Phased Array Ultrasonic Examination
for Welds

Course Objectives

- This Course Covers:
  - Theoretical background of Phased Array (PA) ultrasonic fundamentals including physics of PA, PA beam characterization, digitization principles, parameter selection, scanning methodology and PA ultrasonic application on welds.
  - Scan Plan for the weld and its Heat Affected Zone (HAZ) examination
  - Prepare the work instruction to carry out phased array examination on welds
  - Setup file and its Calibration using Omniscan PA ultrasonic equipment
  - Optimization of display and acquisition parameters of setup file.
  - Parent metal lamination check and scanning of weld in plates to detect discontinuity in weld body and its HAZ.
  - Analyze scan data for location and size of dis-continuity in typical welded butt joints using Tomoview software.
  - Interpret and report the test results.
  - Auditing of PAUT data files and setup files.
  - This course is prepared in accordance with the guidelines of PCN GEN Appendix E9 document.
Chapter 1: Brief introduction and History of AUT development

AUT Techniques/Types

- Automated UT (AUT)
  - Phased Array+TOFD-AUT (Zone Discrimination)
  - Phased Array-AUT (Volumetric)
  - TOFD-AUT (Time of flight Diffraction)

*Note:* Encoded image and manual movement along guide (Semi-automated)
Encoded image and motorized movement along guide (Fully automated)
Automated Ultrasonic Testing - History

- Automated ultrasonic testing involves recording of data in some form with scan/probe position.
- Since 1959, RTD have been working on options for pipeline industry. An example of an early efforts of RTD are shown in the (Rotoscan) in the adjacent figure.
- Single probe and single equipment was used for each channel. For each scan, 3 equipment & 3 probe were used simultaneously for 3 channels as multiplexing was not possible then.
- In 1970, M. Nakayama at Nippon steel product R & D, demonstrated a prototype with a two probes calibrated using 3.2mm through holes with a scanning speed of 100-1000mm/min. Output was recorded on polar graphs with angular position indicate the circumference. The technique detected are quite good but weld geometry indications reduced the signal to noise ratio.

Automated Ultrasonic Testing - History

- With the increasing use of CRC automated welding process for pipeline girth welds since 1970’s, the demand for automated inspection was raising.
- During 1972, Vetco offshore inspection, engineer Tony Richardson (See figure) designed the first UT inspection system using CRC welding process, this was a promising system but attempts to get commercial interest were failed.
- A canadian company NOVA in 1977 used CRC automated welding process on all girth welds has decided to go for automated UT using CRC band. Unaware of the above development which already done in 1972 by Vecto, it has hired RTD for development of AUT system based on CRC automatic welding system. Rotoscan is the system developed by RTD.
- Many systems were developed during this time each one has automated scanning system, however, probe design improvements were necessary due to many false call.
Automated Ultrasonic Testing - History

- Problems annoying signals were caused due to beam divergence, this resulted in development of focused transducers.
- This improved way allowed applying engineering critical assessment (ECA) criteria, i.e. assessing the severity of defect based on vertical extent. The small focal spot sizes allowed the weld to be divided into several zones. This is the single most important aspect in the development of mechanized UT on girth welds.

TOFD

- TOFD was invented by Maurice Silk in 1974. TOFD is a very excellent technique with highest probability of detection and sizing vertical extent of the defect.
- The given plot is a typical example and subjective to project based parameters.
- TOFD has limitation for ID and OD side defects to a extent depending upon frequency of transducer.
- Combination of TOFD in pulse echo AUT systems were very popular and used for heavy wall inspection.
What is Phased Array Ultrasonic

- Phased array (PA) ultrasonic is an advanced method of ultrasonic testing that has applications in medical imaging and industrial non-destructive testing.
- Common applications are to examine the heart noninvasively in medical or to find flaws in manufactured materials such as welds.
- Single-element (non phased array) probes—known technically as monolithic probes—emit a beam in a fixed direction. To test or interrogate a large volume of material, a conventional probe must generally be physically turned or moved to sweep the beam through the area of interest.
- In contrast, the beam from a phased array probe can be moved electronically, without moving the probe, and can be swept through a wide volume of material at high speed.
- The beam is controllable because a phased array probe is made up of multiple small elements, each of which can be pulsed individually at a computer-calculated timing.
- The term phased refers to the timing, and the term array refers to the multiple elements. Phased array ultrasonic testing is based on principles of wave physics that also have applications in fields such as optics and electromagnetic antennae.

Conventional UT Vs Phased Array UT

- Conventional UT uses one beam angle for detection (beam divergence provides additional angle which contributes to detection and sizing of mis-oriented defects). Phased array uses either same beam angle or range of beam angle to detect mis-oriented defect.
- Conventional UT has limited beam angle while phased array can be excited to achieve even a 0.1 degree angular variation.
- For coverage, conventional UT needs raster scanning. Phased array provides good coverage with one or more line (depending upon thickness) scanning.
- Conventional UT is limited in application in complex shaped products. Phased array is more flexible due to beam steering and focusing.
- Conventional UT is slower and PAUT is faster.

Difference Between CONVENTIONAL & PAUT
ToFD Vs Phased Array UT

Compared to Time-of-flight (ToFD) method, phased array technology is progressing rapidly because of the following features.

- Use of the Pulse-echo technique, similar to conventional ultrasonics
- Use of focused beams with an improved signal-to-noise ratio
- Data plotting in 2-D and 3-D is directly linked with the scanning parameters and probe movement
- Sectorial scan ultrasonic views are easily understood by operators and client inspectors.
- Direct visualization in multiple views using the redundancy of information in S-scan, E-scans and other displays offers a powerful imaging tool.
- Combining different inspection configurations in a single setup can be used to assess difficult-to-inspect components.

Features of Phased Array Ultrasonic

- **Speed**
  - Phased arrays allows electronic scanning, which is typically an order of magnitude faster than equivalent conventional raster scanning.

- **Flexibility**
  - A Single Phased array probe can cover a wide range of applications unlike conventional ultrasonic probes.

- **Electronic Setups**
  - Setups are performed by simply loading a file and calibrating. Different Parameter sets are easily accommodated by pre-prepared files

- **Small Probe Dimensions**
  - For some applications, limited access is a major issue and one small phased array probe can provide the equivalent of multiple single transducer probes.
Features of Phased Array Ultrasonic

- Commonly can be used for versatile applications.
- Single PA Probe (Multiple element) produce a steerable, tightly focused, high-resolution beam.
- Produces images with side, end and top view.

- Compared to conventional, PA instruments and probes are more complex and expensive.
- In field, PA technicians require more experience and training than conventional technicians.

Application of Phased Array Ultrasonic Testing

- Cross-country Pipe Line
- Pipe Mills
- Heavy Industry
- Nuclear Industry
- Aerospace Industry
- Refinery and petrochemical plants
- Pressure vessels
- Specific Applications
Cross-Country Pipeline

- Automated girth weld scanning system

Fig 1.9

Cross-Country Pipeline

PIPEWIZARD

- Automated inspection system
- Scanning speed 100mm/s
- 1 minutes to inspect 36” diameter onshore pipeline weld
- Combined with TOFD

Fig 1.10
Pipe Mills

- FBIS – Full body inspection system
- RPFBIS – Rotating pipes full body inspection system
- ERW high speed inline inspection system

Heavy Industry

- Under water structures
- Electron Beam Welds
- Forgings

Mechanical Engineering Books
Nuclear Industry

- Reactor Wall, nozzle, cover
- Fuel Assembly
- Control Rod Assembly
- Turbine
- Pipe

- Steam generator tube

Turbine Inspection

- Root inspection of turbine blades
- Blade remains installed on disc during inspection
- Very fast – 4 blades inspected at a time

Mechanical Engineering Books
Aerospace

- Aircraft manufacturers
- Engine Manufacturers
- Maintenance centers
- Space and defense

Carbon Composite

Fig 1.15

Faster inspection
- One array, not multiple transducers
- Dynamic depth focusing

Laser Weld

T-Joint Composite

Fig 1.16

Mechanical Engineering Books
Refinery and petrochemical Plants

- **Weld integrity**

- **Corrosion Mapping**

Daisy Array PA Probe for tube corrosion mapping

Pressure Vessel

- Cir-seam welds

- Long-seam welds
Specific Application

SCC (Stress Corrosion Cracking)

- Same side sizing for length and depth determinations
- 32 Element phased array probes in a pitch–catch configuration

Specific Application

Narrow Gap Weld Inspections
Specific Application

Military Tank – Road Arm

- Picture of broken road arms
- L-wave S-scan for detection and characterizing

Specific Application

Small Diameter Pipe Welds

Zonal - based

Volumetric - based
Chapter 2: Phased Array Ultrasonic Fundamentals

Huygens Principle

- In the description of the propagation of waves, we apply Huygens' Principle, according to which we assume that the every point of the medium that is reached by a wave, is the source of a new spherical wave (or a circular one when the wave is propagating on a surface). The envelope of these new spherical waves forms a new wave front.

