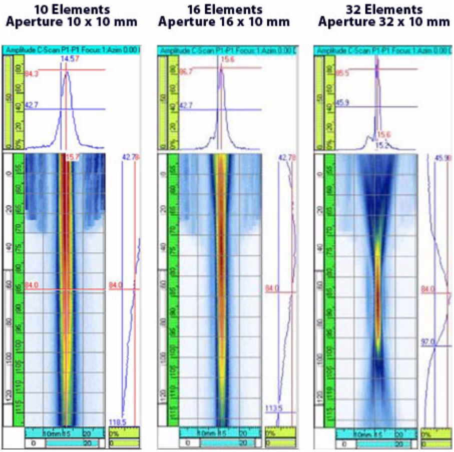


Figure 2-27 Beam focusing with different aperture sizes

2.8 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 2-28 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.

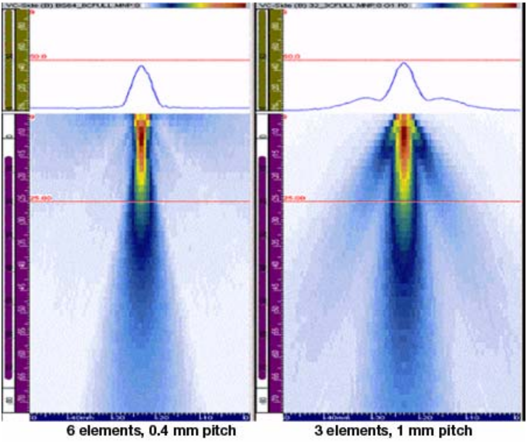


Figure 2-28 Beam profiles with different number of elements

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.

2.9 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 frequency and aperture selection.

The Olympus phased array probe catalog can be viewed at the following address:

www.olympus-ims.com/en/probes/pa/

Consult it to view the full selection of probes and wedges that is available.

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 generate multiple sound paths within one probe, adds a powerful advantage in detection and naturally adds 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:

$$\text{Distance} = \text{Velocity} \times \text{Time}$$

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.

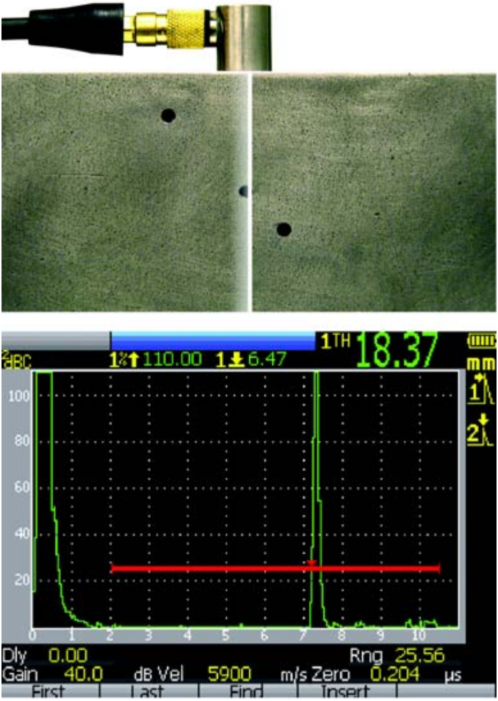


Figure 3-1 A-scan data

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

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.

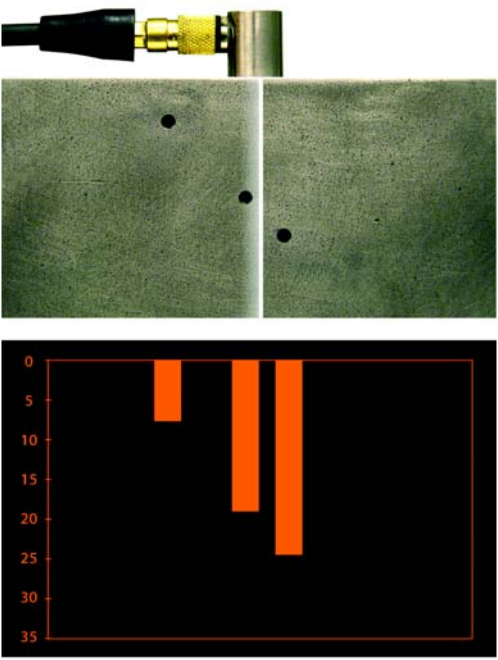


Figure 3-2 B-scan data

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 visualize both the near- and far-surface reflectors within the sample. With this technique, the full waveform 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).

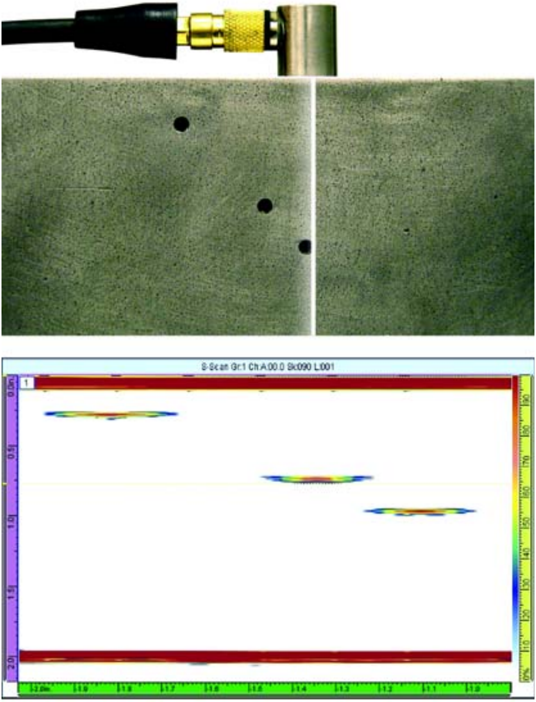


Figure 3-3 Cross-sectional B-scan

3.4 Linear Scans

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.

