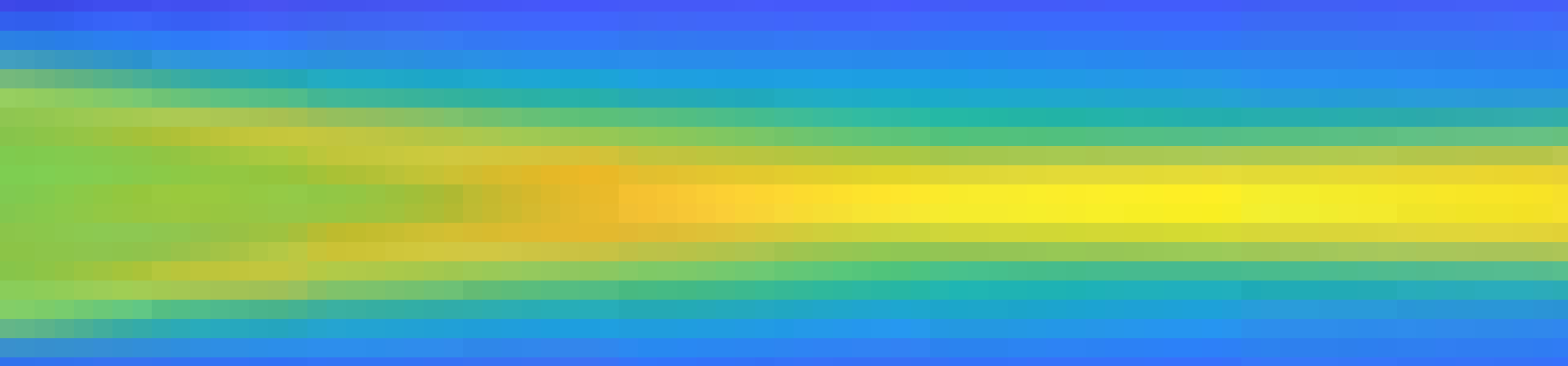


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# Phased Array Technology

Cutting Out the Noise



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## Introduction

Ultrasonic test instruments have been used in industrial applications for more than sixty years. Since the 1940s, the laws of physics that govern the propagation of high-frequency sound waves through solid materials have been exploited to detect flaws. Ultrasound can reveal hidden cracks, voids, porosity, and other internal discontinuities in metals, composites, plastics, and ceramics. The ultrasonic testing (UT) technique is also used to measure the thickness and analyze the properties of materials.

Advances in the field have produced the phased array ultrasonic testing (PAUT) technique. Within these pages, you will find a summary of the basic phased array principles, an overview of the required equipment, explanations of the data generated by the technique, and a brief look at the advantages of phased array compared with conventional ultrasound.

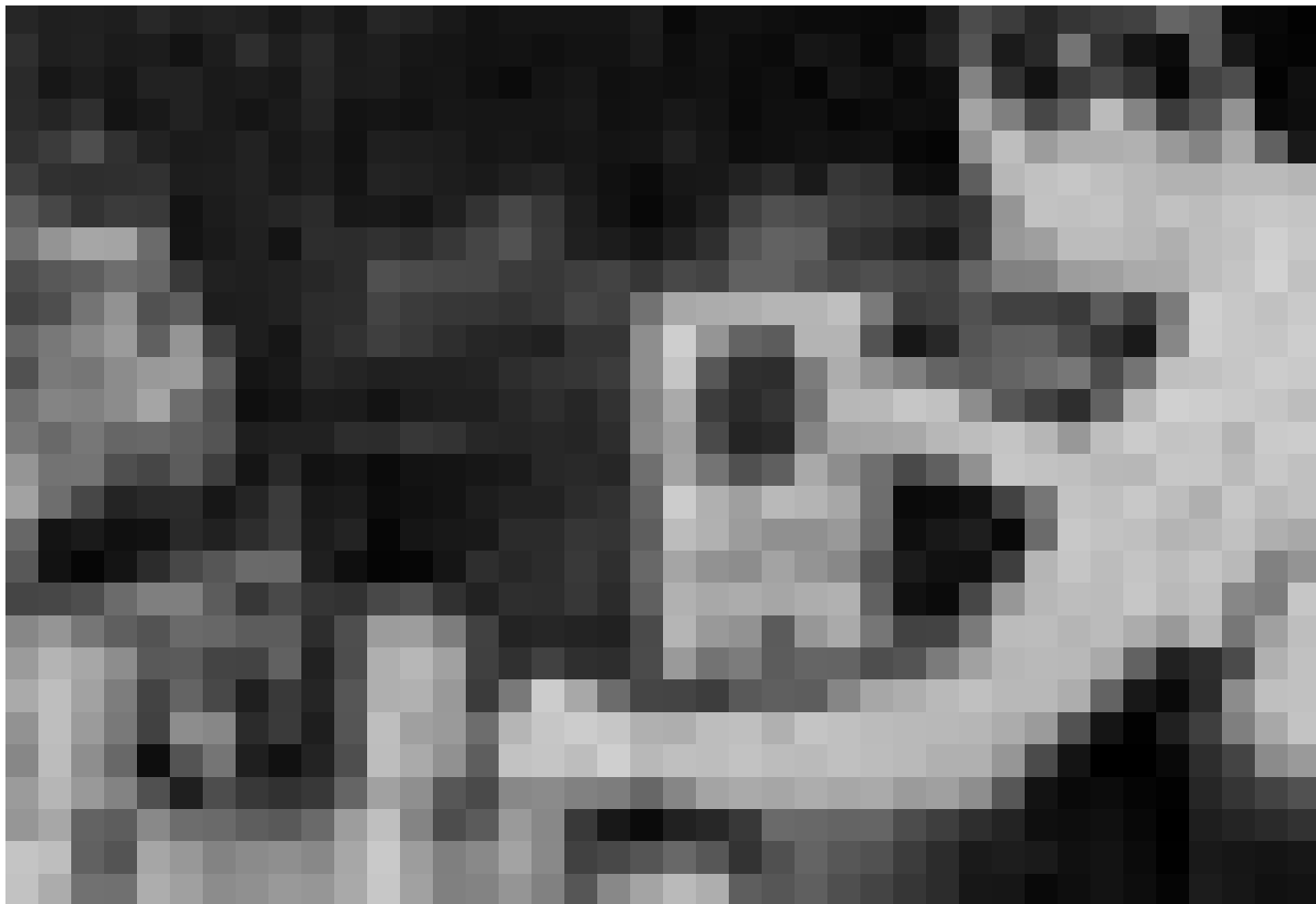


Figure 1—The early days of ultrasonic testing.

# Part 1:

## The Basics of Phased Array

This chapter presents the fundamentals of phased array (PA) ultrasonic testing with a focus on how it differs from conventional ultrasonic testing (UT).

### Why Use Phased Array?

Phased array ultrasonic testing enables users to increase their inspection speed, improve the probability of detection (POD), and achieve better sizing and characterization capabilities than conventional UT.

A conventional UT beam usually only covers a small area of the region of interest (ROI) in the inspected part, for instance, the volume of a weld. To cover the entire region of the weld, including all critical areas, a typical UT inspection technique consists of moving the transducer toward and away from the weld in a sweeping motion. This movement must be repeated at multiple points along the weld's length. Additionally, this process may need to be performed two to three more times using wedges with different angles to increase the POD for flaws of various orientations. The entire process can be cumbersome and time consuming.

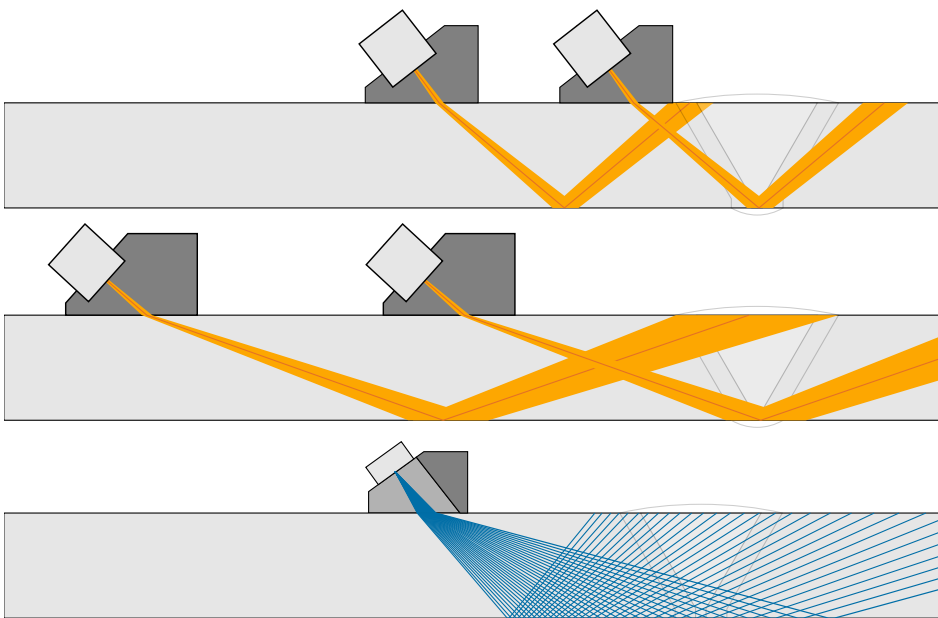


Figure 2 – Acoustic coverage comparison between conventional UT (top, middle) and the PA technique (bottom). Using a PA probe enables the coverage of the entire weld without moving the probe. Conventional UT transducers need to be moved back and forth, perpendicular to the weld, to ensure full coverage.