- Huygens principle is the basis for
  - Wave Formation
  - Reflection and Refraction
  - Diffraction
  - Near Field & Far Field

- Phased Array beam is formed due to constructive interference of beam generated by individual elements.

Fig 2

Fig 2.1

Mechanical Engineering Books
Huygens–Fresnel Principle

- The Huygens–Fresnel principle (named after Dutch physicist Christian Huygens and French physicist Augustin-Jean Fresnel) is a method of analysis applied to problems of wave propagation both in the far-field limit and in near-field diffraction.

Fermat’s Principle

- Fermat’s principle or the principle of least time is the principle that the path taken between two points by a sound wave is the path that can be traversed in the least time. This principle is sometimes taken as the definition of a ray of light or sound travel.

- Fermat’s principle can be used to describe the properties of sound wave reflection, refraction etc.

- It follows mathematically from Huygens principle and is basis for Snell's law.
Interferences

- **Constructive and Destructive Interference**

- Ultrasonic waves interfere together and resultant waveform will be higher or reduced dependant on the 'phase' of the individual waves

- In conventional UT interference is contained within the Near Zone.

- In PAUT the constructive interference takes place until the 'FOCAL' point.

In phase
- i.e. red waves peak and through at same point.
- When summed the waves double amplitude.

90° out of phase
- Red waves now sum to form blue wave due to a mixture of constructive and destructive Interference.

Destructive Interference

180° out of phase or half a λ difference
- i.e. red waves peak and cross timebase totally opposite to each other.
- Therefore when summed they cancel each other totally.
Interference in UT & PAUT

- In Conventional probe, constructive and destructive interference zone is in near field.
- Defects located in near field shows either high amplitude or low depending on whether the defect is in which region.
- Defect that are in constructive zone shows high amplitude and defects in the destructive zone shows lesser amplitude.

- In Phased array Probe, each element generates ultrasound in the same manner as we have particles. However, each element is timed with some delay. Same as particles each elements produces spherical wavefront that interferes with other adjacent element wavefronts to produce constructive interference.
- As there are constructive interferences in near field, Phased arrays allow inspecting in the near field zone unlike conventional probes.

Phased Array Principle of Operation

**Principle of operation**

- The PA probe consists of many small ultrasonic elements, each of which can be pulsed individually.
- By varying the timing, for instance by pulsing the elements one by one in sequence along a row, a pattern of constructive interference is set up that results in a beam at a set angle.
Phased Array Probe

- A mosaic of transducer elements in which the timing of the elements' excitation can be individually controlled to produce certain desired effects, such as steering the beam axis or focusing the beam.

Basically, a phased-array is a long conventional probe cut into many elements.

Features of Phased Arrays

- Important feature of Phased Array technology
- Beam Steering & Beam Focusing
  - Phased array technology is the ability to modify electronically the acoustic probe characteristics which is performed by introducing time shifts in the signals sent to (pulse) and received from (echo) individual elements of an array probe
  - Application for detection is much the same as conventional UT, which means any UT technique for flaw detection and sizing can be applied using phased array probes
**Conventional Beam Steering**

**Conventional - Transmitter side**
- Beam Steering using conventional UT Probe
- Beam generated by Huygens principle
- Angled wedge results in delay during emission to generate angled beam

**Conventional - Receiver side**
- Beam Steering using conventional UT Probe
- Beam in wedge generated by Huygens principle
- Angled wedge results in delay on reception, so that only waves "in phase" yield constructive interference on crystal

| Steering is the resultant of combined zone delays from the angled wedge. |
| Combined zone delays are depended on respective angle of wedge. |

**Phased Array Beam Steering**

**Phased Array Transmitter side**
- Beam Steering using Phased Array Probe
- Beam generated by Huygens principle
- Delay introduced electronically during emission to generate angled beam

**Phased Array Receiver side**
- Beam Steering using Phased Array Probe (receiver)
- Delay introduced electronically during reception
- Only signals "satisfying" delay law shall be "in phase" generate significant signal after summation

| Steering is the resultant of electronic delay from individual elements. |
| Pattern (slope) of delay is dependent on the desired angle. |
Illustration of Beam Steering

For shear waves, the time delay pattern has a “slant” as shown here.

Focusing can be performed by using “parabolic” time delays (see previous slide), as well as the slant.

Delay Law on Individual Element

Fig 2.11

Fig 2.12
Focusing in Conventional Ultrasonic

- Focusing improves resolutions and sensitivity as the beam diameter in focusing is smaller than probe diameter at the focal point.
- Focusing can be achieved by using lens. Delay is obtained using curved wedges unlike slant/slope wedges for angle beam.

![Fig 2.13](image)

Phased Array Beam Focusing

- The beam focusing is obtained in phased array by delaying the excitation of elements in the center.
- Delay applied depends on the desired focal depth

![Fig 2.14](image)

![Fig 2.15](image)
Illustration - Beam Focusing

Beam shaping is performed by pulsing the elements with different time delays.

This picture shows the elements in the array, and the delay applied to each element.

These time delays (green histogram) generate a focused normal beam, from the symmetrical "parabolic" time delays.

Illustration - Beam Steering and Focusing

The picture shows the generated beams in very early stage, mid-stage, late stage and at focus.

For angling and focusing, we use a combined slant and parabola.
Beam Steering & Focusing

- large range of inspection angles (sweeping)
- multiple modes with a single probe

Fig 2.19

Focal Law

- A Focal law is the term given to a set of calculated time delays required to excite an array in a manner that will generate a wave front with predetermined direction and depth of focus. It is a combination of element delay, element number & element gain.
- Multiple angles or depths of focus require multiple focal laws typically generated within the phased array instrument.
- Manually calculating time delay is very cumbersome if not impossible. Powerful software and fast processors in phased array instrument does this job.
- Operator just needs to key in the desired focal depth and angle. Applying required focal laws is done by instrument.

Fig 2.20

Mechanical Engineering Books
Phase Shift or Delay Values in each element

- As learned in the previous slides, the beam steering and focusing is created by exciting individual element of the group with calculated delay.
- Calculated delay (amount of delay) on each element, which element to excite first and how many quantity of elements are excited depends on the required steering angles and focusing.
- We will learn some important aspects on which delay law applied are dependent.

Delay Values dependence on element pitch

Delay values increases as element size or pitch increases for same focal depth

Fig 2.21
Delay Value Dependence for probe on wedge

- Example of delay dependence and its shape for probe on wedge. In the above example probe has 16 elements and is placed on a 37° Plexiglas wedge (natural angle 45 degrees in steel).
- Delay has parabolic for natural angle i.e 45 degrees
- For angles smaller than natural angle delay increases from back towards the front of the probe.
- For angles greater than natural angle the delay is higher for the back, so front elements excited first.
- Delay value depends up on element position and also the refracted angle.

Fundamental of UT – Formula’s

- Velocity (mm/sec) = frequency (Hz) X Wavelength (mm)
- Time period (time of travel for 1 cycle)= 1/Frequency (Hz)
- Snells Law: \( V_1/\sin \theta_1 = V_2/\sin \theta_2 \)
- Near Field = \( D^2D/(4*\lambda) = D^2D*F/(4*V) \)
- \( \sin \theta = (1.2*\lambda)/D \)
Chapter 3: Phased Array Probes

General Requirements of PA probes

- Very low lateral mode vibration for reduced cross-talk amplitudes.
- Low value of quality factor
- High value of electromechanical coupling
- Higher SNR.
- Easy dice-and-fill technology for machining.
- Constant properties over a large temperature range
- Easy to match the acoustic impedance of different materials (from water to steel)
- Easy to apodize
Phased Array Probes

- Phased Array probes are made of piezo-composite which is uniformly oriented piezoelectric rods embedded in an epoxy matrix. The piezo-ceramic embedded in a polymer resin has 1-D connectivity (oscillating in one direction towards test specimen) while polymer has 3-D connectivity.
- Piezo-composite material developed in mid 80s in US were primarily for medical applications. They are fabricated using 1-3 structure.
- PZT in combination with polymer matrix has higher value of transmitting and receiving efficiency.

<table>
<thead>
<tr>
<th>1-3 PZT-polymer matrix Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT + Silicone rubber</td>
</tr>
<tr>
<td>PZT rods + Spurs epoxy</td>
</tr>
<tr>
<td>PZT rods + Polyurethane</td>
</tr>
<tr>
<td>PZT rods + REN epoxy</td>
</tr>
</tbody>
</table>

Advantages of 1-3 piezocomposite probes

- Very low lateral mode vibration; cross-talk amplitudes typically less than -34dB to 40dB.
- Low value of quality factor
- Increased bandwidth (80% to 100%)
- High value of electromechanical coupling
- Higher sensitivity and an increased SNR versus normal PZT probes
- Easy dice-and-fill technology for machining. Aspherically focused phased array probes and complex-shaped probes can be made.
- Constant properties over a large temperature range
- Easy to change the velocity, impedance, relative dielectric constant, and electromechanical factor as a function of volume fraction of ceramic material
- Easy to match the acoustic impedance of different materials (from water to steel)
- Reduction of the need for multiple matching layers
- Manufacturing costs comparable to those of an equivalent multiprobe system
- Possibility of acoustic sensitivity apodization
Matching layer and cable requirements

- The key point in matching layer requirements are:
  - Optimization of the mechanical energy transfer
  - Influence of pulse duration
  - Contact protection for piezocomposite elements (wear resistance)
  - Layer thickness of $\lambda/4$.