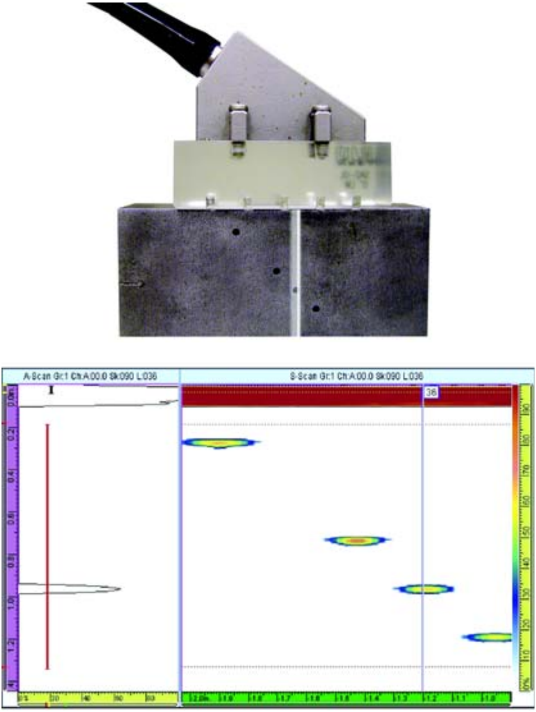


Figure 3-4 Normal beam linear scan

It is also possible to scan at a fixed angle across elements (see Figure 3-5). As discussed in section 5.3, on page 69, this is very useful for automated weld inspections. Using a 64-element 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.

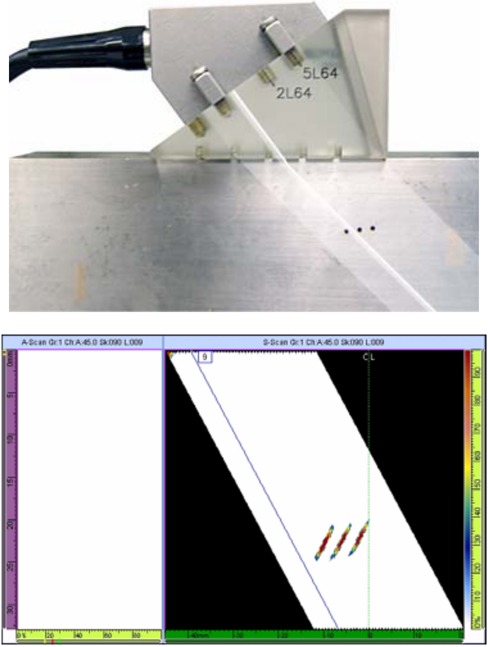


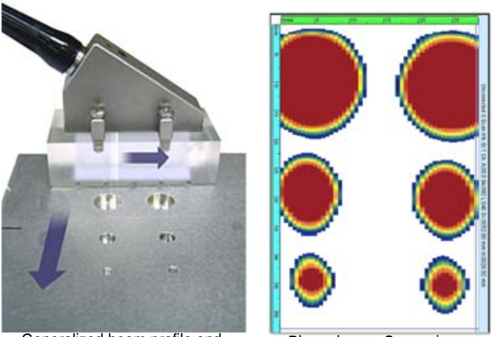
Figure 3-5 Angle beam linear scan

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 on flat parts by tracking data 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.

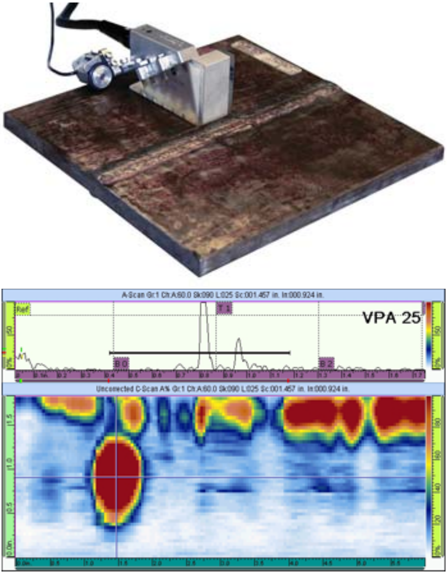


Figure 3-7 One-line scan for weld inspection using an encoded 2.25 MHz 64-element probe steered at 60 degrees

3.6 S-Scans

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).

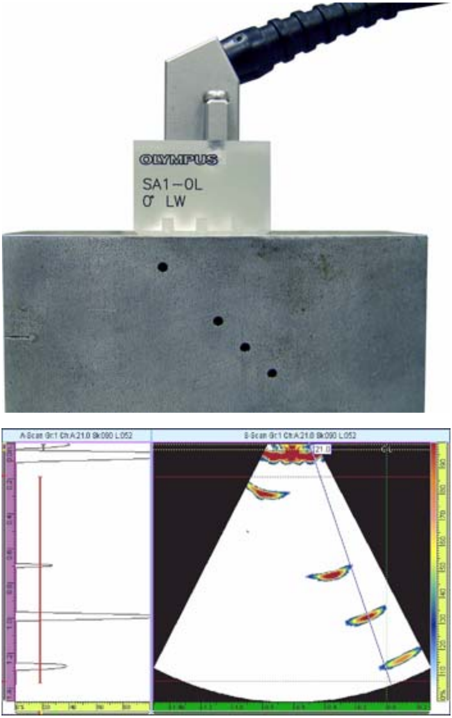


Figure 3-8 –30° to +30° S-scan

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 conventional angle beam inspection, except that the beam sweeps through a range of angles rather than a single fixed angle 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).