Using phased array inspection technology, an operator can use a single probe and wedge combination to cover the entire weld volume, scanning the probe parallel to the weld at a fixed distance along the entire length. This is possible because a phased array setup can generate a multitude of beams at different angles at a very high rate. This advantage is illustrated in Figure 2. Each beam generates a different A-scan—similar to a time trace signal in conventional UT. These A-scans can be combined to produce 2D images of the region of interest, enabling easier data interpretation and thereby improving characterization capabilities. Figure 3 shows an example of a conventional A-scan signal and a 2D image generated by a phased array system using numerous A-scans.

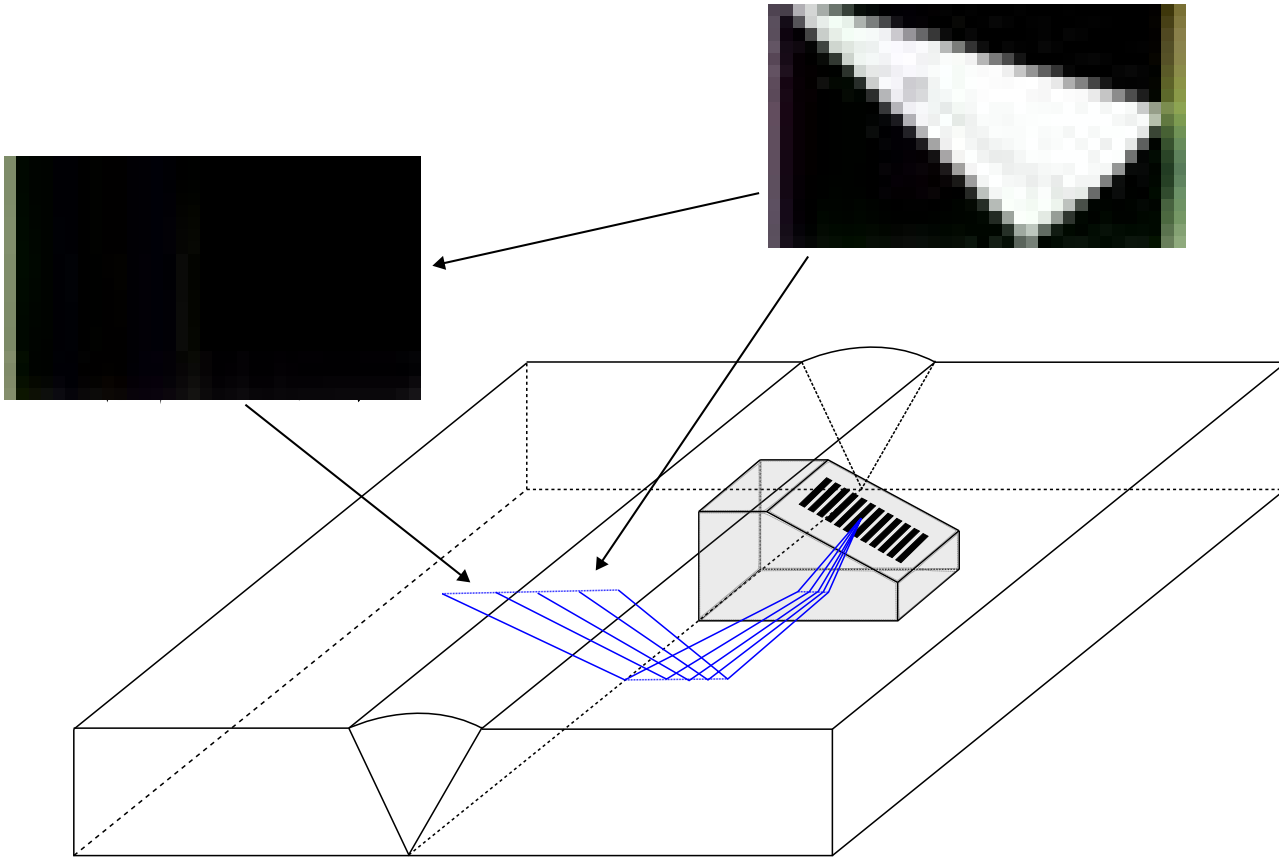


Figure 3 – Example of (top left) a single amplitude time trace (A-scan) obtained using a conventional UT instrument, and (top right) a sectorial scan 2D image produced from a multitude of A-scans generated by a phased array instrument.

While phased array ultrasound might seem radically different from conventional UT, the same underlying physical phenomena apply. These include beam divergence and directivity and near-field constraints. These considerations are discussed in more detail in [Similarities of Phased Array to Conventional UT](#), where a parallel is drawn with conventional UT.

## How Phased Array Works

Phased array ultrasonic probes contain a series of small piezoelectric elements, each with its own connector, time-delay circuit, and analog-to-digital converter. An array is like a series of small UT transducers that can be controlled independently.

In the PA technique, acoustic beams are formed by a linear combination of a series of individual, short-duration wavefronts pulsed by each element—or a subset of elements (subaperture). The elements are activated according to a precalculated time-delay sequence that ensures all the pulses arrive synchronously at a desired position in the inspected part. These time delays enable the control of the beam direction and focusing depth.

The flexibility of this beam control provides operators the option to use one PA probe instead of several mechanically adapted conventional UT transducers with fixed focal positions. A multitude of acoustic beam variations can be generated using the same array of elements simply by modifying the delay of the electronic pulses. Figure 4 shows acoustic beams in the form of a pressure field corresponding to the maximum pressure over time at each grid position. The beams are generated at different propagation angles and with different focal distances, using different time delays.

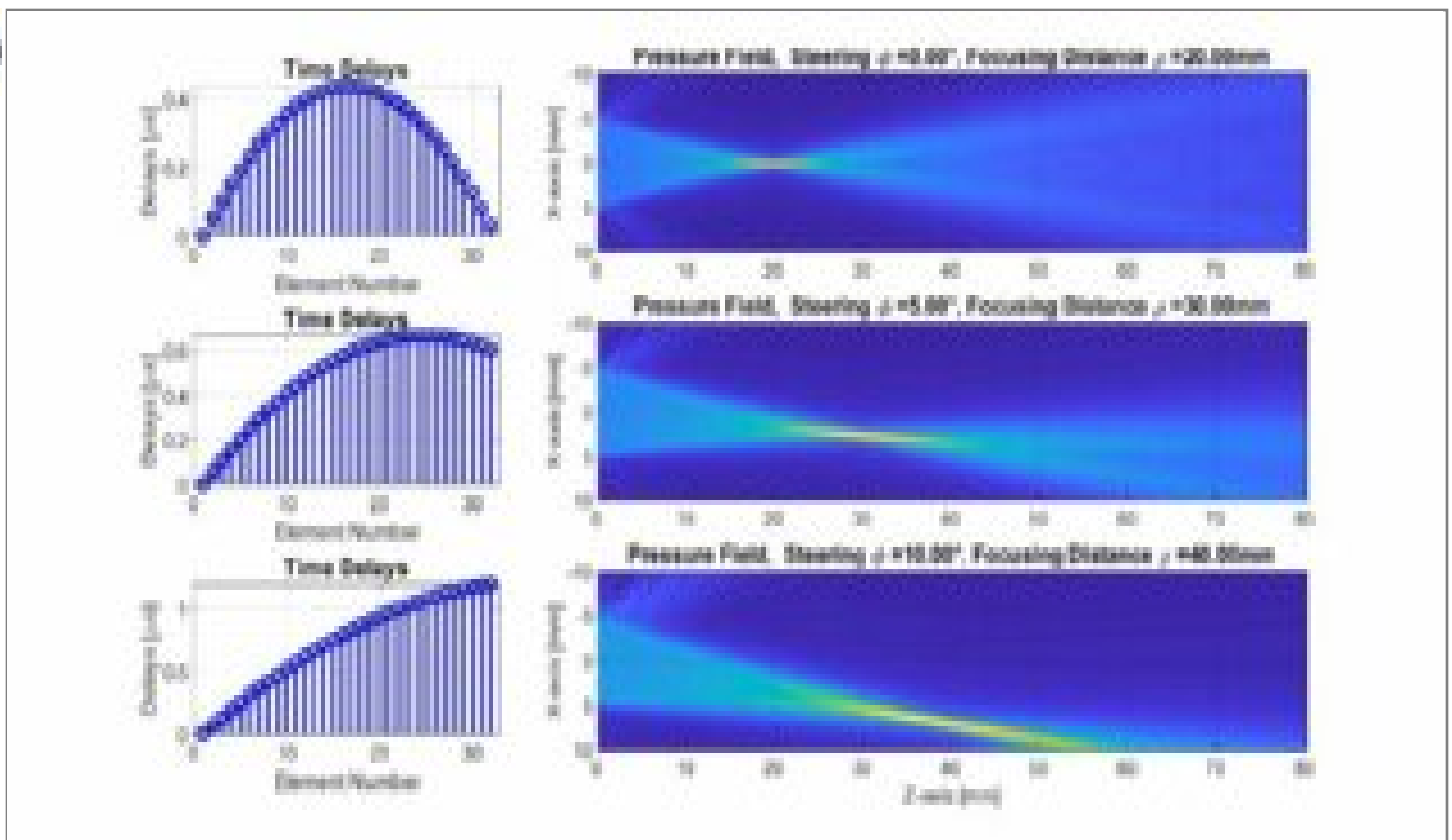


Figure 4 – Beam focusing and steering of an array composed of 32 elements separated by a pitch (interelement spacing) of  $p = 0.32$  mm and central frequency of  $f_0 = 5$  MHz. The selected elements are fired with precalculated delays to effectively focus the energy at a certain direction and distance from the array surface.

At reception, each element of the array—or of the same subaperture used during transmission—acquires an individual A-scan. This elementary A-scan is the digitized pressure measurement produced when the returning echo contacts the element (or elements). Then, the same time delays used in transmission are applied to each elementary A-scan. Finally, these time-delayed A-scans are summed to produce a single A-scan. Figure 5 shows an example of five elements receiving an acoustic wavefront. The delayed and undelayed A-scans are shown.