- The key point in a cable requirements are:
  - Low transfer (gain drop) loss & Low impedance ($50\Omega$, ideally)
  - Elimination/reduction of cable reflection (cable speed: $2/3$ of velocity of light)
  - Water resistance, Mechanical endurance for bending, mechanical pressure, accidental drops
  - Avoidance of internal wire twists.

- Key features of backing material are:
  - Attenuating of high amplitude echoes reflected back from the crystal face (high acoustic attenuation) (Mechanical Damping)

Types of Phased Array Probes

Typical Phased Array probes widely available

<table>
<thead>
<tr>
<th>Type</th>
<th>Deflection</th>
<th>Beam Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annular</td>
<td>Depth – z</td>
<td>Spherical</td>
</tr>
<tr>
<td>1-D Linear Planar</td>
<td>Depth, angle</td>
<td>Elliptical</td>
</tr>
<tr>
<td>2-D matrix</td>
<td>Depth, solid angle</td>
<td>Elliptical</td>
</tr>
<tr>
<td>2-D segmented annular</td>
<td>Depth, solid angle</td>
<td>Spherical / Elliptical</td>
</tr>
<tr>
<td>1.5-D matrix</td>
<td>Depth, small solid angle</td>
<td>Elliptical</td>
</tr>
</tbody>
</table>
Types of Phased Array Probes

- Annular
- Linear
- Daisy Array
- 1.5 D Matrix
- Segmented Annular
- 2-D Matrix

Probe element geometry

- 1D linear array
- 2D matrix
- 1D annular array
- 2D sectorial annular
1-D Annual Array

- Advantages
  - Spherical focusing at different depths
  - Very good for detecting and sizing small inclusions, normal beam or mirror applications

- Disadvantage
  - No steering capability
  - Difficult to program the focal laws
  - Require large aperture for small defect resolution

1-D Plan Linear Array

- Linear arrays are the most commonly used phased array probes for industrial applications

- Advantages
  - Easy design
  - Easy Manufacturing
  - Easy Programming and Simulation
  - Easy applications with wedges, direct contact and immersion
  - Relatively low cost
  - Versatile

- Disadvantage
  - Require large aperture for deeper focusing
  - Beam divergence increases with angle and depth
  - No skewing capability
1.5D Planar Matrix Probe

◆ Advantages
  ◆ Small steering capability (within +/- 10 degrees left and right)
  ◆ Elliptical focusing at different depths and different angles
  ◆ Reduces grating lobes amplitude.

◆ Disadvantage
  ◆ Complex design and manufacturing process
  ◆ Expensive
  ◆ Difficult to program the focal laws
  ◆ Require a large no. of pulser-receivers.

2-D Planar Matrix Probe

◆ Advantages
  ◆ Steering capability in 3-D
  ◆ Spherical or elliptical beam shape

◆ Disadvantage
  ◆ Complex design and manufacturing process
  ◆ Expensive
  ◆ Difficult to program the focal laws
  ◆ Require a large no. of pulser-receivers.
Other Types of Array Probes

DUAL-ARRAY PROBES:

- Consist of separate transmitter (T) and Receiver (R) arrays
- In side-by-side configuration, all considerations for conventional TRL probes remain valid:
  - Pseudo-focusing effect
  - Absence of interface echo
  - Improved SNR in attenuating materials

Phased Array probe nomenclature

Numbering System Used to Order Phased-Array Probes

For ordering probes, one would need to know probe identification and probe nomenclature used by the manufacturer.

For more information on probes refer to manufacturers catalogue.
**Phased Array Wedge**

Wedge delay ($D_W$) [μs] is the time of flight for specific angles in the wedge (full path). The computation is detailed in following figure.

For Weld examination most PA shear wave and longitudinal wave applications for weld inspections require probe mounted on wedges to optimize acoustic efficiency and also to minimize wear.

**Delay Difference in Wedge**

The focal law (difference in delay to reach the focal point) for each element is then calculated.

**Fermat principle:**

The actual path between two points taken by a beam of light (or sound) is the one that is crossed in the shortest time.

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**WEDGE PARAMETERS**

- Velocity in wedge ($v_w$)
- Wedge angle ($\omega$)
- Height of first element ($h_1$)
- Offset first element ($x_1$)

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**Mechanical Engineering Books**
Beam Deflection on Wedge

Fig 3.5

Phased Array wedge nomenclature
**Design Parameters of Phased-Array Probes**

**PROBE PARAMETERS**
- Frequency (f), wavelength (λ)
- Total number of elements in array (n)
- Total aperture in steering direction (A)
- Height, aperture in passive direction (H)
- Width of an individual element (e)
- Pitch, center-to-center distance between two successive elements (p)
- With OmniScan, array data is input electronically, and wedge number is input by operator.

**Characteristic of Linear Array – Active Aperture**

**Active Aperture**

The active aperture (A) is the total probe active length. Aperture length is given by formula:

\[ A = ne + g(n-1) \]

OR Simply = p x n

- A = active aperture (mm)
- g = gap between two adjacent elements (mm)
- n = number of active elements
- e = element width (mm)

**Active Plane**

Active Plane term is given to the axis of arrays along which beam steering and focusing capability can be achieved with variation of focal laws / delay laws. Linear arrays have only one active plane.

**Aperture depends on**
- Type of equipment module or no of pulsar's that can be used: 16:128 or 32:128
- Total No of elements in Probe (16, 32 or 64)
- No of elements chosen by operator
**Characteristic of Linear Array – Active Aperture**

**Elementary Pitch**
The elementary pitch $p$ [mm] is the distance between the two centers of adjacent elements:

$$p = e + g$$

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

**Element Width**
The element width $e$ [mm] is the width of a single piezocomposite element. The general rule is keep pitch $< 0.67\lambda$ to avoid grating lobes at large steering angles:

$$e < \frac{\lambda}{2}$$

**Maximum Element Size**
The maximum element size $e_{\text{max}}$ depends on the maximum refracted angle:

$$e_{\text{max}} < \frac{0.514\lambda}{\sin \beta_{\text{max}}}, \quad e_{\text{min}} > \frac{W_{\text{pass}}}{10}$$

Some probes are manufactured with pitch/element size larger than general design which are limited steering capability. Adjacent figure (data from Imasonic probe design) shows the relation between probe frequency and pitch.

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*Mechanical Engineering Books*
Characteristic of Linear Array – Passive Aperture

- Passive aperture (W) contributes for sensitivity and defect sizing.
- Maximum efficiency is obtained by \( W = A \).
- Passive aperture also affects beam diffracted pattern and beam width.
- Generally, PA probe designed \( W/p > 10 \) or \( W = 0.7 \) to 1.0 A.
- Linear array probe with large aperture will have deeper range focusing effect and narrower beam.
- Passive Plane is an axis perpendicular to Active plane in which no steering capability can be obtained.
- Beam is divergent in passive Plane.
- Height of Passive plane is much larger than the individual element width in the active plane or vice versa.

Beam Width

- Beam Width
  - Beam width is measured by -6dB drop for Pulse echo techniques of transverse amplitude echo-dynamic profile.
  - Beam width on active axis and beam length on passive axis is determined by
  - See adjacent Figures
  - Other formula for Beam dimension calculation
  - Beam Width = \( \lambda \times z / A \)
  - Narrow Beam width gives good lateral resolution.

Fig 3.9
Influence of passive aperture width on beam length (\( \Delta Y_{6dB} \)) and shape:
(a) deflection principle and beam dimensions;
(b) beam shape for \( W = 10 \)mm;
(c) beam shape for \( W = 8 \)mm, 5MHz shear wave, \( p=1 \)mm ; \( n=32 \) elements ; \( F=50 \)mm in steel

Fig 3.10
Resolution

- **Near Surface Resolution**
  - Near surface resolution is the minimum distance from the scanning surface where the reflector (SDH or FBH) has more than 6dB amplitude compared with decay amplitude from the main bang for a normal beam.

- **Far Surface Resolution**
  - Far surface resolution is the minimum distance from the inner surface where the phased array probe can resolve from a specific reflectors (SDH or FBH) located at a height of 1mm to 5mm from the flat or cylindrical back wall.

- **Axial Surface Resolution**
  - Axial resolution is the minimum distance along acoustic axis for the same angle for which two adjacent defects located at different depths are clearly resolved, displayed by amplitude decay of more than 6dB from peak to valley. Shorter pulse duration (highly damped probe and/or high frequency) will produce a better axial resolution.