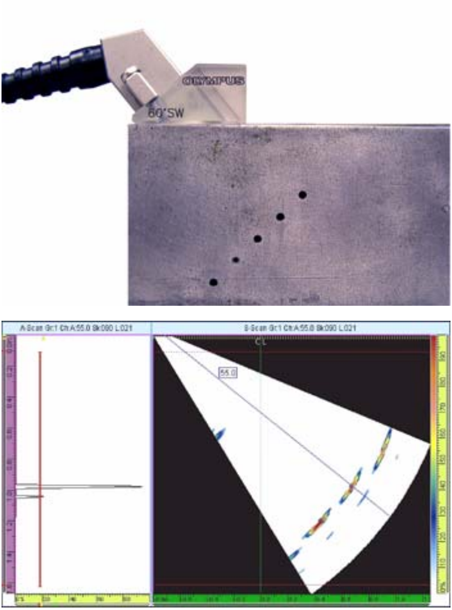


Figure 3-9 +35° to +70° S-scan

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 at the same time.

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.

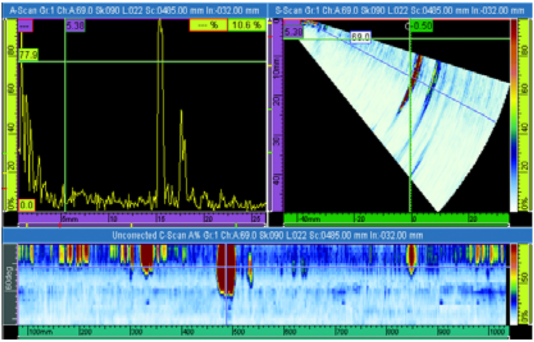


Figure 3-10 Multiple image types display

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 resolution.

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.

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:

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

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

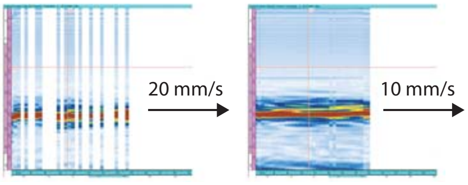


Figure 3-11 Example of the scanning speed influence on acquisition rate

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, Composite, Averaged, Hollow, Filled, 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 more focal laws as they support greater element apertures and/or more aperture steps in linear scanning. Note 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.

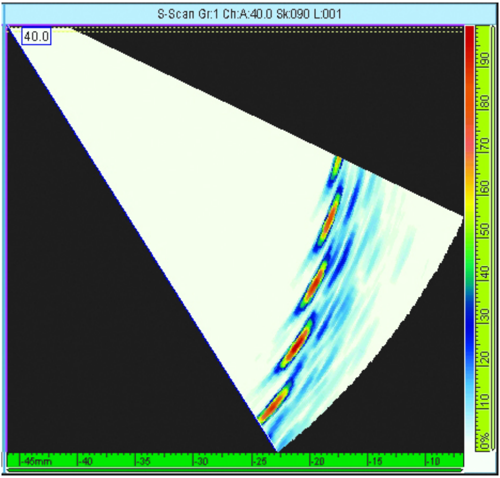


Figure 4-1 40 to 70 degrees S-scan: steering with 1 degree (31 laws) steps

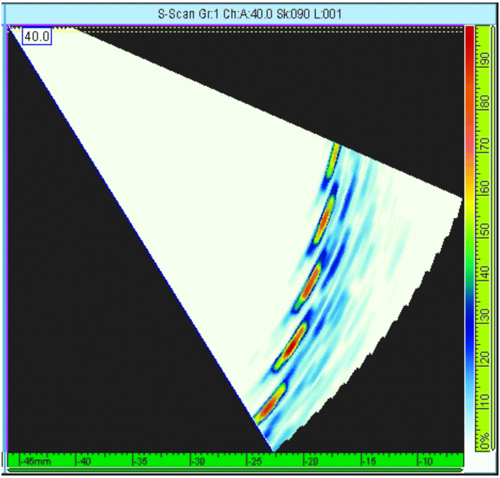


Figure 4-2 40 to 70 degrees S-scan: steering with 2 degree (16 laws) steps

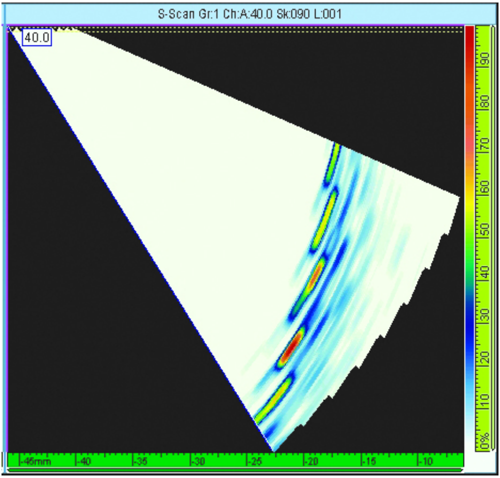


Figure 4-3 40 to 70 degrees S-scan: steering with 4 degree (8 laws) steps

Table 4-1 shows examples for the number of focal laws required to perform linear scans with varying combinations of virtual probe apertures and total element counts are shown in Table 4-1.