Figure 5 – Five elements (green circles) receiving a soundwave generated by a point source (red circle). The waveform generated by the source is shown for three different time points ( $t$ ). The generated A-scan for each element is shown with and without delays applied to the element's received signal. The same representation is used for the summed A-scan, i.e., with delays applied (blue) and without (dashed red).

The transmission and reception process can be performed multiple times to generate beams over a range of angles or over a range of subapertures (or both). Each of these beams results in a single A-scan, which can be converted into different types of images or data representations. Typical PA imaging types are discussed in more detail in [Part 3: Imaging Techniques](#).

## Similarities of Phased Array to Conventional UT

While phased array technology enables greater flexibility and control of the acoustic beam propagation direction and focusing depth than conventional UT, there are limits on the maximum steering angle and the focal region. These limitations are governed by the same typical acoustic parameters as conventional UT, namely the near-field length and beam divergence.

Like conventional UT, the near-field length of a phased array probe defines its maximum focusing distance from the probe. For a flat, circular, single-frequency, single-element UT transducer on a test piece with a single medium of propagation, determining the near-field length can be achieved with a simple equation. In this case, the distance from the probe's surface to the last maximum of acoustic amplitude depends on the transducer's diameter and the wavelength in the propagation medium ( ).

Although an exact, closed-form expression for the near-field length is not available for arbitrarily shaped transducers, the concept of near-field length still applies to phased array probes. In the case of phased array probes, the near-field length corresponds to the last maximum of acoustic amplitude of the array when the time delays of the elements that form the aperture are set to zero (see Figure 6). Like in the case of the flat, circular UT transducer, the near-field length increases by augmenting the size of the aperture (i.e., adding phased array elements to the aperture) or by using a higher frequency probe. A larger near-field length increases the ultimate acoustic focal distance, providing an extended capacity to focus farther from the probe.

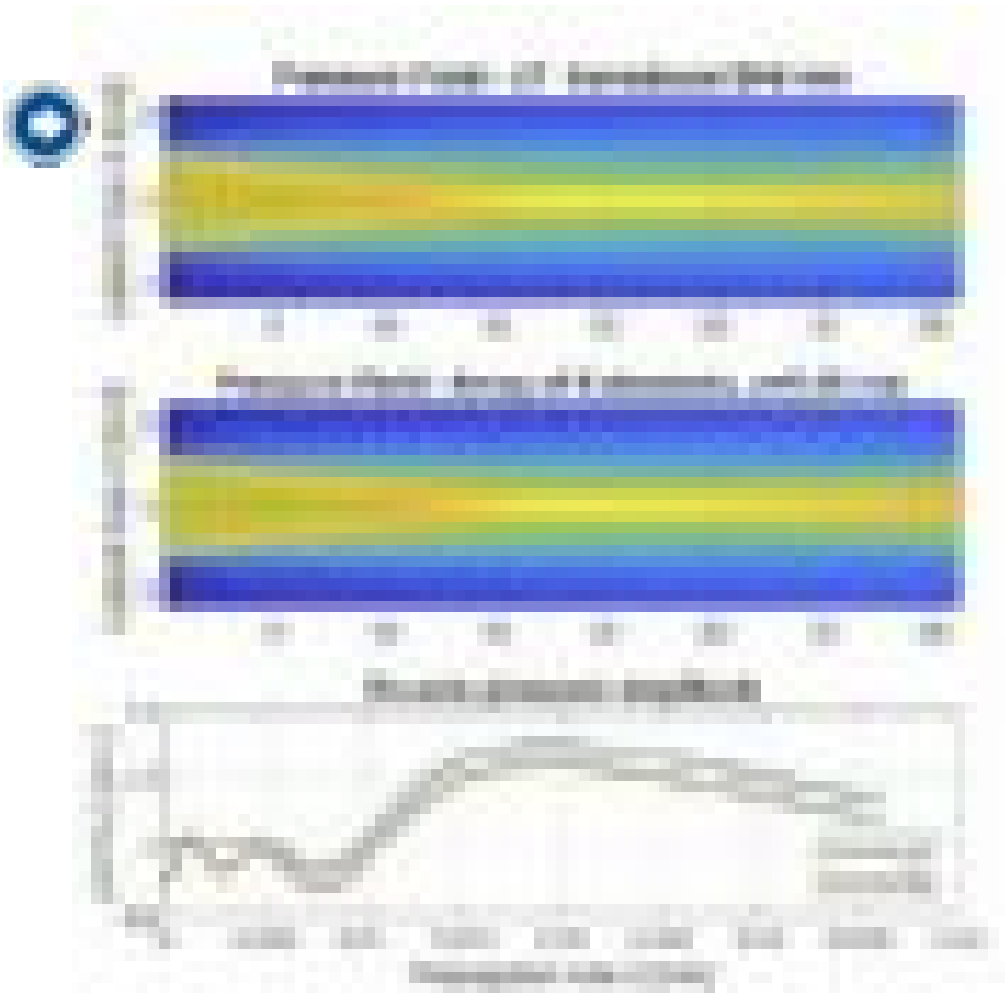


Figure 6 – Pressure field for a conventional UT transducer with a diameter of  $D = 6$  mm (top), pressure field for an unfocused array of 6 elements with a total aperture length of 6 mm (middle), and the on-axis pressure amplitude for both the UT transducer and the PA elements (bottom). Simulation in water ( $c = 1480$  m/s) using elements with central frequencies of  $f_0 = 2.25$  MHz.



It is possible, using time-delayed pulses, to focus beams within the near-field length of a phased array probe, but not beyond it. Figure 7 shows an example of beam focusing behavior before and beyond the near-field length for an array of 32 elements with central frequency  $f_0 = 5$  MHz in water. In this figure, the focal position  $R_0$  along the propagation axis is moved from half the near-field distance to about three times the near-field distance. The amplitude profile of the focused beam converges to the profile of the unfocused beam. Although time delays are used in an attempt to focus the beam beyond the near-field length, the maximum amplitude position of the on-axis pressure profile does not go past the near-field length.

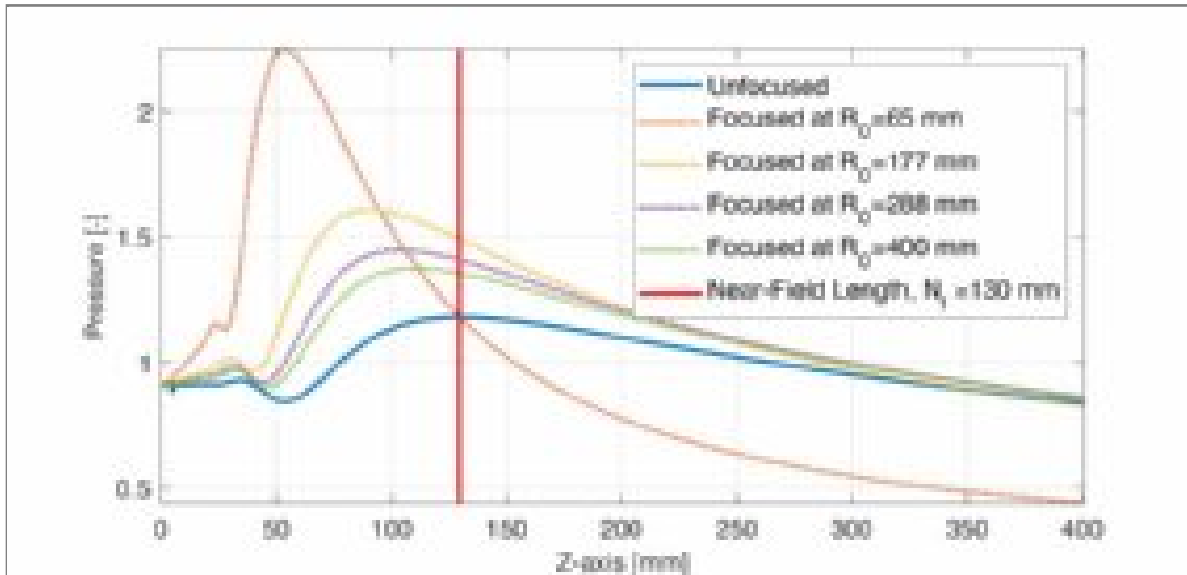


Figure 7 – The on-axis pressure behavior as a function of the focal distance  $R_0$ . The on-axis pressure amplitude of the unfocused array is shown for comparison. The probe is composed of 32 elements with an element spacing of  $p = 0.32$  mm and central frequency  $f_0 = 5$  MHz in water. Note that even when the focal distance is greater than the near-field length, the maximum pressure position does not exceed the near-field length of the array.

While the near-field length of the PA probe defines its focusing capabilities, the beam divergence of its individual elements defines the array's steering capabilities. In conventional UT, the beam divergence corresponds to the opening angle of the beam, which is again defined by the transducer's diameter and the wavelength. Figure 8 shows examples of two beams generated in the same medium by transducers of two different sizes.

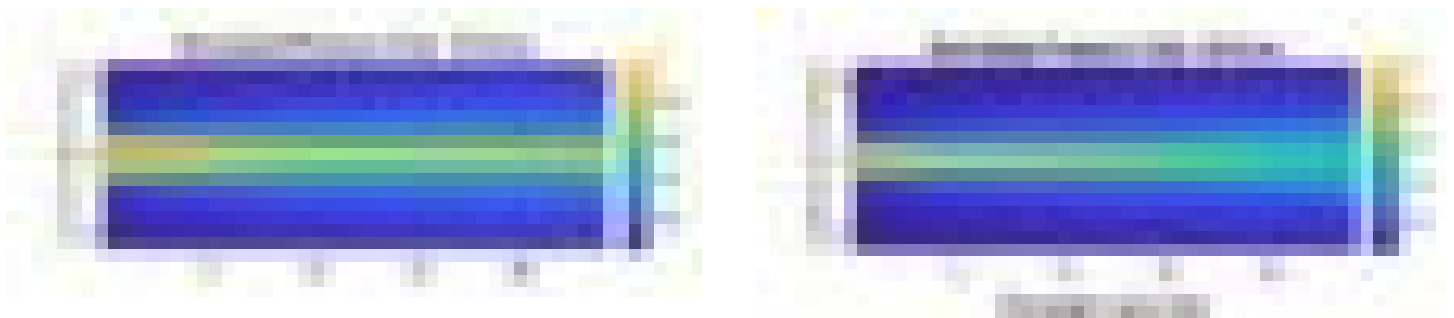


Figure 8 – Pressure fields of two conventional transducers of different diameters (top = 3 mm, bottom = 2 mm). Simulation in water ( $c = 1480$  m/s) using transducers with central frequencies of  $f_0 = 5$  MHz. The smaller transducer has a larger beam divergence.