- **Lateral Resolution**
  - Lateral resolution is the minimum distance between two adjacent defects located at the same depths, which produces amplitudes clearly separated by at least 6dB from peak to valley. Lateral resolution depends upon beam width or beam length. Depends upon effective aperture, frequency and defect location. **Narrow beam width produce good lateral resolution but poor axial resolution.**

Illustration of Resolution

- [Near Surface & Far Surface Resolution](Fig 3.11)
- [Axial Resolution](Fig 3.11)
- [Lateral Resolution](Fig 3.12)

Mechanical Engineering Books
Angular Resolution

- Angular resolution is the minimum angular value between two A-Scan where adjacent defects located at the same depth are resolvable

![Angular Resolution Diagram](image)

Probe Band Width (Damping)

- General guideline for ferrite materials and planar defect but not typically valid for austenitic or dissimilar material
  - Narrow Bandwidth (15-30%) – best for detection
  - Medium bandwidth (31-75%) – detection & sizing
  - Broad (wide) bandwidth (76-100%) best for sizing
- Pulse shape (duration) has direct effect on axial resolution (with fixed angle and stationary probe). For good axial resolution, reflectors should produce peak amplitudes separated by 6dB peak-valley
- PA Probes are typically broad bandwidth and provides high sizing performance and good detection. Also increases steering capability

![Probe Band Width Diagram](image)

Fig 3.14 Probe clarifications based on relative bandwidth
Key Concept

- **Phased arrays do not change the physics of ultrasound**

- PAs are merely a method of generating and receiving a signal (and also displaying images)

- If you obtain X dB using conventional UT, you should obtain the same signal amplitude using PAs.
Chapter 4: Beam Shaping and Beam Steering Capabilities

UT Phased Arrays
Principles and Capabilities

◆ OVERVIEW
	♦ Beam focusing
	♦ Beam steering
	♦ Array lobes
Design Parameters of Phased-Array Probes

Beam Focusing

- Is the capability to converge the acoustic energy into a small focal spot
- Allows for focusing at several depths, using a single probe
- Symmetrical (e.g., parabolic) focal laws (time delay vs. element position)
- Is limited to near-field only
- Can only perform in the steering plane, when using a 1D-array
- Near field length is dependent upon effective probe aperture, wedge used and the specific refracted angle generated
Beam Focusing

- Focused Beam Vs Unfocused Beam
  - Both in conventional UT and Phased Array UT focusing is limited to Near Field distance. (See formula in next page)
  - Focusing is required for increased sensitivity, increased resolution and better sizing.
  - Most of the conventional UT examination is performed after 1 near field and within 3 near fields i.e. in unfocused beam.
  - For conventional UT beam to focus at different location in the area of examination, different curved wedge are required, which makes impractical to test at different focusing.
  - Phased array UT allows focusing at different area by modifying the delay values electronically.

Beam Focusing

**UNFOCUSED BEAM:**

- Near-field and natural divergence of acoustic beam are determined by total aperture $A$ and wavelength $\lambda$ (not by number of elements)
- Near-field $N = \frac{A^2}{4 \cdot \lambda}$
- Divergence (half angle $\theta$, at $-6$ dB) $\sin \theta = 0.5 \cdot \frac{\lambda}{A}$
- Beam dimension (at depth $z$) $d = \frac{\lambda \cdot z}{A}$
- If $Z$ (focal depth) is not given consider $z$ is Near field then Beam dimension (at depth NF=z) $d = \frac{A}{4}$
Beam Focusing

The ultrasonic beam may be focused by geometric means only for \( F < N \)
A focused beam is characterized by the focusing factor or Focusing Power or normalized focus depth:

\[
K = \frac{F}{N}
\]

with \( 0 \leq K \leq 1 \) and \( F \leq N \), and \( F \) is the actual focal depth, \( N \) is Near Field

The focused beam may be classified as

- **Strong focusing** for \( 0.1 \leq K \leq 0.33 \)
- **Medium focusing** for \( 0.33 \leq K \leq 0.67 \)
- **Weak focusing** for \( 0.67 \leq K \leq 1.0 \)

Most of the industrial applications that work with focal beam use \( K \leq 0.6 \)

- **Focusing factor or power** \( (K) \) increases as the focal depth \( (F) \) decreases which is strong focusing
- **As Focusing power increases**, Depth of field decreases.

Focal Depth & Depth of Field

**Definition of focal depth and depth of field (focal length)**

- The distance along the acoustic axis where the maximum Amplitude response is obtained is **focal depth or depth of focus**
- The vertical height of the beam where maximum amplitude is Obtained when measured at 6dB drop method is **Depth of field**

- For \( S_a < 0.6 \), the depth of field, \( L_{6dB} = \frac{F_p}{D_{beam}} \), Beam diameter at -6dB drop = \( \frac{AF_p}{D_{beam}} \)
- Higher probe frequency produce narrower beam than lower frequency for same diameter
- Field depth and beam diameter is smaller for smaller \( S_a \)
- Constant lateral resolution over large UT range is obtained by having probes with different \( S_a \) or by using phased array probes with DDF feature.
- Beam width increases as the Focal depth and Beam angle increases
- Depth of field increases as Focal depth increases.
Different Types of Focusing in S-Scan

(a) projection S-scan is very useful for narrow-gap weld inspection; (b) true depth is useful for detection and sizing defects at a constant depth (for example, inner wall fatigue cracks); (c) half-path S-scan is the most commonly used S-scan; (d) focal plane S-scan is useful for detection of lack of fusion along the weld geometric preparation.

Effect of Aperture on Beam focusing and Beam Width

Increasing the number of elements or aperture will decrease beam width and also depth of field
Beam Steering

- Is the capability to modify the refracted angle of the beam generated by the array probe
- Allows for multiple angle inspections, using a single probe
- Applies asymmetrical focal laws
- Can only be performed in steering plane, when using 1D-arrays
- Can generate both L (compression) and SV (shear) waves, using a single probe

Beam Steering

- Steering capability is related to the width of an individual element of the array
- Maximum steering angle (at –6 dB), given by

$$\sin \theta_{st} = 0.5 \cdot \frac{\lambda}{e}$$

- Steering range can be modified using an angled wedge
**Element Size and Beam Forming**

Point A is ok because all rays are within elemental beam width.

Point B yields unexpected results because rays are outside elemental beam width.

Conclusion: The smaller the ‘e’, better for steering.

\[
\sin \theta = 0.5 \cdot \frac{\lambda}{e}
\]

**Phased Array Probe Selection**

- Depends on
  - Frequency
  - Element Width (e)
  - Number of elements (n)
  - Pitch (p)
Element Frequency

- Whatever applies in conventional approach applies for PA too!! - you can use same frequency as you use for conventional UT.
- In practice, Higher frequencies (an larger apertures) may provide better signal/noise ratio (due to tighter, optimized focal spot)
- Manufacturing problems occur at higher frequencies (>15MHz)

Element size (e)

- Element Size is key issue, As ‘e’ decreases
  - Beam steering capability increases
  - No. of elements increases rapidly
  - Manufacturing problems may arise (minimum size 0.15 to 0.20 mm)
- Limiting factors are often budget not physics or manufacturing.
Number of Element (n)

- No. of element is a compromise between
  - Desired physical coverage of the probe and sensitivity
  - As “n” value increases
  - Focusing capability increases
  - **Beam width decreases**
  - Steering capability increases
  - Electronic system capability decreases
  - Cost is higher.

Design Compromise for Sectorial and Linear Sector

- Sectorial Scan: Different focal laws applied to same group of elements. Smaller elements needed to maximize steering capability smaller no. require small pitch (<1mm)
- Linear scan: same focal laws multiplexed through many elements. Physical coverage important. Greater no. to cover physical area- larger pitch (1mm)
Pitch / Aperture

- Number of active elements per firing
- Max. Aperture = Pitch X No. of elements
- For high steering range, p must be small
- For good sensitivity, large fresnel distance, good focusing coeff >>> ‘A’ must be large
- Challenge is to find best compromise in terms of ratio of A/p

Element Positioning (p)

- Typical arrays positioned side by side with acoustic insulation gap.
- Grating lobes usually be minimized by selecting suitable element width
- Sparse array with larger gaps between elements may reduce cost. The stronger grating lobes produced by sparse array may be reduced by using random arrangements of the elements.

- **Dead elements Create** Large gaps which may cause strong grating lobes
Main Lobe, Side Lobes, Grating Lobes

- **Main Lobe**
  - Acoustic Pressure directed in the direction of programmed angle

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

- **Grating Lobe**
  - Grating lobes are produced by acoustic pressure due to even sampling across the probe elements. Location depends upon frequency and pitch.