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
4	64	1	61
8	64	1	57
16	64	1	49
8	128	1	121
16	128	1	113
8	256	1	249
16	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:

$$\text{PRF} \times \text{Number of focal laws} = \text{Maximum image display rate}$$

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.

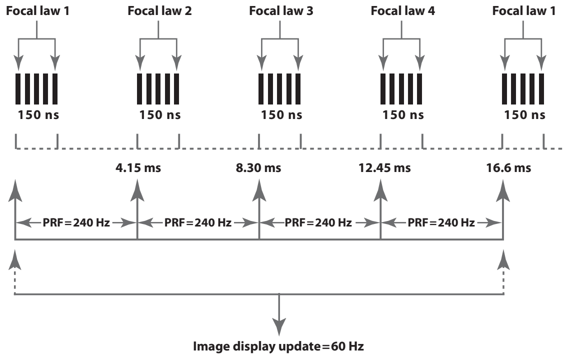


Figure 4-4 Example of a reduced four-focal-law linear scan sequence

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 encoded.

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.

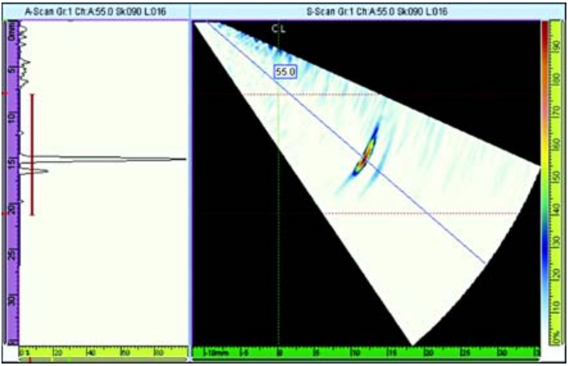


Figure 4-5 Angular cursor

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.

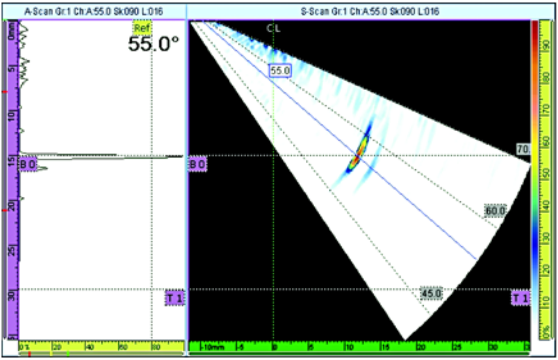


Figure 4-6 Angular and horizontal cursors

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.

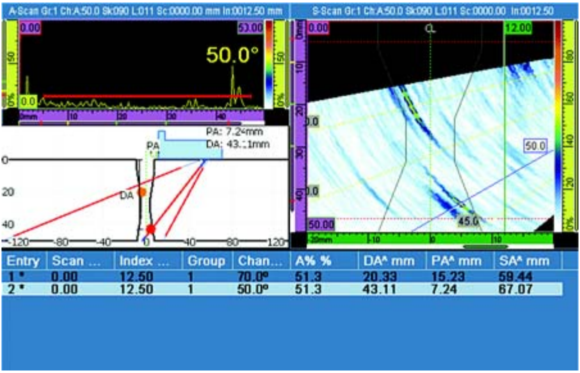


Figure 4-7 Multiple display formats

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 through out 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 the material being inspected needs 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 programmed focal sequence, but also provides accurate and enhanced visualization through the images that 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

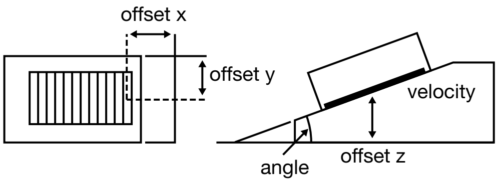


Figure 5-2 Wedge parameters

Focal law setup

The instrument must have the basic probe and wedge settings entered, either manually or by using automatic probe 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 example, the user programmed the focal 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.

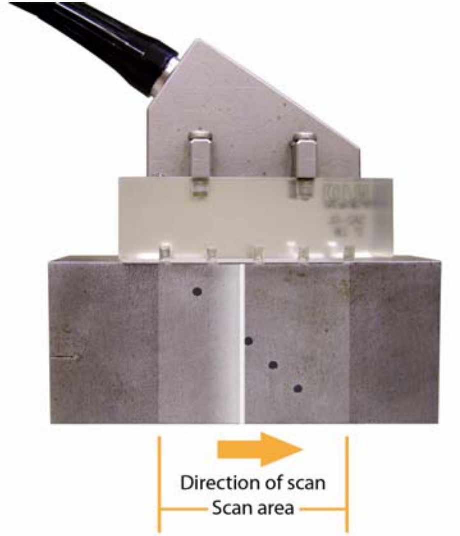


Figure 5-3 Normal beam linear scanning

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.