For phased array probes, the same principle applies at the individual element level. Because the elements are usually smaller than a conventional UT transducer, the beam divergence of each element is greater, enabling steering control using time-delayed pulses. Since the acoustic beam generated by the array is the sum of each element's beam, then the maximum steering capabilities of the array is directly defined by its elementary beam divergence. Figure 9 shows how the beam profile is affected by a high steering angle.

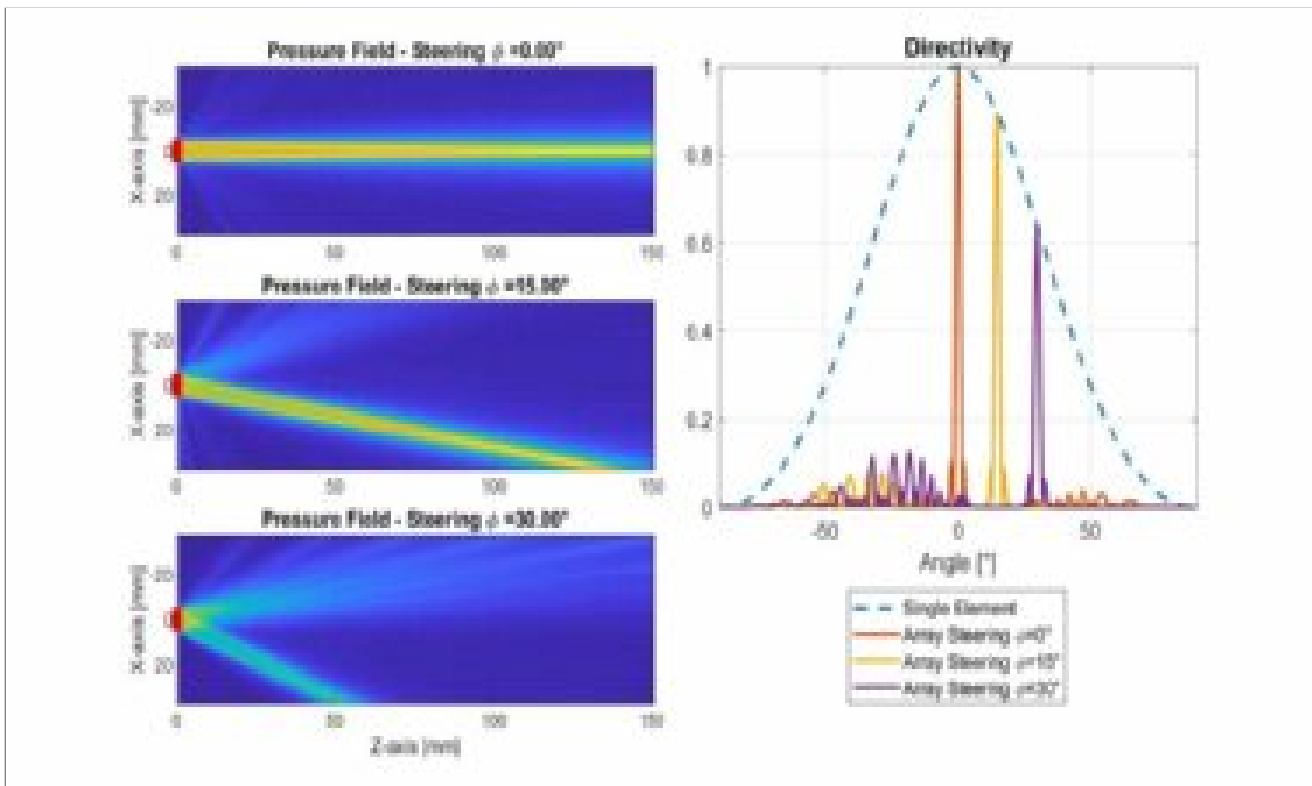


Figure 9 – Beam amplitude and directivity for various steering angles between 0° and 30°. Note the reduction of the main lobe amplitude as the steering angle increases. The amplitude of the main lobe follows the directivity function of a single element. This is an array of 32 elements with an element spacing of  $p = 0.32$  mm and central frequency of  $f_0 = 5$  MHz.

The beam divergence of each element of a phased array probe is also defined by its size, and the resulting wavelength in the propagation medium, just like UT transducers. For instance, if we compare two PA probes with identical frequencies, the one with smaller elements will offer better steering capabilities because the smaller elements have a larger beam divergence. Equivalently, for two PA probes with elements of the same size, the one with the lower central frequency will offer a larger beam divergence and hence better steering capabilities.

Conversely, the probe's physical specifications—including the number, size, and frequency of the elements—limit its steering capacity. This limitation explains why wedges are commonly used with phased array probes. While it is possible to electronically steer the beams of a PA probe and attain large refraction angles while maintaining sufficient amplitude (e.g., 40° to 70° for a shear wave in a steel weld), this cannot be achieved by time delays alone. Figure 9 illustrates the steering limitation of an array caused by the element size. To mitigate this limitation, a wedge can be used to mechanically pre-orient the array at the center of the refraction range (e.g., typically around 55° in steel), and then time delays can steer the acoustic beam around this center refraction angle.

The ideal phased array probe would be composed of an infinite number of infinitely small elements, ensuring an optimal focusing region (i.e., a large near field) and a large beam divergence for optimal beam steering capabilities. In reality, the number of elements is constrained by the number of available pulsers on the acquisition unit (which is typically around 128 pulsers) and the size of the elements limits the amount of energy—or lack thereof—produced. Indeed, the sound power generated by a piezoelectric element is proportional to its surface area, so if the element is too small, it will not produce enough acoustic energy to generate a useful signal.

## Advantages and Limitations of Phased Array

One of the main advantages of phased array compared to conventional UT is its imaging capabilities. While conventional UT analysis mostly relies on a single A-scan, phased array technology has the ability to create a live acoustic image of the ROI, considerably easing the indication sizing and characterization process. Indications are discontinuities in the data, or peaks in amplitude, caused by reflected echoes, like in conventional UT. An example is shown in Figure 10 where a simple side-drilled hole is detected using conventional UT and a phased array compound scan.



Figure 10 – A side-drilled hole flaw (left) detected using a single A-scan (middle) and an S-scan generated using a phased array instrument (right).

With this imaging capability comes the possibility to record the acoustic data for post-inspection analysis and data archiving. Although conventional UT data can be saved, without precise encoding capabilities, the scope of the post-inspection analysis is limited.

As mentioned, phased array focusing and steering capabilities are limited by the element dimensions and frequency used. While a PA probe and wedge configuration is more flexible than a conventional UT probe and wedge, there is no one-size-fits-all solution. The selected acoustic probe and wedge configuration must not only enable focusing in the region of interest, but also allow the acoustic beams to propagate at an optimal orientation to increase the probability of detection.

To achieve this steering and focusing flexibility, the PA probe and wedge are typically large in dimension. This can be a problem for restricted-access inspections or for curved surfaces that require a specially designed curved wedge. In addition to requiring more wedges, a special calibration block may be needed for code compliance.

The advantages and limitations of the phased array technique are summarized in Table 1.

**Table 1 – Advantages and limitations of the phased array technique.**

Advantages	Limitations
<ul style="list-style-type: none"> <li>• Imaging capabilities enable easier data interpretation, better sizing, and improved characterization capabilities.</li> <li>• Data archiving for post-inspection analysis and periodic inspection comparison (trend analysis).</li> <li>• Faster inspection: The entire ROI can be covered in a single encoded pass.</li> </ul>	<ul style="list-style-type: none"> <li>• Large probe and wedge footprint can inhibit inspection in restricted spaces.</li> <li>• Larger wedge footprint also means specially adapted wedges with curved interfaces are required for tube or complex geometry inspections.</li> <li>• Requires thorough training for optimal use.</li> </ul>

## Part 2: Phased Array Equipment

This chapter presents the equipment that is used to perform phased array inspections, including phased array probes, wedges, and acquisition units.

### Phased Array Probes

Phased array probes come in a variety of shapes and sizes to accommodate different applications. Typical Olympus phased array probes have a central frequency ranging between 0.5 MHz and 13 MHz and have from 8 to 256 elements. The maximum number of elements in the probe is limited by the dimensions of the piezoelectric crystal elements and the number of individual channels of the acquisition instrument. The most commonly used probes have between 64 and 256 elements. Figure 11 illustrates the dimensional parameters of a 1D linear phased array probe.



Figure 11 – Linear phased array probe dimensions.

A = Aperture: total length of all elements in the active plane

H = Height of the elements in the passive plane, which is also called the element elevation

p = Pitch: center-to-center distance between two adjacent elements

e = Size: the width of an individual element

g = Gap (or kerf): the spacing between two adjacent elements

For users who are already accustomed to the conventional UT technique, there is a simple approach to choosing the right phased array probe:

- If, for example, your application would require a conventional UT transducer with a frequency of 10 MHz, use a phased array probe with the same frequency.
- If the conventional UT technique would require a 10 mm aperture, use a PA probe that can provide a similar aperture in both the active and passive axes, such as a PA probe where A=20 mm and H=10 mm, and half the elements are used to create an active aperture of 10 mm × 10 mm.