- **Probe design optimization is obtained by**
  - Minimizing the main lobe width.
  - Suppressing the side lobes
  - Eliminating the grating lobes

\[ \beta_{grating} = \sin^{-1}\left(\frac{m\lambda}{p}\right) \]
\[ m = \pm 1, \pm 2, \pm 3, \ldots \]

**Fig 4.6**

Grating Lobe Dependence on Wavelength

- **Rule of thumb:**
  - Element Size (e) ≥ Wavelength --- Grating lobes occur
  - Element size (e) < ½ wavelength --- no grating lobes
  - Element Size (e) > ½ wavelength to 1 wavelength --- grating lobes depend on steering angle
Grating Lobe Dependence on Pitch

Influence of pitch $p$ (for $A = $ fixed):

- If $p \downarrow$, or $n \uparrow$
  then lobe distance $\uparrow$
  and lobe amplitude $\downarrow$

**Solution**: Design array lobes out.

![Grating Lobes Animation](variation of pitch and no. of element)

Array Lobes

- Grating Lobe Amplitude
- Grating Lobe Damping
- Grating Lobe Frequency
Reducing Grating Lobes

Grating lobes may be reduced though:

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

Beam Apodization

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

- Side lobes
  - [Reducing the side lobes (cant eliminate) by apodization](#)
Chapter 5: Phased Array Scanning

Type of Beam Scans

- For electronic scans, arrays are multiplexed using the same Focal Law.
- For sectorial scans, the same elements are used, but the Focal Laws are changed.
- For Dynamic Depth Focusing, the receiver Focal Laws are only changed in hardware.
Sectorial Scanning

Sectorial Scanning (S-Scan, azimuthal scanning or angular scanning: In sectorial scan beam is swept through an angular range for a specific focal depth using same elements. Other sweep ranges with different focal depths may be added, the angular sectors could have different sweep values. The start and finish angle range depends on probe design, associated wedge, and type of wave, the range is dictated by laws of physics.

Electronic Scanning

- Electronic Scanning (E-Scan, Linear Scanning) – Same focal law and delay is multiplexed across a group of active elements.
- Scanning is performed at a constant angle and along the phased array probe length by group of active elements called virtual probe aperture (VPA) (which is equivalent to conventional ultrasonic transducer performing raster scan for corrosion mapping or shear wave inspection of weld.
- When wedge is used focal laws compensate for different time delays inside wedge.
- This scanning is very useful in detecting lack of side wall fusion or inner surface breaking defects
- Scanning extent is limited by:
  - number of elements in array
  - number of “channels” in acquisition system
- It is desirable to have large no. of elements and more available channels in instrument to create more beams (VPA) to sweep maximum area of product inspected
Electronic Scanning

Fig 5.5

Electronic Scanning for welds

Fig 5.6

Aperture size 16 elements
Total no. of elements 32
No. of beam 17 (32-16+1)
This setup needs 4 scans at different standoffs or offset for complete coverage of weld

Aperture size 16 elements
Total no. of elements 60
No. of beam / VPA = 45 (60-16+1)
This setup needs just one scan at one standoff or offset for complete coverage of weld

VPA mean 1 beam = (total elements selected – aperture size)+1

Mechanical Engineering Books
**Depth Focusing**

- Dynamic Depth focusing (DDF) Scanning is performed with different focal depths. This is performed by transmitting a single focused pulse and refocusing is performed on reception for all programmed depths of required range.

**Multi Group Scanning**

- The phased-array technique allows for almost any combination of processing capabilities:
  - Typical example of scanning in groups
    - focusing + steering
    - electronic scanning + Sectorial + focusing
    - electronic scanning + focusing

Fig 5.7
Parabolic pattern gives beam focusing: The delay will focus the beam at 0 degree. End elements are fired first followed by next in sequence.

Slant Pattern gives beam steering: The delay will steer the beam in direction from left to right.

Slant and Parabola pattern gives focussing and steering: The beam is focussed and steered in direction from left to right.

Scanning Tubular Products

Scanning Welds
Scanning Methods

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

The inspection can be:

- Automated: The probe carrier is moved by a motor-controlled drive unit; (with encoder)
- Semi-automated: The probe carrier is moved by hand or by using a hand scanner, but the movement is encoded and data collected; or
- Manual (or time-based, sometimes called free-running): the phased array probe is moved by hand and data is saved, based on acquisition time(s), or data is not saved.

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

## Type of Scanning Pattern

<table>
<thead>
<tr>
<th>Scanning Pattern</th>
<th>Number of axes</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>1</td>
<td>All data is recorded in a single axial pass</td>
</tr>
<tr>
<td>Bi-directional</td>
<td>2</td>
<td>Acquisition is performed in both scanning directions</td>
</tr>
<tr>
<td>Unidirectional</td>
<td>2</td>
<td>Acquisition is performed in only one scanning direction; scanner is moved back and forth on each scanning length.</td>
</tr>
</tbody>
</table>

Mechanical Engineering Books
Linear Scan Pattern

A linear scan is one-axis scanning sequence using only one position encoder (either scan or index) to determine the position of the acquisition. The linear scan is unidimensional and proceeds along a linear path. The only settings that must be provided are the speed, the limits along the scan axis, and the spacing between acquisitions, which may depend on the encoder resolution. Linear scans are frequently used for such applications as weld inspections and corrosion mapping. Linear scans with electronic scanning are typically an order of magnitude faster than equivalent conventional ultrasonic raster scans. Linear scans are very useful for probe characterization over a reference block with side-drilled holes.

Electronic scanning 45° SW

Fig 5.12 Linear scan pattern for probe characterization

Uni & Bi-Directional Pattern

Bidirectional Scan
In a bidirectional sequence, data acquisition is carried out in both the forward and backward directions along the scan axis.

Unidirectional Scan
In a unidirectional sequence, data acquisition is carried out in one direction only along the scan axis. The scanner is then stepped for another pass.
Beam Skew Directions

Beam Directions

The beam direction of the phased array probe may have the directions showing in Figure 6-5 compared with the scan and index axes. These directions are defined by the probe skew angle. Usually scan orientations are termed as Skew

![Diagram of beam skew directions](image)

Fig. 5.14 Probe position and beam direction related to scan and index axis. Skew angle must be input in the focal law calculator.
Selection of parameters

- Selection of parameters depends on
  - Equipment and Probe
  - Material type, thickness, weld configuration, accessibility
  - Code/Standards Specific requirements (such as workmanship criteria or code case).
Considerations – Equipment & Probe

✦ Essential parameters to consider
  ✦ Equipment Configuration (16:128 or 32:128 etc), 128 is the total no of channels out of which 16 or 32 pulsers can be used at a time.
  ✦ Type of probe (elements quantity, pitch etc)
  ✦ Scanning options (manual or Automatic or semi-automatic)
  ✦ Line scan or raster scanning (or multiple line scan)
  ✦ one group or multi group (availability of features in the equipment)
  ✦ Speed of inspection (availability of PRF features in the equipment)

Considerations - Weld Examination

✦ Essential parameters to consider
  ✦ Material Type
  ✦ Part thickness
  ✦ Weld bevel angle & configuration
  ✦ One side of two side access (on the either side of weld)
Considerations - Codes & Standards

◆ Code requirements for examination
  ◇ Calibration requirements
  ◇ Parameter selection.

◆ Acceptance criteria
  ◇ Workmanship
  ◇ ECA criteria

Calibrations

◆ Velocity calibration
  ◇ The velocity calibration will fine tune the velocity to that of the calibration block. It will require two reflectors of the same size at two different known depths.

◆ Wedge Delay
  ◇ Wedge Delay will enter compensation for the travel of the beams through the wedge medium and account for the various exit points.

◆ Sensitivity
  ◇ Sensitivity calibrations equalize the sensitivity (amplitude) to a given reflector through all the angles. It’s a unique feature of PAUT.
  ◇ This will insure no matter what angle the reflector is seen at the % FSH is the same for rejection or detection purposes as well as for the amplitude based color coded imaging selections.
Calibrations

- **Encoder calibration**
  - Used to determine the resolution of encoder by physically moving the encoder for a known distance.
  - *It is recorded in steps/mm or pulse/mm.*

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

Preparing a Technique / Scan Plan

- Much of the parameter selection similar to the conventional UT. Criteria remains same!
- Some of the information that you have to consider from Conventional UT, which is most appropriate.
  - Frequency selection (based on material type and sensitivity needed)
  - 60 degree UT beam for LOF for 30 degree bevel.
  - 70 degree UT beam for root examination
  - 45 degree UT beam for OD and HAZ zone
Preparing a Technique / Scan Plan

- Phased array UT is most often primarily used for its speed and detectability...but improperly applied will lead to lesser detectability than conventional UT.
- When preparing a technique/Scan Plan, important consideration to be taken care of:
  - Coverage (weld and HAZ area)
  - Detectability with LOF

- Bevel angle (the beam incident angles BIA for beam angles you have chosen shall be within 10 degree and better still if within 5 degrees)
- Beam coverage, if you are using line scan ensure the probe positioning is such that all beams cover the weld notwithstanding the above point.
- In some cases you may have to examine the weld with 2 different probe positions!!!
- If once side access, the detectability to fusion defects on the opposite side to probe position is lesser and in thicker materials you may miss.
- If accessibility is not available, you may ground flush the weld for good detectability.
- Of course radiography too has limitation with fusion defects!!!