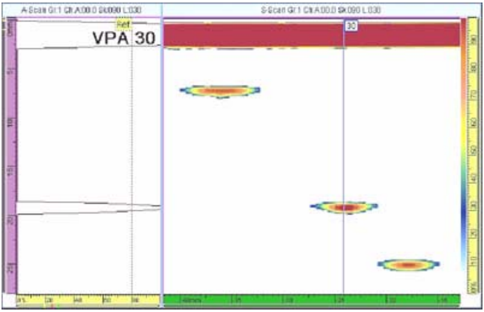


Figure 5-4 Normal beam linear scan

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.

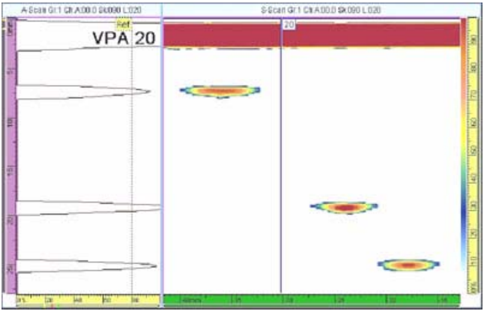


Figure 5-5 Normal beam linear scan image with all laws A-scan

Yet another A-scan source mode on some more advanced instruments allows the A-scan to be sourced from the first or maximum signal within the gated region.

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.

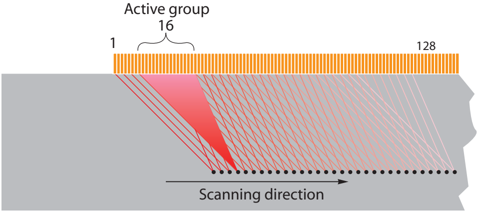


Figure 5-6 Single-angle beam scanning across the length of the probe

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*).

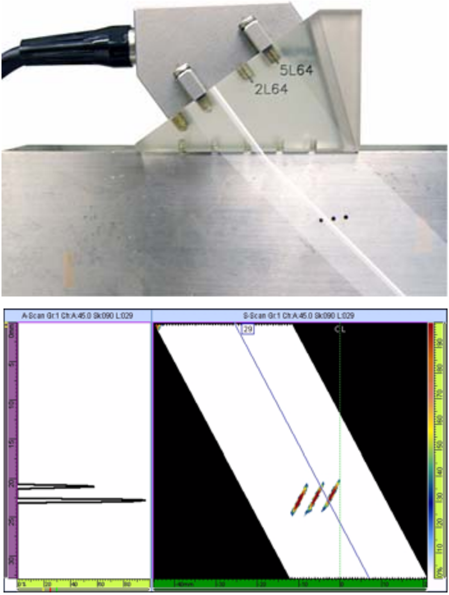


Figure 5-7 Angle beam linear scan (*top*), with A-scan and linear scan display (*bottom*)

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.

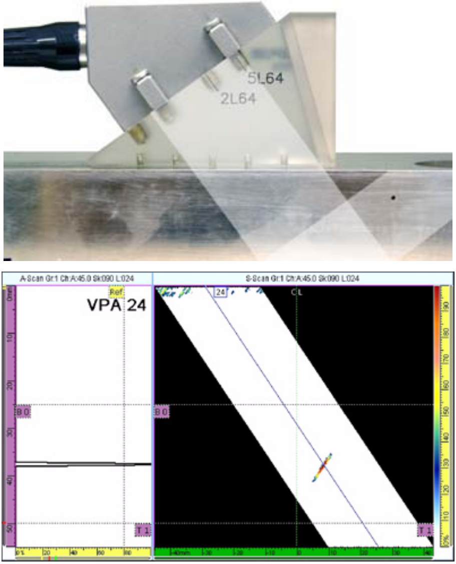


Figure 5-8 Measurement to second leg reflector

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-Scan Display Examples

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).

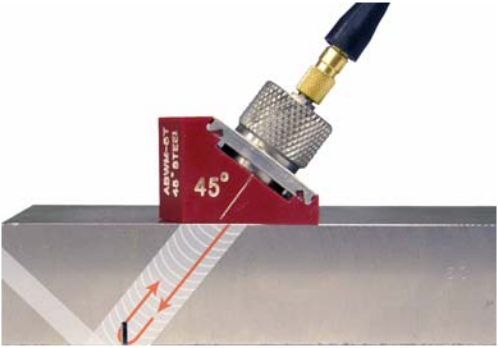


Figure 5-9 Conventional angle beam test

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 typically represents one selected angular component of the scan. Trigonometric calculation uses the measured 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.