The element array of a PA probe can also be two-dimensional (see Figure 12); for example, a matrix array. With 2D arrays, the user needs to define time-delay sequences on both axes. Such probes enable the user to focus the beam outside the typical focal plane of a linear probe. Matrix array probes are mainly used for specialized applications, such as dissimilar weld and spot weld inspections.

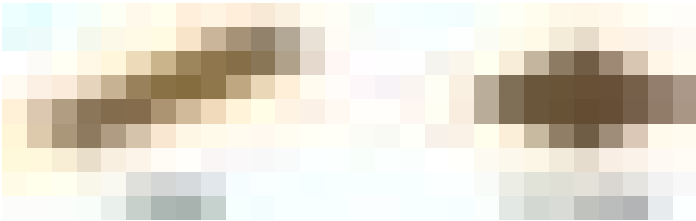


Figure 12 – Examples of elements in linear array and 2D array configurations.

The Olympus probe definition is provided in Figure 13 and can also be found in the Olympus probe catalog.

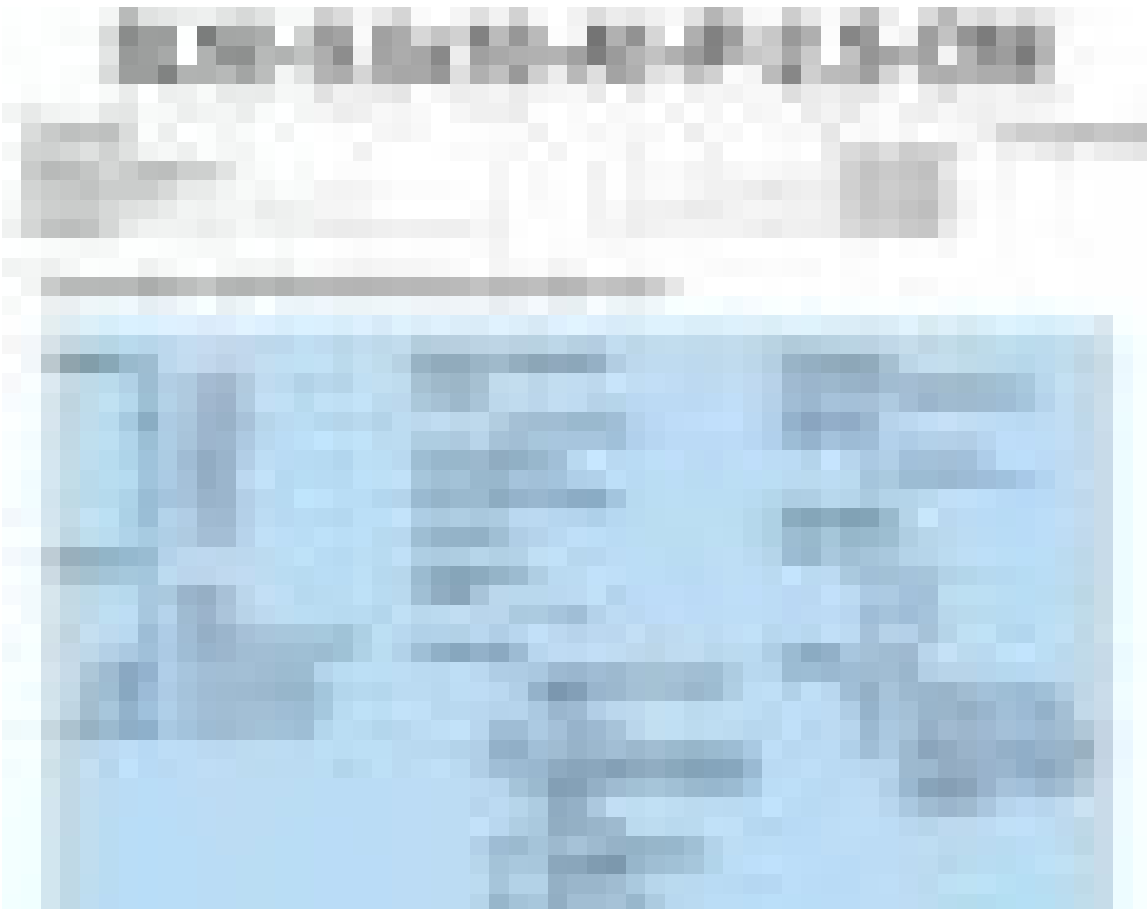


Figure 13 – Nomenclature for Olympus probes.

## Phased Array Wedges

Phased array wedges perform the same function as conventional UT wedges. They couple sound energy from the probe to the material, protect the probe's surface, and improve the near-surface resolution. They are also used to assist the beam formation, which is limited by the element directivity. They come in a wide variety of shapes and sizes for various applications and are an essential part of the inspection process.

In conventional UT, the wedge's main purposes are to steer the sound in the desired direction and protect the surface integrity of the probe. Each wedge has a prescribed angle, which is usually defined by the sound's refraction angle in the inspected part and a wedge delay. The wedge delay corresponds to the distance between the probe's face and the part—taken normal to the probe surface—divided by the sound velocity in the material. Figure 14 shows typical conventional UT wedges.



Figure 14 – Examples of conventional UT wedges.

Each PA wedge has at least three prescribed parameters that define it (illustrated in Figure 15):

- Angle ( $\theta$ ): Usually determined by the refraction angle in the inspected part
- Height ( $h$ ): The distance between the wedge's bottom surface and the first element position
- Lateral offset ( $x_l$ ): The distance between the wedge front (or back) face and the first element

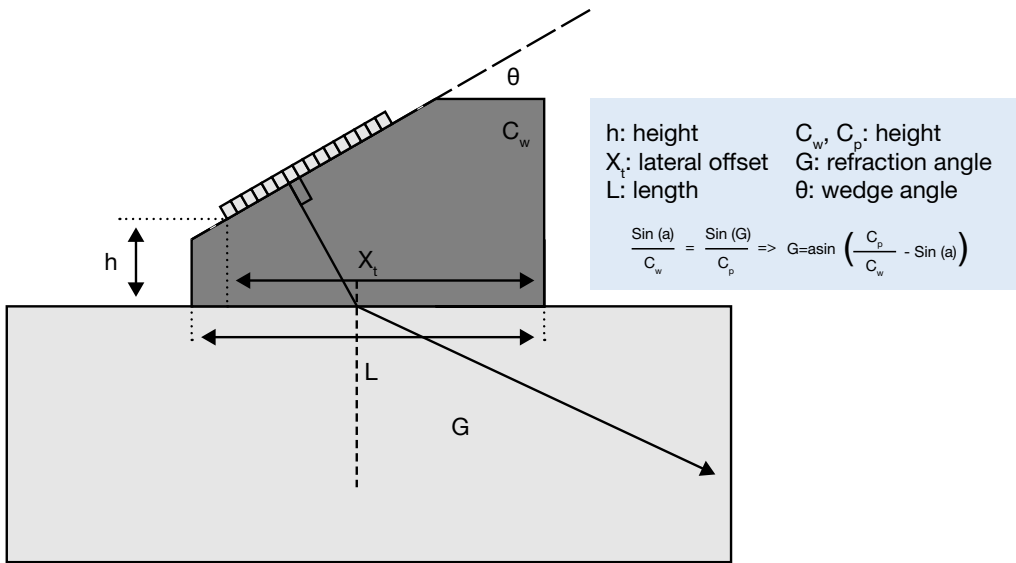


Figure 15 – Schematic of a typical PA wedge.

Figure 16 shows typical PA wedges.

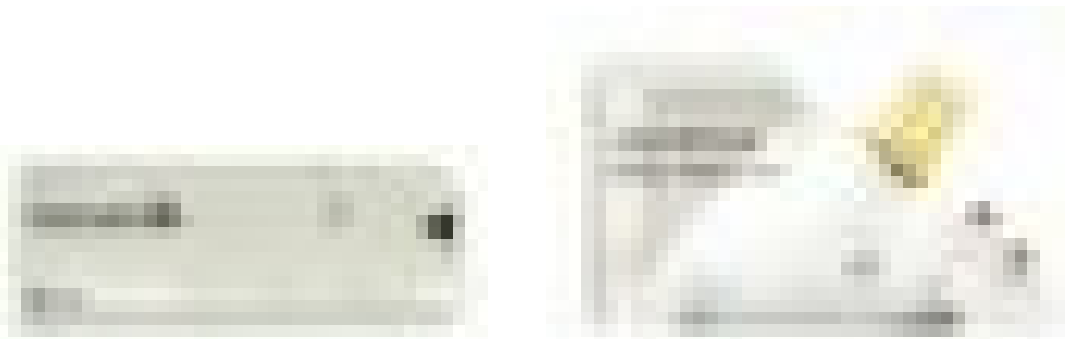


Figure 16 – Example of phased array wedges for 0° inspection (left) and for angle beam inspection (right).

There are two main types of PA wedges; the first type is for zero-degree (0°) inspection (e.g., corrosion inspection) and the second type is for angle beam inspection (e.g., weld inspection).

For 0° inspection, the wedge is typically called a delay line and is often a water column instead of a plastic part. Since 0° inspection does not usually require beam steering, the delay line is used to improve the near-surface resolution and protect the probe's surface integrity.

As stated previously, the main purpose of the wedge for angle beam inspection is to increase the steering capabilities of the array (illustrated in Figure 9). The main factors that influence the steering capabilities of an array are the number of elements, the size of the elements, the probe frequency, and the desired acoustic mode (pressure/longitudinal or transverse/shear wave). With all these factors combined, the steering angle of a typical array ranges between  $\pm 15^\circ$ . However, using a wedge that has a refraction angle of  $55^\circ$ , for example, enables the probe to generate refraction angles between  $40^\circ$  and  $70^\circ$ .