Probe Position for Linear Scanning

Shown 90, 270 similar

Only for LOF detection
**Probe Position for Sectorial Scan**

Shown 90, 270 skew similar

Coverage and Detectability of LOF in lower area and all other mis-oriented defects

**Technique Development**

- Code and Standard requirements for Weld Examination
- Part Details
  - Part thickness
  - Bevel Angle / weld preparation
  - Material
  - Part Geometry (Plate/Pipe)
  - Accessibility
- Technique Selection
  - Scan Type (Sectorial / Linear)
  - Single Group / Multi-group
  - Refracted angles (for sectorial angle range)
  - Angle Resolution
  - Focusing Type & Focal Depth
Technique Development

- **Probe Details**
  - Probe Type
  - Wedge Type
  - Quantity of elements
  - Start and end element
  - Probe Offset (Index Offset)
  - Pulser / Receiver
  - Filters

Technique Development

- **Scan Details**
  - Scan Offset
  - Scan Resolution
  - Scan Area
- **Encoder Details**
  - Encoder Type
  - Encoder Resolution
- **Calibration**
  - Velocity
  - Wedge
  - Sensitivity (ACG)
  - TCG
  - Encoder
Chapter 7: Data View and Display

Basic Views in Phased Array Ultrasound inspection

- There are 5 basic data views in phased array ultrasound inspection

<table>
<thead>
<tr>
<th>View</th>
<th>Axis content</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-scan</td>
<td>Amplitude vs Ultrasound</td>
</tr>
<tr>
<td>B-scan</td>
<td>Ultrasound vs Scan (side view)</td>
</tr>
<tr>
<td>C-scan</td>
<td>Scan vs Index (top view)</td>
</tr>
<tr>
<td>D-scan</td>
<td>Ultrasound vs Index (front view)</td>
</tr>
<tr>
<td>S-scan</td>
<td>Ultrasound vs Profile (projected distance, depth, and reflected angles)</td>
</tr>
</tbody>
</table>
A-Scan

• Rectified A-Scan
  ♦ 2-D view with ultrasound path on horizontal axis and amplitude on vertical axis.
  ♦ Ultrasound path is measured in mm, inches or time of flight and amplitude in percentage of FSH (Full screen height)
  ♦ Ultrasonic path may be represented in half path, true depth, full path

• Un-Rectified A-Scan
  ♦ 2-D view with ultrasound path on horizontal axis and amplitude on vertical axis
  ♦ Ultrasound path is measured in mm, inches or time of flight and amplitude in percentage of FSH (Full screen height)
  ♦ Ultrasonic path may be represented in half path, true depth, full path.

B-Scan

• 2-D view of ultrasound data display with scanning length as one axis and ultrasound path as other axis. Length and depth of defects will be known.
• Position of displayed data is related to encoder position at the moment of acquisition.
• If ultrasound path is in depth and refracted angle is included, B-Scan corresponds to side view or cross section of the part over scanning lines
• B-Scan images are particularly useful to analyze root defect.
C-Scan

- 2-D view of ultrasound data display with scanning length as one axis and index length on the other axis.
- Position of data displayed data is related to the encoder positions during acquisition.
- Maximum amplitude for each point (pixel) is projected on the scan-index plan.
- C-Scan is called top or cross sectional view (Show below is Corrected C-Scan)
- C-Scan uncorrected display with scanning length on one axis and refracted angles on another is a display on omni-scan C-Scan.

D-Scan

- 2-D view of ultrasound data display with ultrasound in one axis and index length on the other axis.
- If ultrasound path is corrected for angle and units are in true depth, the D-Scan represents end view of inspected part.
S-Scan

- 2-D view of ultrasound data that links the phased array probe features (ultrasound path, refracted angle, index, projected distance to the reflector)
- One of the axis is index and another is ultrasound path in (True depth)
- Start to finish angles are represented
- If ultrasound path is in half path, S-Scan is called uncorrected

![Display Axis in Omni-Scan](image)

- A Scan – amplitude Vs True Depth (or sound path)
- B Scan – Scan Axis Vs True Depth
- C Scan – Angle Vs Scan Axis
- S Scan – Index axis Vs True Depth

- A Scan displays data acquired by one focal law (angle) at a time (linked to the angle cursor in S Scan)
- B Scan – displays data acquired by one angle (linked to angle cursor in S & C Scan) for all probe position in the scan axis
- C Scan – displays data acquired by all angles for probe position in all the scan axis (contains all data)
- S Scan – displays probe position data (linked to scan cursor in B or C Scan) acquired by all the angles in the sector or linear scan
Imaging – Linear Electronic Scan

- By using the electronic scanning capability of the phased array technology, imaging becomes possible without mechanical movement.
- Arrays are multiplexed using the same focal law and the resulting A-scan of each beam is color-encoded and displayed in a linear S-scan.

A linear electronic scan can also be performed with a steering angle (15° in the image below).
Imaging – Sectorial Scan

Beams are not infinitely small.

Need to consider beam width, and maybe plot beam profile.

Remember S-scans etc. are just stacked A-scans.

Fig 7.9

Corrected and Uncorrected Image

B-scans, C-scans and S-scans can be “true depth” or uncorrected.

Check.

Fig 7.10
Chapter 8: Instrument Features and Digitization Principles

Basic Component of PAUT

The main components required for a basic scanning system with phased array instruments are presented in the following figure.

Basic components a phased array system and their interconnectivity
**Block Diagram of PA Instrument**

**Fig 8.1**

**Beam Forming and time delay for pulsing and receiving multiple beams (same phase and amplitude)**

---

**Main Instrument Features**

*Table 7-1* Main ultrasonic features of phased array instruments

<table>
<thead>
<tr>
<th>General</th>
<th>Pulse-Receiver</th>
<th>Digitizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>Voltage</td>
<td>Digitizing frequency</td>
</tr>
<tr>
<td>Ultrasonic start</td>
<td>Pulse width</td>
<td>Averaging</td>
</tr>
<tr>
<td>Ultrasonic range</td>
<td>Rectification</td>
<td>Repetition rate (PRF)</td>
</tr>
<tr>
<td>Velocity</td>
<td>Band-pass filters</td>
<td>Compression</td>
</tr>
<tr>
<td>Wedge delay</td>
<td>Smoothing</td>
<td>Acquisition rate</td>
</tr>
</tbody>
</table>

The features might be found under different tabs, depending on instrument and software version.
Pulser / Receiver

- Maximum voltage depends on frequency (crystal thickness) and element pitch
- Lower the voltage, life of probe increases and no extra cooling needed
- Low voltage can be compensated with increasing gain
- Excitation of an array is controlled by pulse voltage and time delay

Fig 8.2 Maximum voltage dependence on frequency (left) and on pitch (right).

Pulser Width Duration

- **Pulse width** refers to the time duration of high voltage square pulse used to excite the transducer element.

- Calculated by formula based on probe center frequency.

\[
PW_{\text{pulser}} \times f_c = 500 \text{ (in ns)}
\]

- Software in equipment optimizes this parameter based on \( f_c \) or else need to be calculated based on the above formula.

Fig 8.3 Pulser pulse width dependence on probe center frequency
Time Frequency Response Features

- Pulse Duration (µs) : Pulse duration is the time of flight value of the radio frequency signal amplitude from a specific reflector (generally a back-wall) cut at -20dB (10%) from positive to negative maximum values.

- Pulse Length is the value in millimeters or inches of the pulse duration for a specific type of material and type of wave.

![Fig 8.4 Pulse Duration and Pulse Length](image)

\[ \Delta L_{-20 \text{ dB}} = \nu \Delta \tau_{-20 \text{ dB}} \]

Signal to Noise Ratio

- Signal to noise Ratio (SNR) is given by
  \[ \text{SNR (dB)} = 20 \log_{10} \left( \frac{A_{\text{defect}}}{A_{\text{noise}}} \right) \]
- Acceptable SNR value is 3:1
- Averaging improve SNR but in PA it will increase file size and reduce scan speed. Hence for most application averaging is kept at 1 (More about averaging will be learned in digitization chapter)

![Fig 8.5 Signal to Noise Ratio](image)
Band Pass filter

- **Choose Band Pass filter** according to probe center frequency
- Actual choice depends on beam spread and attenuation and beam path.
- Best solution is to try different filters to optimize the image.
- HP Filter is set at 0.5 X Probe Frequency and LP Filter is set at 2 times the Probe frequency.
- If high pass filter is selected wrongly, then it will leads to **missing detection of defects** as defect indication would return with slightly lesser frequencies than generated.

![Band Pass filter diagram](image)

Smoothing

- **Smoothing** is electronic feature to create an envelope over the rectified signal for reducing the amplitude error.
- Provides better display of crack tip detection, reduces the digitizing frequency and keeps vertical linearity errors at low values (less than 2 to 5%).
- Improves the readability of the display.

![Smoothing diagram](image)
**Signal Averaging**

- Averaging is the number of samples (A-Scans) summed for each acquisition step on each A-Scan displayed.
- Averaging increases the SNR by reducing random noise.
- Averaging function reduces acquisition speed.

**Digitization**

- Need for digitization:
  - To have a permanent record of data for re-analysis and other reasons.
  - Compare the result with previous inspection which helps in maintenance operations of life assessment of plant or equipment.
  - Images are digitized and stored in static form (freeze option in many conventional instrument) or dynamic form (in real time as indications are formed on the screen).
  - Sending results to far consultants to analysis and receive the advise / consulting without having time and money to spend in travelling.
**Digitizer**

- Key Parameters of digitizer
  - Frequency (Digitizer)
  - Processor (no. of bits or amount of information that can be handled)
  - Averaging
  - PRF
  - Acquisition Rate
  - Soft Gain

**Analog to Digital Conversion (ADC)**

- Ultrasonic signals received are electrical signal represented in Amplitude Vs Time.
- These signals are converted to digital by ADC
- Whether single or multi-channel, the continuously varying received analog output is sampled to create a discrete digital sequence that is sent to the digital signal processor for manipulation.