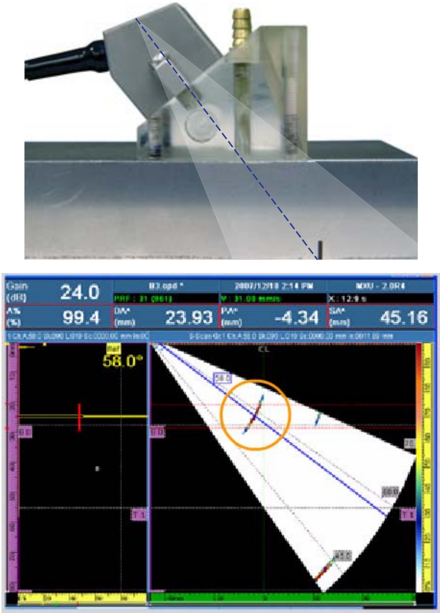


Figure 5-12 The 58° beam component

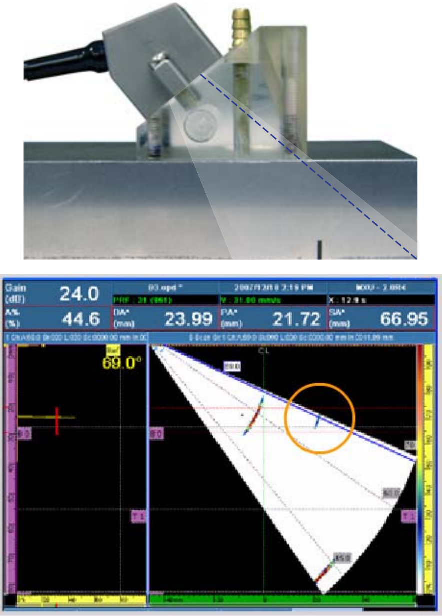


Figure 5-13 The 69° beam component

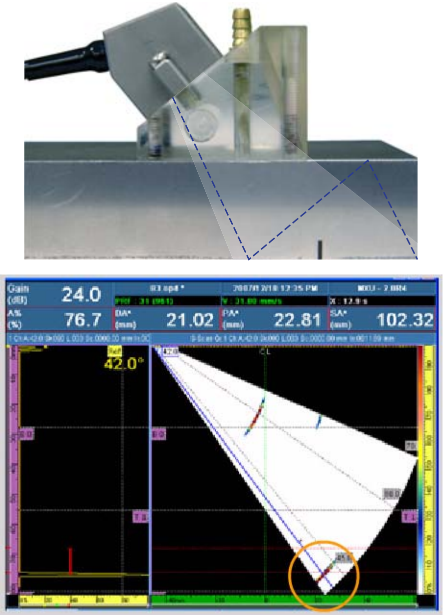


Figure 5-14 The 42° beam component

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.

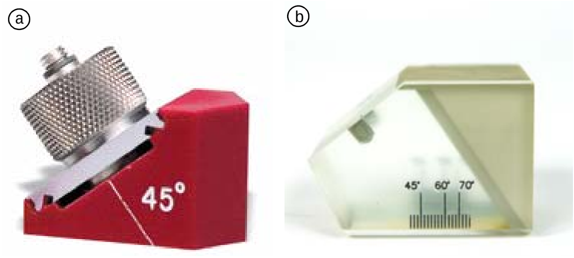


Figure 5-15 Beam index points on a conventional wedge (a) and phased array wedge (b)

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:

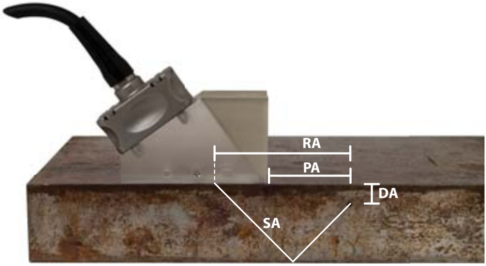


Figure 5-16 Dimensions for referencing a flaw position

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 the screen show the reflector's location.

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).

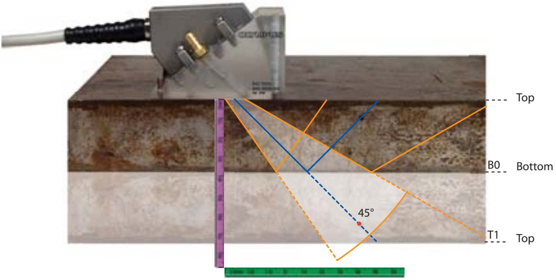


Figure 5-19 Display of the second leg compared to the path in the test piece

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/m^2] ρ = mass density [kg/m^3] μ = Poisson's ratio; $\mu = \dfrac{(E-2G)}{2G}$ G = shear modulus [N/m^2]
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; $\text{MHz} = 10^6\ \text{Hz} = \dfrac{10^6}{\text{s}}$; also: $f = \dfrac{c}{\lambda}$
Wavelength (Table A-3)	$\lambda = \dfrac{v}{f}$; also: $\lambda = \dfrac{\text{PL}}{\text{CN}}$ [mm/in.] PL = pulse length ($v \bullet \Delta\tau_{-20\ \text{dB}}$) [mm/in.] CN = cycle number

Table A-1 Main ultrasonic features and their definition or relationship *(continued)*

Feature	Definition / formula / units / remarks
Near-field length (circular) [see Table A-4]	$N_0 = \frac{(D^2 - \lambda^2)}{4\lambda}$; $N_0 = \frac{D^2 f}{4v}$ [mm/in.] for $\frac{D}{\lambda} > 10$ D = active crystal diameter [mm/in.]
Near-field length (rectangular) [see Table A-5]	$N_{rectangular} = \frac{k_{\square} L^2 f}{4v}$ [mm/in.]
Near-field length (effective)	$N_{eff} = \left(\frac{D^2 f}{4v}\right) \bullet \left(\frac{\cos\beta}{\cos\alpha}\right)^2$ [mm/in.] for disc-shaped crystal; $N_{eff\,\square} = \frac{k_{\square}\left(\frac{L_{probe}\cos\beta}{\cos\alpha}\right)^2 f}{4v_{test\ piece}} - \frac{L_{wedge} v_{wedge}}{v_{test\ piece}}$ 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] $k_{\square}$ = near-field correction factor
Beam diameter (circular)	$\Phi_{-\Delta dB} = \frac{2k_{free\text{-}field}\lambda z}{D}$ [1] [mm/in.] z = UT path [mm/in.]; $\Phi_{(-6\ dB)\ PE} = \frac{\lambda z}{D}$
Beam width (rectangular)	$\Phi_{(-\Delta dB)W} = \frac{2k_{free\text{-}field}\lambda z}{W}$ [mm/in.] W = crystal width [mm/in.]