The complete part number definition for Olympus wedges is available in Figure 17 and in the Olympus probe catalog. The part number is divided into 4 sections and may or may not contain the last two.

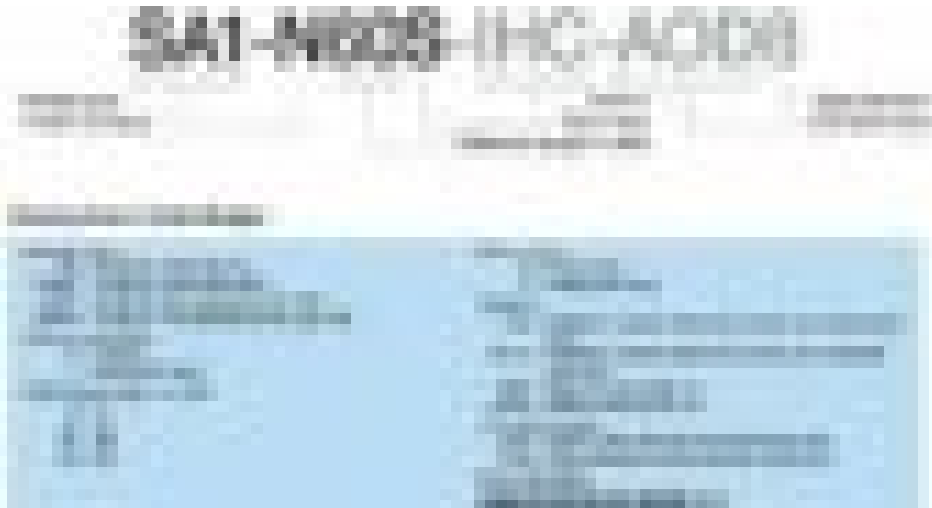


Figure 17 – Nomenclature for Olympus wedges.

Olympus wedges are manufactured to be compatible with a specific family of probe casings. Typical probe and casing types are A10, A31, A32, etc. and are printed on the probe and wedge and referenced in the catalog. The SA31 wedge (see Figure 18) offers different models for shear wave angle beam, longitudinal wave angle beam, and longitudinal straight beam.

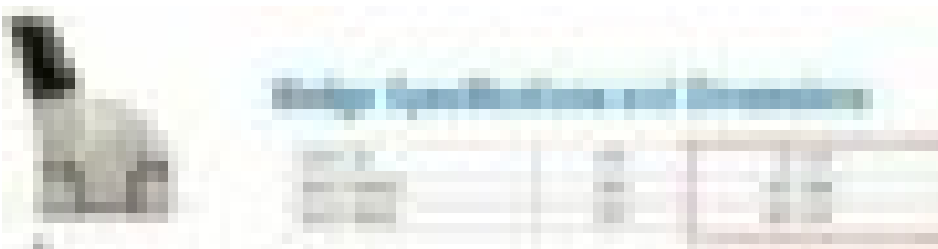


Figure 18 – Example of wedge specifications for Olympus' A31 probe casing.



## Phased Array Acquisition Instruments

The main differences between UT and PA instruments are the number of available pulsers and the overall size of these devices. Conventional UT instruments require simpler electronics, a less powerful power source, and a smaller screen size. Typical UT instruments have between two and eight independent pulser connectors. Phased array instruments tend to have between two and four independent UT connectors and an additional multiplexer (MUX) connector, usually with a capacity for around 128 pulsers. It is this MUX connector that is used with a phased array probe.

An example of a phased array flaw detector is shown in Figure 19.



Figure 19 – OmniScan™ X3 phased array flaw detector.

The pulser capabilities of phased array instrument models are commonly identified by two sets of numbers separated by a colon (YY:ZZZ).

The first number (YY) corresponds to the maximum number of elements that can be activated simultaneously. In other words, this number corresponds to the maximum number of elements that can be used to create one single beam. The selected elements can differ from one beam to another (e.g., in a linear scan), so even with a 128-element probe, the maximum aperture size that can be used corresponds to  $YY \cdot p$ , where  $p$  is the pitch of the array.

The second number (ZZZ) corresponds to the maximum number of elements that can be connected to the instrument. The most commonly used PA instruments are 32:128, 16:128, and 16:64 models. Instruments with more pulsers are more expensive but usually more flexible in terms of the types of inspections that can be performed.

16:128 and 16:64 instruments are commonly used for corrosion or composite inspection, often employing the linear scan technique. A typical corrosion setup uses an aperture of four to eight elements on a probe with a high number of elements (typically 64 or 128). For this kind of inspection, a 32:128 or even a 64:128 instrument is not required.

On the other hand, a typical weld inspection setup uses a smaller probe with around 32 to 64 elements, but the beam is generated using a larger aperture, i.e., more elements. It is common to use up to a 32-element aperture for a sectorial scan or compound scan. In this case, a 32:128 instrument is required.

## Part 3: Imaging Techniques

As mentioned, one of the main advantages of phased array over conventional UT is its imaging capabilities. This chapter will cover the typical imaging techniques used in phased array, from linear 0° inspections to complex angular and aperture sweeping techniques.

### Electronic Scanning Types

The first step of acquiring PA data is configuring the focal laws for the type of scan to perform. Focal laws, and the resulting groups of A-scans, can be configured in many ways and are dependent on the software, instrument, and probe capabilities (see Figure 20).

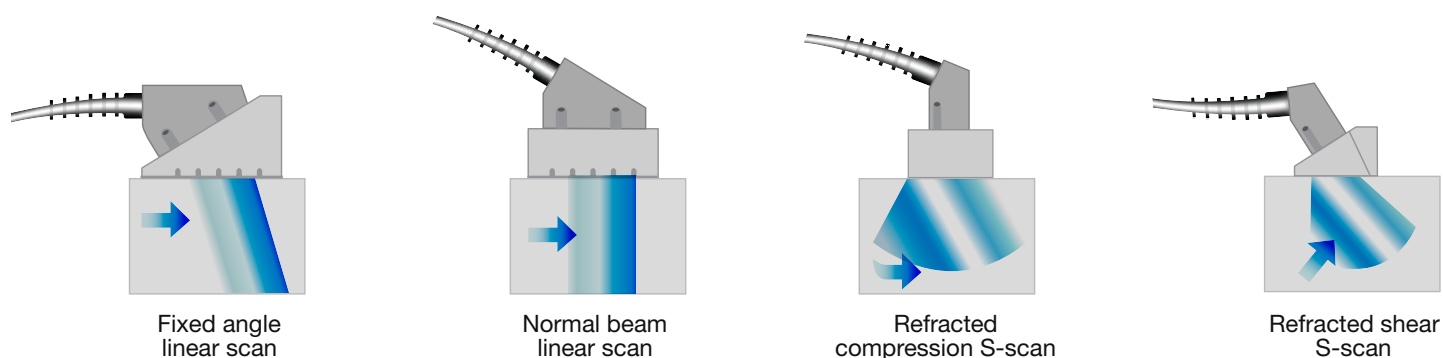


Figure 20 – Typical focal law types used in nondestructive testing with a linear array probe.

## Linear Scan

A linear scan is produced by applying the same time-delay function over a series of element sets. This means that the beams generated have the same propagation angle. The movement of the acoustic beams is along the array's length. An example of linear scanning is shown in Figure 21. Each ray represents a different beam going from the center of the selected aperture in a direction corresponding to the steering angle. Each beam has the same propagation direction, but a different origin position. This is equivalent to moving a conventional UT transducer from the back to the front of the wedge.



Figure 21 – Linear scan inspection using a linear array probe.

Linear scan advantages and limitations are listed in Table 2.

**Table 2 – Advantages and limitations of the linear scan technique.**

Advantages	Limitations
<ul style="list-style-type: none"><li>• Replaces conventional UT raster scanning.</li><li>• Eases calibration because all the acoustics beams have the same refraction angle.</li><li>• Complies with existing codes referencing single-angle inspections.</li><li>• Beam-to-beam resolution is the same, regardless of sound path.</li></ul>	<ul style="list-style-type: none"><li>• Requires many focal laws, thereby reducing the acquisition speed.</li><li>• Low coverage with a single group compared with a sectorial or compound scan.</li><li>• Multiple groups are often required for complete weld coverage, resulting in long setup and calibration times as well as large data files.</li></ul>

## Sectorial Scan

A sectorial scan is obtained by producing beams with different steering angles, emanating from a common aperture. The A-scan density and coverage are defined by the range of refraction angles (e.g., 40° to 70° in shear wave mode) and the angle resolution, which is typically 1° between each beam. Figure 22 illustrates a typical sectorial scan using all the elements in the array. Each beam has the same origin point—corresponding to the middle of the selected aperture—but different refraction angles. Sectorial scans usually enable complete coverage of the weld without any probe motion. This is equivalent to using a single UT transducer with several wedges of different angles.



Figure 22 – Sectorial scan configuration using a linear array probe.

Sectorial scan advantages and limitations are listed in Table 3.

**Table 3 – Advantages and limitations of the sectorial scan technique.**

Advantages	Limitations
<ul style="list-style-type: none"><li>• Large coverage with a small footprint on the part's surface.</li><li>• Improved flaw characterization due to the multiple incident angles.</li><li>• Small element count required for the instrument and probes (e.g., 16 or 32).</li></ul>	<ul style="list-style-type: none"><li>• Beam-to-beam resolution worsens as sound path increases.</li><li>• Limitations in the ability to calibrate multiple time-corrected gain (TCG) points for long sound paths, mostly for the high-refraction angle range.</li></ul>

## Compound Scan

A compound scan is a combination of a linear scan and a sectorial scan. In a compound scan, both the steering angle and aperture position change for each beam that composes the group. This results in a scanning configuration with greater coverage than a sectorial scan or linear scan. In this case, the A-scan density and coverage are defined by the angular range (e.g., 40° to 70°), angular resolution (e.g., 1°), and the probe aperture span. Figure 23 shows an example of a compound scan using the same linear array as in Figure 21 and Figure 22. Each beam has a different refraction angle and origin on the array. An equivalent conventional UT inspection would require raster scans involving several probe and wedge configurations.