![Diagram](image)
Function of digitizer – Time Axis

- Digitizer operate at frequency which converts data at an interval. For analog signal to convert to digital by digitizing the time axis
  - A continuous time analog signal has to be converted into a sequence of discrete time signals, represented by a sequence of numbers by periodic sampling.
  - The sampling frequency has to be greater than the bandwidth of the signal being sampled.
  - According to the Nyquist Sampling Theorem, for a correct representation of a digitized signal, the sampling frequency has to be at least twice as high as the bandwidth.
  - It is recommended that digitizer frequency is at least 5 times the probe central frequency to reduce the amplitude error to within 10%.

$$\text{Error} \% = \left(1 - \frac{R}{\sqrt{1+R^2}}\right) \times 100$$

Where R is the ratio of Digitizer Frequency to Probe Central Frequency.

Under sampling

![Diagram showing under sampling](image)

Fig 8.10
Aliasing Effect

- The Nyquist theorem states that a signal must be sampled at a rate greater than twice the highest frequency component of the signal to accurately reconstruct the waveform; otherwise, the high-frequency content will alias at a frequency inside the spectrum of interest (passband).
- An alias is a false lower frequency component that appears in sampled data acquired at too low a sampling rate. The following figure shows a 5 MHz sine wave digitized by a 6 MS/s ADC. The dotted line indicates the aliased signal recorded by the ADC and is sampled as a 1 MHz signal instead of a 5 MHz signal.

Sampling rate Calculation

- If a digitization frequency is 25MHz
  - Which means 25 million samples per 1 sec
  - Or we can write as 25 samples per 1 micro sec
  - Or we can otherwise write as 1 sample per 0.04 micro sec
- Now, please calculate the sampling rate for 45MHz, 70MHz and 150MHz
Calculating no. of samples

- No. of samples depend on the time required for one wavelength (i.e., we call as no. of samples per one time period)
- If you divide Digitizer Frequency by probe Frequency you will get no. of samples
- Calculate the no. of samples for
  - Probe frequency of 5 MHz at digitization rate of 50 MHz, 75 MHz, and 125 MHz
  - Probe frequency of 10 MHz at digitization rate of 40 MHz, 65 MHz, and 110 MHz

Function of digitizer - Amplitude

- For analog signal to convert to digital by
  - Digitizing the Amplitude
    - Signal amplitude is quantized into a sequence of finite precision samples before signal processing.
    - The precision or quantized error depends on no. of amplitude quantization levels. The quantization error is represented as additional noise signals.
    - Part (a) will have 2^8 or only 8 levels of amplitude granularity resulting in the digital representation illustrated in part (b), with its associated quantization error in (c). Parts (d) and (e) illustrate the case for 8 bit quantization note the decrease in quantization error from 0.2 to <0.005 for the 8-bit case. The effect of quantization error on the signal retrieval capabilities of a instrument can best be understood in terms of loss in the system's dynamic range.
    - Stated differently, the dynamic range of the 3-bit system is approximately 18 dB, while that of the 8-bit is 48 dB. That means that if the signal of interest is below that value it can never be retrieved simply because it was never sampled properly in the first place.

For Pulse Echo (FWRF), the 8-bit digitizer steps are 0 to 255 and for RF waveform -127 to +128
Digitizer - Amplitude

12 bit digitizers provide better resolution and signal to noise than 8 bit. However, file size is increased.

Calculation of Dynamic Range

- For 8 bit digitizer $2^8 - 256$ Levels
  \[ dB = 20 \log_{10} \left( \frac{256}{1} \right) = 48 \text{dB} \]

- For 10 Bit Digitizer $2^{10} - 1024$ levels
  \[ dB = 20 \log_{10} \left( \frac{1024}{1} \right) = 60 \text{dB} \]
**Compression**

- Compression is reduction in the number of sampled data points based on position and maximum amplitude. Compression reduces file size without compromising on defect detection.
- In omni-scan compression factor is automatically selected based on selected range whereas in Focus LT, user need to specify otherwise you will not able to adjust the range to required value.
- Check this out practically!!!

![Fig 8.14 Compression by a factor of 4:1 of an A-Scan](image)

**Pulse Repetition Rate**

The repetition rate (PRF, or pulse-repetition frequency) is the firing frequency of the ultrasonic signal. PRF depends on averaging, acquisition time, delay before acquisition, gate length, processing time, and the update rate of the parameters. In general, the PRF should be set as high as reasonable, ensuring that any ghost echoes are out of the acquisition range.

PRF depends on ultrasonic path and averaging, according to the following formula:

\[
PRF < \left( \frac{1}{(\text{start} + \text{range})} \right) \times \text{averaging}
\]

Where start and range are time-of-flight values (in seconds) of the ultrasonic inspection window.
Effect of PRF

- PRF is rate of voltage pulses transmitted from pulser to transducer (remember this is not probe frequency!!!!!!!)

- Selecting low PRF results in loss of data or missing scan data which are caused due to high scan speed, wide beam angles chosen, high resolution, low communication speed

- Increasing PRF too high results in ghost or phantom signals

Mechanical Engineering Books
Soft Gain

- Use of soft gain is only available with tomoview software (analysis software), which allows to adjust gain in analysis has following advantages:
  - Eliminates need of another channel with increased gain.
  - In 12 bit data dynamic range is increased by 24 dB compared to 8 bit. By increasing soft gain, low amplitude signal is properly displayed without distortion.
  - Improves the image quality
  - Allows recording with low hard gain.

![Example of 8-bit (left) and 12-bit (right) use of soft gain in crack sizing. Dynamic range is increased by 24 dB for 12-bit soft gain, without A-scan signal distortion.](image)

Saturation

Saturation is an electronic phenomenon inherent in the phased array technology. Within a single phased array probe, the different elements of a virtual aperture contribute differently to the final signal. Some elements can deliver a weak signal, while others transfer a very high amplitude signal above 100%. When at least one element receives an amplitude signal higher than 100% the signal from that particular element is said to be saturated because the electronic circuit cannot deliver a signal amplitude greater than 100%. When this happens, the final signal derived from the sum of the different elements is also called saturated.

<table>
<thead>
<tr>
<th>Element</th>
<th>Amplitude (%)</th>
<th>GAIN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.0</td>
<td>12.0</td>
</tr>
<tr>
<td>1</td>
<td>10.0</td>
<td>20.0</td>
</tr>
<tr>
<td>2</td>
<td>15.0</td>
<td>29.9</td>
</tr>
<tr>
<td>3</td>
<td>20.0</td>
<td>39.9</td>
</tr>
<tr>
<td>4</td>
<td>30.0</td>
<td>59.9</td>
</tr>
<tr>
<td>5</td>
<td>40.0</td>
<td>79.8</td>
</tr>
<tr>
<td>6</td>
<td>50.0</td>
<td>99.8</td>
</tr>
<tr>
<td>7</td>
<td>40.0</td>
<td>79.8</td>
</tr>
<tr>
<td>8</td>
<td>30.0</td>
<td>59.9</td>
</tr>
<tr>
<td>9</td>
<td>20.0</td>
<td>39.9</td>
</tr>
<tr>
<td>10</td>
<td>15.0</td>
<td>29.9</td>
</tr>
<tr>
<td>11</td>
<td>10.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Sum amplitude</td>
<td>25.5</td>
<td>51.0</td>
</tr>
</tbody>
</table>
**Saturation**

Fig 8.18

In the OmniScan phased array instrument, the gate blinks as soon as one element is saturated, advising the user that the signal amplification is no longer linear.

Fig 8.19

Influence of saturation on final amplitude signal for 11 elements
At more than 8 dB of gain, some elements are saturated and the final amplitude no longer corresponds to the expected amplitude.