Table A-1 Main ultrasonic features and their definition or relationship *(continued)*

Feature	Definition / formula / units / remarks
Beam length (rectangular)	$\Phi_{(-\Delta dB)L} = \frac{2k_{\text{free-field}}\lambda z}{L}$ [mm/in.]
Half-angle beam divergence (circular)	$\gamma_{-\Delta dB} = \operatorname{asin}\left(\frac{k_{-\Delta dB}\lambda}{D}\right)$ [rad/°]; $\gamma_{(-3\text{ dB})\text{ free field}} = \gamma_{(-6\text{ dB})\text{ pulse-echo}} \approx \frac{0.5\lambda}{D}$ [rad / °] $k_{-\Delta dB}$ = half-angle beam divergence constant[1]
Half-angle beam divergence (rectangular)	$\gamma_{(-6\text{ dB})L} = \operatorname{asin}(0.44\lambda/L)$ [rad/°] $\gamma_{(-6\text{ dB})W} = \operatorname{asin}(0.44\lambda/W)$ [rad/°]
Acoustic impedance	$Z = v \bullet \rho$ [kg/m^2 s = Rayl] (generally 10^6 [MRayl]) [see Table A-2]
Reflection coefficient	$R = \frac{(Z_2 - Z_1)}{(Z_1 + Z_2)}$
Transmission coefficient	$T = \frac{2Z_2}{(Z_1 + Z_2)}$
Transmission loss	$\Delta G_{\text{transmission}} = -10\log_{10}\left[\frac{4Z_1Z_2}{(Z_1 + Z_2)^2}\right]$ [dB]
Snell's law	$\frac{\sin\alpha}{\sin\beta} = \frac{v_1}{v_2}$

Table A-2 Acoustic properties of materials

MATERIAL	Longitudinal velocity		Shear velocity		Acoustic impedance
	in./μs	m/s	in./μs	m/s	kg/m^{2}s × 10^6
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 UT inspection

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	0.126
2	3	0.118	1.6	0.063
4	1.5	0.059	0.8	0.032
5	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	0.118
2	3	0.118	1.5	0.059
4	1.5	0.059	0.8	0.032
5	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	4
2	9	6	15	5	64	2.5	90	2
4	N/A	N/A	30	2.5	128	1.2	180	1
5	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.
	1 m	= 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	1 g	= 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^2s	= 0.001423 $lb/in.^2s$ = 0.204816 lb/ft^2s
Temperature	°C	= (5/9) × (°F – 32)
	(°C × 1.8) + 32	= °F

Appendix C: Support and Training

Support

Olympus offers the opportunity to participate in a Web-hosted discussion forum. The experts that contributed to *Phased Array Testing: Basic Theory for Industrial Applications* guide are online to answer your questions and post added information concerning phased array technology and its practical applications.

Feel free to browse this vast source of information, post your own questions, and contribute to this collective project.

You will find the Web site forum link at the following address:

www.olympus-ims.com/en/ndt-forum/

Training

The Olympus IMS Web site at www.olympus-ims.com contains a wide variety of information designed to help users of phased array products and other Olympus inspection and maintenance instruments.

Information on both introductory and advanced phased array training classes are offered by Olympus training partners at locations around the world. These classes offer hands-on training and specific problem-solving cases in addition to a review of basic theory. Details can be found at:

Home page > Support > Training Academy

We also offer an interactive self-study tutorial that covers basic phased array theory, found at:

Home page > Technologies > Theories > Phased Array Tutorial

Webinars covering several related technical subjects can be viewed at:

Home page > Support > Webinars

The Application Notes section of the Olympus IMS Web site includes a number of documents describing specific phased array test applications. These can be viewed at:

Home page > Applications

Finally, you can obtain further information regarding Olympus nondestructive testing equipment, publications, applications, and technical support by filling out the *Applications Support* form found at:

Home page > Technologies > Theories > Applications Support

Appendix D: Types of Equipment Available

As with other categories of ultrasonic test equipment, phased array systems are available in a variety of models with increasing complexity and capability. Instruments range from basic models that perform simple sector and linear scans with 16-element probes to advanced systems that offer multichannel capability and advanced interpretive software with probes of up to 256 elements.

Olympus has a complete NDT portfolio. For more information, consult the Web site at the following address:

www.olympus-ims.com/en/ndt-forum/

This appendix presents an overview of the following equipment:

- EPOCH 1000 Series — Advanced Ultrasonic Flaw Detectors with Phased Array Imaging
- OmniScan Series — Modular Advanced Flaw Detectors with UT, PA, EC, and ECA Technologies
- TomoScan FOCUS LT — Powerful, Flexible, and Compact UT Data Acquisition System
- TomoView — UT Data Acquisition and Analysis Software

D.1 EPOCH 1000 Series — Advanced Ultrasonic Flaw Detectors with Phased Array Imaging

The EPOCH™ 1000 flaw detectors combine the highest level of performance for conventional portable flaw detection with the power of phased array imaging. The EPOCH 1000, 1000*iR*, and 1000*i* feature a horizontal case style with full VGA display, knob, and navigation arrows for parameter adjustment, and full EN12668-1 compliance. The advanced conventional ultrasonic functionality of the EPOCH 1000 series is augmented in the EPOCH 1000*i* (see figure) with phased array imaging capabilities.