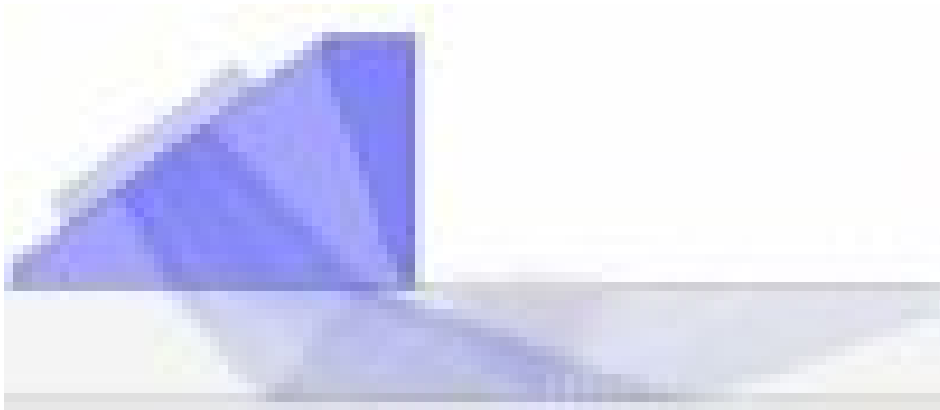


Figure 23 – Compound scan configuration using a linear array probe.

Compound scan advantages and limitation are listed in Table 4.

**Table 4 – Advantages and limitation of the compound scan technique.**

Advantages	Limitations
<ul style="list-style-type: none"><li>• Larger volume coverage than both sectorial and linear scans.</li><li>• Combines the benefits of using multiple angles while exploiting the whole length of the probe, like with a linear scan.</li></ul>	<ul style="list-style-type: none"><li>• Beam-to-beam resolution worsens as the sound path increases. The effect is even more pronounced than a sectorial scan.</li></ul>

## Data Representations

PA instruments can display acquired data in various ways, offering users more powerful and flexible characterization and sizing tools. This section describes four of the main views used by PA users for data analysis.

The views described in the following subsections are linked to two different setup configurations. The first configuration is a corrosion inspection setup (shown in Figure 24), the second configuration is a weld inspection setup with two different flaws, a toe crack and lack of side-wall fusion (shown in Figure 25).

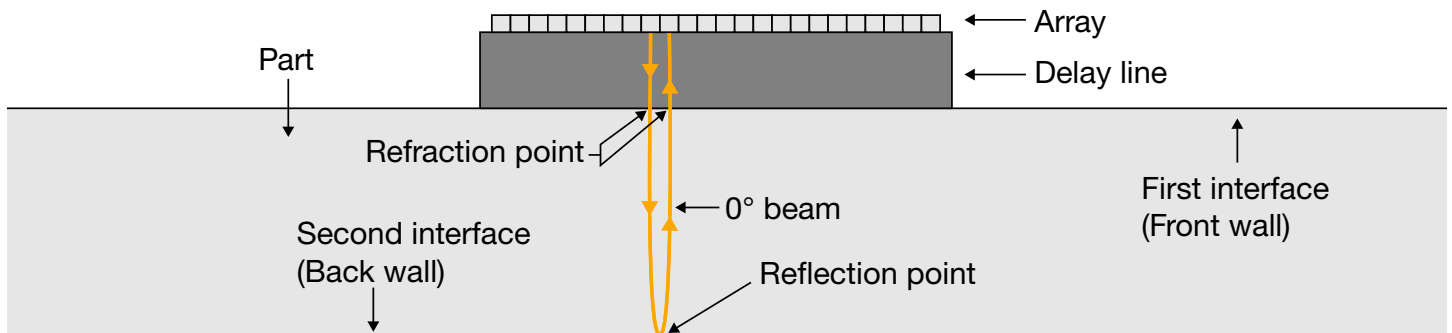


Figure 24 – Corrosion inspection setup with an array, a delay line, and a part. A single beam is shown going from the array, passing through the first interface (front wall), reflecting off the back wall, and returning to the probe surface.

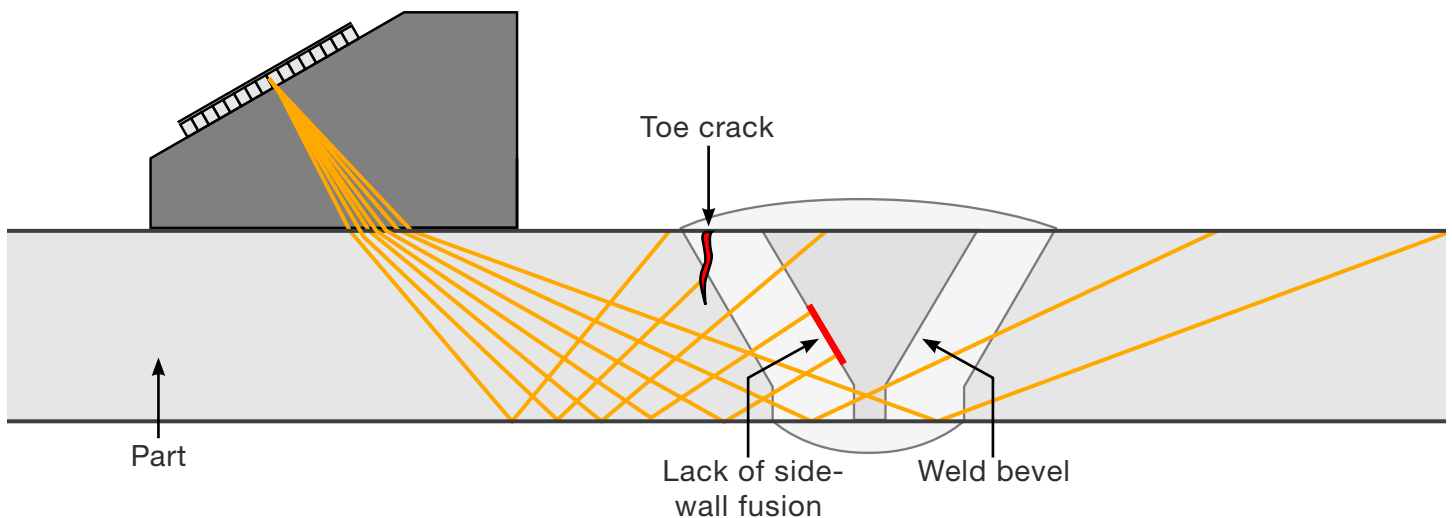


Figure 25 – Weld inspection setup with an array, an angle wedge, and a part with a double-V weld bevel. Two different flaws are shown, a toe crack on top and a lack of side-wall fusion at the bottom of the weld.

## A-Scan Data View

All phased array data views are based on the A-scan (short for amplitude scan). Like conventional UT, a phased array A-scan represents the amplitude time trace of a specific beam. The vertical axis of the A-scan corresponds to the signal amplitude while the horizontal axis corresponds to either the acoustic sound path (in mm), travel time (in microseconds), or depth (in mm). There are as many A-scans as there are reception beams generated by the phased array setup.

In a typical zero-degree inspection (see Figure 24), the A-scan presents a strong initial echo, resulting from the entry of the ultrasound into the material, which is called the interface echo. This is followed by another echo at the expected thickness value of the material wall, which is called the back wall echo. Figure 26 illustrates an example of the interface and back wall echoes in a 0° inspection A-scan.

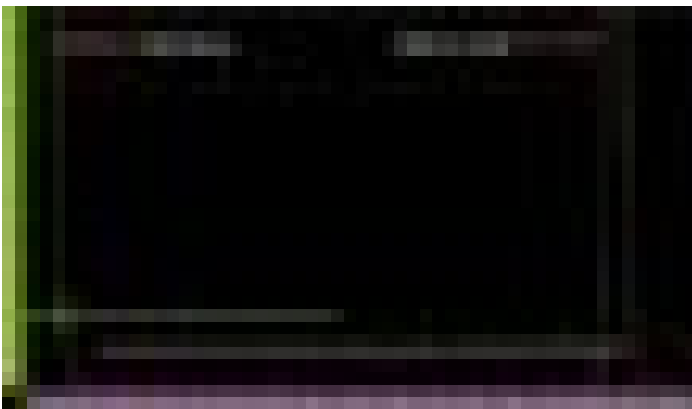


Figure 26 – Echo from the interface between the wedge and the surface of the part (left) and the echo from the part's back wall (right) in a typical zero-degree inspection A-scan.

The displacement of the back wall echo relative to the interface echo indicates a change in wall thickness of the material. When the distance between the back wall and interface echoes is smaller, the material is thinner. This is illustrated in Figure 27.

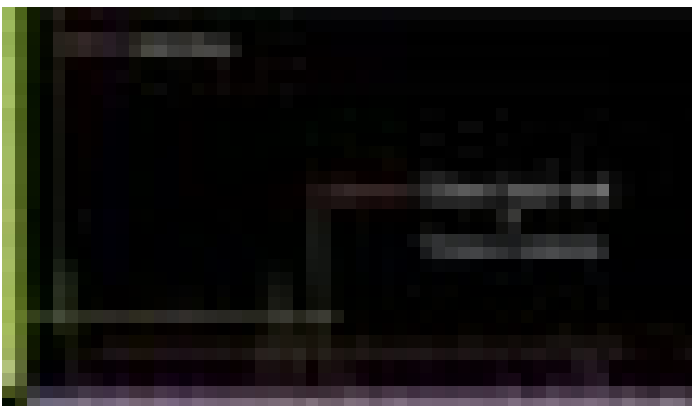


Figure 27 – Effect on the back wall echo on a thinner section of the part. The distance between the back wall and interface echo is smaller than in Figure 26, meaning the material is thinner at that position.

For weld inspection (see Figure 25), a commonly used technique is to send ultrasound waves into the material at several angles to cover the weld's entire volume. If no energy is returned to the probe, the covered area is considered free of indications. However, if an echo is detected on the A-scan, it means that a discontinuity in the material has reflected the ultrasound energy back to the probe. The echo's characteristics—i.e., its location, amplitude, and A-scan signature—help determine the type of indication. Illustrated below are two indication types that can be found in a weld: a lack of side-wall fusion, characterized by its high amplitude and streamlined peak (Figure 28), and a crack, characterized by its multiple peaks caused by the crack's multiple facets (Figure 29).



Figure 28 – Lack of side-wall fusion in a 25 mm thick weld.

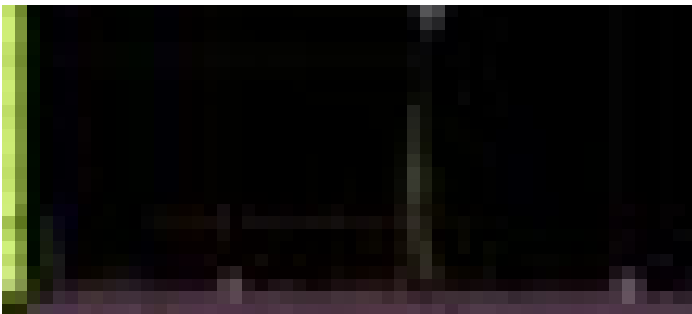


Figure 29 – Toe crack in a 25 mm thick weld.



## S-Scan Data View

In phased array, A-scan data can be grouped to form a 2D image representing the returning sound wave in the part. For example, when you perform a sectorial scan, each beam generates its own A-scan. Viewing the data as an S-scan instead of an A-scan enables you to obtain the information from all the beams in a single color-coded representation. This comprehensive overview of the data explains why the most common 2D view used in phased array is the S-scan.

The linear scanning technique is especially useful for zero-degree inspections as it can cover a large area in a single scan making the inspection more efficient. The S-scan data view of a linear scan shows the profile of the back wall signal so you can easily identify the thinnest spot (as shown in Figure 30). In this case, the horizontal axis corresponds to the position along the array's length, while the vertical axis corresponds to the depth in the part. The acquisition instrument calculates the depth by multiplying the time of flight of the ultrasound wave by its velocity, and then dividing this value by a factor of two to account for the roundtrip travel.



Figure 30 – Linear scan acquired S-scan data view showing the profile of a corroded area on a carbon steel plate. The interface echo is seen at the top of the depth axis.

S-scan representations of sectorial and compound scans are similar. To generate S-scans for both types, the acquisition instrument's software positions the A-scans with their corresponding refraction angle in the part, effectively forming a pie-slice image. Figure 31 shows examples of S-scans produced from compound (left) and sectorial (right) scanning data. Typically, in such cases, the vertical axis refers to the depth while the horizontal axis corresponds to the index axis (axis perpendicular to the scan axis).

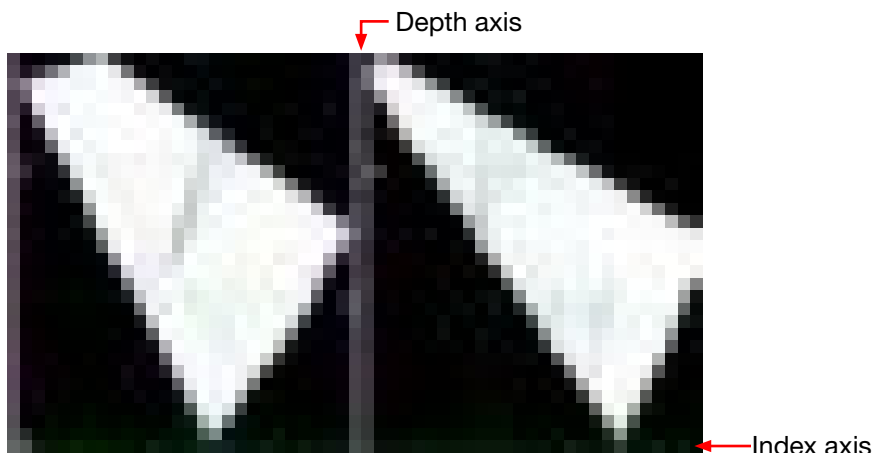


Figure 31 – S-scan data views of a compound scan (left) and a sectorial scan (right) on the same lack of side-wall fusion. The compound scan provides more coverage.

## B-Scan Data View

The B-scan data view enables you to see the data generated by a single beam over the entire scan length. The B-scan's vertical axis represents the depth while the horizontal axis represents the scan position. Figure 32 illustrates an example of a B-scan for a weld inspection.



Figure 32 – Example of a B-scan view for an angle beam inspection. The vertical axis is the depth while the horizontal axis is the scan position. The data corresponds to a single beam (A-scan) along the scan axis.

The operator can use the B-scan view to quickly detect flaws along the entire length of the scan by scrolling through the different beams. Figure 33 shows an example of B-scan views from several refracted angle beams, and flaws are clearly detected.



Figure 33 – B-scan views of different angled beams of the same sectorial scan. As the operator scrolls through the beam angles, the flaws are clearly detected in the B-scan.

## C-Scan Data View

While S-scan and B-scan views show all the data generated, it is possible for the operator to select a specific region in the volume for faster analysis. This is equivalent to using a gate in conventional UT. In phased array, gates can be set up to save the maximum amplitude within the gate or the time of flight of the first peak that crosses a specified amplitude threshold, for example.

Figure 34 presents A-scan and S-scan views with a typical amplitude gate. In this case, the maximum amplitude within the gate on each beam (i.e., A-scan) is saved and then displayed in the C-scan view. The amplitude C-scan represents the maximum amplitude on each beam (vertical axis) over the length of the scan (horizontal axis). As shown, it is a powerful tool to detect flaws quickly.



Figure 34 – The gate is displayed in the A-scan and S-scan views, and the signal detected in the A-scan is also detected on the S-scan and C-scan; the red color is typical of high amplitude.

Using a time-of-flight gate instead of an amplitude gate results in a thickness C-scan data view, as illustrated in Figure 35. In this case, the colors correspond to the part's thickness—computed using the measured time of flight and the acoustic velocity—and the vertical axis corresponds to the index position (along the array) while the horizontal axis corresponds to the scan direction.

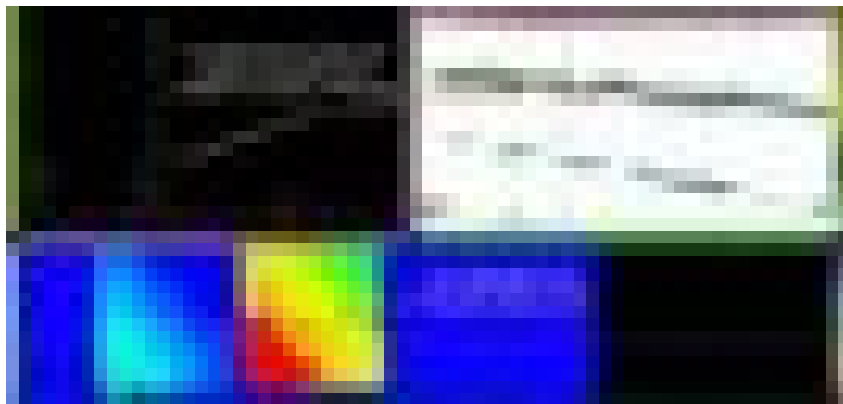


Figure 35 – Example of a thickness C-scan using a time-of-flight gate (red line). The corrosion area can easily be mapped into a 2D image.

## Conclusion

Using phased array ultrasonic testing results in faster inspections, a higher probability of detection, and better sizing and characterization capabilities than conventional UT.

Compared to a conventional ultrasonic transducer, a phased array probe provides additional sound-wave control capabilities including the possibility to steer the ultrasound beams in different directions and focus at various depths in the part using electronic delays. This makes a linear phased array probe more versatile than its conventional UT counterpart. A single phased array probe and wedge can effectively replace a series of different UT transducers and wedges, offering a simpler setup and more efficient scanning.

Although phased array can be used to steer and focus the acoustic energy at different angles and distances, the same physical limitations apply to PA and UT ultrasonic testing. The focusing capabilities of an array are limited to the near-field region while the steering is limited by the directivity profile of the individual elements of the array. To increase the focal distance, a larger aperture or a higher frequency can be used. To expand steering capabilities, smaller elements or a lower frequency should be used. Although electronic steering is possible, a wedge is still used to pre-orient the array in a specific direction.

A PA acquisition instrument generates acoustic beams at a range of refraction angles, originating at the same or at different positions on the array. The most common types of phased array acquisition schemes are the linear scan, the sectorial scan, and the compound scan. The generated beams can be merged to generate 2D acoustic images of the inspected region, enabling easier and faster data interpretation. From the generated acoustic data, several other views, such as the B-scan and the C-scan, can be used by the operator for faster flaw detection.

We hope this e-book contributes to improving your understanding of phased array technology. For a more in-depth look at phased array, refer to our other documentation on the subject:

- [Advances in Phased Array Ultrasonic Testing Applications](#)
- [Phased Array Testing: Basic Theory for Industrial Applications](#)
- [Introduction to Phased Array Ultrasonic Technology Applications](#)

Keep our best practice recommendations in mind and remember that several factors influence the optimal instrument settings, so do not hesitate to consult your local Olympus representative for assistance. Visit our website at [www.olympus-ims.com](http://www.olympus-ims.com), and go to the Contact Us page to find the service center contact information for your area.

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