Key Features

- Available with Phased Array Imaging package
- EN12668-1 compliant
- 37 digital receiver filter selections
- 6 kHz pulse-repetition rate for high-speed scanning
- Automatic phased array probe recognition
- Intuitive wedge delay and sensitivity calibration for all focal laws
- Programmable analog/alarm outputs
- IP66 environmental rating for harsh environments
- Horizontal design with navigation panel and knob parameter adjustment
- Digital high dynamic range receiver
- Full VGA sunlight readable display
- ClearWave™ Visual Enhancement package for conventional A-scan interpretation
- Sureview™ visualization feature
- Reference and measurement cursors
- Standard dynamic DAC/TVG
- Standard onboard DGS/AVG

D.2 OmniScan Series — Modular Advanced Flaw Detectors with UT, PA, EC, and ECA Technologies

With thousands of units being used throughout the world, the OmniScan® (see figure) is Olympus NDT's most successful portable and modular phased array and eddy current array test instrument. The OmniScan family includes the innovative phased array and eddy current array test modules, as well as the conventional eddy current and ultrasound modules, all designed to meet the most demanding NDT requirements.

The OmniScan offers a high acquisition rate and powerful software features—in a portable, modular instrument—to efficiently perform manual and automated inspections.

Key Features

- Rugged, portable, and battery operated
- Compact and lightweight (only 4.6 kg, 10.1 lb)
- 8.4-inch real-time display (60 Hz A-scan refresh rate) with SVGA resolution of 800 × 600
- Phased array module and software:
  16:16, 16:16M, 16:64M, 16:128, 32:32, 32:128 phased array modules
- Full-featured A-scan, B-scan, and C-scan displays
- Full-featured sectorial scan
- Real-time volume-corrected representation
- Advanced real-time data processing
- Real-time data interpolation to improve spatial representation of defects during acquisition of data
- User-selectable high-pass and low-pass filters to enhance A-scan and imaging quality
- Wizards for groups and focal laws

D.3 TomoScan FOCUS LT — Powerful, Flexible, and Compact UT Data Acquisition System

The TomoScan FOCUS LT™ (see figure) is designed for your most demanding automated UT inspection needs. This new benchmark of ultrasound phased array instruments offers exceptional performance for both conventional UT and ultrasound phased array with multiple probe configurations.

The TomoScan FOCUS LT offers a lighter, more compact, and even more reliable solution to your most advanced inspection requirements. The TomoScan FOCUS LT is also available in a 3U rackmount version.

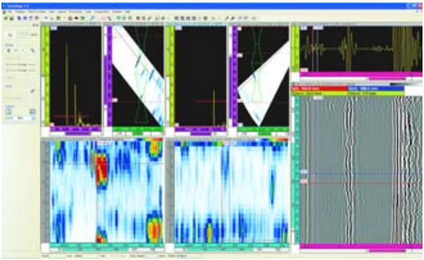
Key Features

- Full-featured PC-based software for data acquisition and analysis (TomoView™)
- Multiple channels or phased array probe configuration
- Combined phased array and conventional UT configuration (TOFD + P/E)
- File size of up to 1 GB
- Fast 100Base-T data transfer (4 MB/s)
- Configuration of up to 64:128
- Pulse repetition rate (PRF) up to 20 kHz
- Real-time data compression and signal averaging
- Interface to external motor controller and scanners

D.4 TomoView — UT Data Acquisition and Analysis Software

TomoView™ is a PC-based software for data acquisition and visualization of ultrasonic signals. Configuration of ultrasonic parameters is flexible and different views can be displayed ensuring it can be used in a large variety of applications from industrial needs to research purposes. TomoView is designed to perform ultrasonic testing (UT) data acquisition with several Olympus phased array (PA) or conventional UT units.

Compatible with Microsoft Windows, XP, Windows Vista, and Windows 7, TomoView can run efficiently on standard laptop computers as well as on high-end desktop workstations, and it is capable of handling large data files (up to 1 GB). Its ability to read OmniScan® (.oud, .opd) data files and its user-friendly reporting capabilities make TomoView an ideal tool for interpreting OmniScan data.



- Powerful tool for UT data
- Acquisition and analysis
- Flexible data imaging
- Easy, comprehensive reporting
- Perfect complement to the OmniScan
- Offline analysis of A, B, C, D, and S (sectorial) scans
- Measurement utilities, zooming, and customizable color palettes
- Compatible with the Advanced Focal Law Calculator

In addition to the full TomoView software program, Olympus also offers TomoView Lite and TomoVIEWER.

TomoView Lite is a version of TomoView primarily designed for OmniScan data file analysis. It incorporates the main TomoView features such as volumetric views, merged views, and a multigroup display.

TomoVIEWER is a free software for phased array and ultrasonic data viewing. This software provides the ability to load data files generated by TomoView or OmniScan PA and UT software.

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 reflector at each data point.

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 portion of a sound beam beyond the last on-axis pressure maximum. Beam spreading occurs in the far 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 interaction of two or more waves of the same frequency but with different time delays, which could result 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.

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NDT Field Guides

This *Phased Array Testing* field guide is designed as an easy-to-follow introduction to ultrasonic phased array testing for both newcomers and more experienced users who wish to review basic principles. It explains what phased array testing is and how it works, outlines considerations for selecting probes and instruments, and references sources for further reference. A phased array glossary is included.

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