**Effect of parameters on scanning speed**

- 1 focal law = 1 channel
- 1 channel is subdivided into no. of active elements and each active element has individual delay
- So 1 pulse fro PRF is split into no. of active elements with associated delays.
- Using swept angle each point of resolution requires an individual A-Scan (for scan of 30 to 70 degrees with desired resolution of 1 degree, 41 A-Scans are required
- If collection rate is one swept beam per mm, 41 A-Scans per sweep requires pulser to run for 41 times the scan speed measure in mm/Sec, i.e. 41X150mm/sec = 6150 pulses per second (this is minimum PRF)
PRF and SCAN Speed

- As per previous example 6150 pulses per sec i.e. PRF = 6150Hz
- If you use averaging of 16, then the no. of pulses increases by 41x16x150mm/sec = 98400 pulses per sec!!!!!! Don’t you think this is exorbitant value!!!!!! Impossible to have this minimum PRF!!!!
- So what should you do:
  - Reduce averaging
  - Reduce sweep angle resolution
  - Reduce beam sweep (no. of angles)
  - Reduce scan speed
  - Reduce sweep range

Schematic Representation of Dynamic Depth Focusing

DDF is an excellent way of inspecting thick components in a single pulse. The beam is refocused electronically on its return.
**Dynamic Depth Focusing**

**DDF Advantages**

DDF has the following advantages:

- The depth-of-field generated by an optimized DDF is improved by a factor of four in practical applications with respect to standard focusing.
- The beam spot produced by DDF is always as small as the one produced by standard focusing, or smaller.
- The use of DDF creates very small beam spreads. Half angles as small as 0.30 and 0.14 degrees were obtained using linear- and annular- array probes.
- DDF diminishes the beam spread without altering the dimensions of the beam obtained with the standard phased array.
- The SNR$_{DDF}$ is greater than the SNR$_{SPAF}$.
- File size is greatly reduced because only one A-scan is recorded at each mechanical position.
- Effective PRF is increased because only one A-scan is needed to cover a long sound path instead of multiple pulses from individual transducers.
Factor that Affect Acquisition Speed

Factor affecting the acquisition speed

<table>
<thead>
<tr>
<th>Factor</th>
<th>Changing</th>
<th>Acquisition rate changing</th>
</tr>
</thead>
<tbody>
<tr>
<td>UT range</td>
<td>Increases ↑</td>
<td>Decreases ↓</td>
</tr>
<tr>
<td>Averaging</td>
<td>Increases ↑</td>
<td>Decreases ↓</td>
</tr>
<tr>
<td>Repetition rate (PRF)</td>
<td>Increases ↑</td>
<td>Increases ↑</td>
</tr>
<tr>
<td>Digitizing frequency</td>
<td>Increases ↑</td>
<td>Decreases ↓</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>Increases ↑</td>
<td>Decreases ↓</td>
</tr>
<tr>
<td>Transfer rate</td>
<td>Increases ↑</td>
<td>Increases ↑</td>
</tr>
<tr>
<td>Number of samples</td>
<td>Increases ↑</td>
<td>Decreases ↓</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>Increases ↑</td>
<td>Increases ↑</td>
</tr>
</tbody>
</table>

The following relationship must be satisfied:

- \[ \text{Acquisition rate} > \frac{\text{Scanning speed}}{\text{Scan axis resolution}} \]
- \[ \text{Acquisition rate} < \frac{\text{PRF}}{\text{Number of focal laws}} \] (if PRF is identical for all A-scans)
Chapter 9: Data Analysis

Phased Array Analysis on Omniscan MXU

In addition to the calibration requirements and scan plan requirements, code compliance also requires accepting or rejecting welds based on their amplitude compared to the reference standard, or their characterization of flaw type stated an unacceptable no matter the length and height (Typical of cracks and lack of fusion in some codes).

When the following parameters are known, a weld flaw can be interpreted as acceptable/rejectable to any of the codes in use today such as ASME, AWS, API, or similar.

For some of the codes, only one or two of these parameters are necessary to make a decision.

- The Depth of the flaw
- The Height or “Thru Wall Dimension of the Flaw
- The Type of flaw (Slag, Porosity, Crack, etc)
- The Location of the flaw within the weld volume (ID connected, Embedded, Centerline, etc)
- The Length of the flaw
- The Amplitude of the flaw compared to a reference standard
Phased Array Analysis on Omniscan MXU

In determining if a signal is a flaw, geometric reflectors from the ID or weld crown, or a non-relevant indication, the following factors are considered in descending order of importance.

- The Location of the flaw within the weld volume (Embedded, ID or OD connected, centerline of the weld, etc)
- The A-scan characterization of the flaw
- Was the flaw detected on both sides of the weld or not?
- Was the flaw detected on both the PA and TOFD channels?

The Phased Array inspection techniques combined with TOFD channels greatly assist the operator in making this determination for all the reasons above.

No single piece of information should be weighted more heavily than location within the weld volume when determining flaw type.

---

Phased Array Analysis on Omniscan MXU

- Knowledge of the weld process and bevel geometry is critical to the inspection. Example: When evaluating data on weld processes that do not produce slag such as Tungsten Inert Gas (TIG), you can eliminate slag from your list of possible defects.

  Example: Mechanized Inert Gas (MIG) is especially prone to porosity and volumetric flaws analyzed in the TOFD channels and PA channels are more likely to be characterized correctly if the process is known to the operator and weighted more heavily when determining flaw type.

- One of the critical parameters in these inspections is keeping the constant gap between probe position and weld centerline. This is made worse when the weld centerline is not where you think it is. For wide weld crowns it is sometimes necessary to mark a weld reference a fixed distance from the weld centerline as a reference for the AUT. Slower scanning speeds will assist in this are sometimes necessary. This is evident in the data when the weld root wanders and can be corrected to some extent in analysis mode. Of course it is always better to acquire the data as precise as possible.

- Scan plans should account for a wander error of at least a few millimeters where is it not easy to determine the weld centerline with precision.
Phased Array Flaw Characterization

Every different type of flaw or geometric reflector has unique features that assist the operator in determining flaw type. Knowledge of the weld process and experience in the particular application is crucial and cannot be over emphasized. The codes themselves and these techniques are designed to find 100% of gross flaws and a sliding curve downward for flaws are low in amplitude and marginally acceptable or rejectable.

The next series of slides give a description of various flaw types and how they are characterized.

- ID Crack
- Lack of Side Wall Fusion
- Porosity
- OD Toe Crack
- Inadequate Penetration
- Slag

Flaw Characterization – ID Connected Crack

- Multiple facets and edges visible in the A-scan and sector scan. Distinct start and stop on A-scan.
- Significant walk to the signal as the probe is moved in and out from the weld. (See echo dynamic envelope on A-scan in 70 degree linear channel)
- Detection and correct plot from both sides of the weld.
- Best detection on the sector scan and linear 70 degree channels.
- Plots to the ID (B0) skip line.
Flaw Characterization – Lack of Sidewall Fusion

- Plots correctly on weld fusion line.
- Significantly different response from each side of the weld. Near side is typical >6 dB above reference sensitivity.
- Detected by 50%-+ of focal laws in sector scan from the same position.
- A-scan fast rise and fall time with short pulse duration indicative of planar flaw.
- No multiple facets or tips.
- Detected with high amplitude near side.
- Mode converted multiple signals that rise and fall together and maintain equal separation is typical

Flaw Characterization – Porosity

- Multiple signal responses varying in amplitude and position.
- Plots correctly to weld volume.
- Start and stop positions blend with background at low amplitude.
- May not be detected from both sides of the weld equally.
- Best characterized by sector scan and/or linear 52 and 60 channels on second leg.
- Typically not greater then reference sensitivity and difficult to distinguish from slag.
- A-scan slow rise and fall time with long pulse duration indicative of non-planar flaw.
- Best characterization is achieved on full V-path skip (Between B0 and T1)
- Multiple indications without significant length
Flaw Characterization – OD Toe Crack

- Multiple facets and edges visible in the A-scan and sector scan.
- Significant walk to the signal as the probe is moved in and out from the weld.
- Detection and plot from both sides of the weld.
- Best characterized on the sector scan and low angle (45, 50, or 60 degree linear channels) on second leg.
- Plots to the OD (T1) skip line.

Fig 9.7

Fig 9.8

Flaw Characterization – Inadequate Penetration

- High amplitude signal with significant walk or travel over the ID (B0) skip line. (See envelope on A-scan)
- Similar response and plot from both sides of the weld. Plots right at weld centerline at ID (B0).
- Do not confuse with excessive root reinforcement (convexity) or ID centerline crack.
- Detected on all channels with highest amplitude on 70 degree linear scan.
- A-scan fast rise and fall time with short pulse duration indicative of a planar flaw.

Fig 9.9

Fig 9.10
Flaw Characterization – Slag

- Multiple facets and edges visible in the A-scan and sector scan.
- A-scan slow rise and fall time with long pulse duration indicative of non-planar flaw.
- Typically lower amplitude than planer flaws.
- Similar response and plot from both sides of the weld. Plots to weld volume.
- Difficult to distinguish from porosity.
- Best characterized with sector scan.

Flaw Characterization – Crack Sizing

Although not typical of code based new construction inspections, advanced techniques for in-service cracking can also be performed from a standard system on the phased array channels with use of specialized wedges and set ups. Most of these can be combined on a single channel.

- High Angle L-wave inspection
- Focus Shear Wave Tip Diffraction
- ID Creeping Wave (KK-WSY or Parametric CDS type)
- Relative Arrival Time Technique (RATT)
- Absolute Arrival Time Technique (AATT)
- Many more
Display Axis

- **A Scan** – amplitude Vs True Depth (or sound path)
- **B Scan** – Scan Axis Vs True Depth
- **C Scan** – Angle Vs Scan Axis
- **S Scan** – Index axis Vs True Depth

---

**Phased Array Analysis on Omniscan MXU**

The following movie will demonstrate the following functions from a single channel 45-70 sector scan phased array acquisition. The quality and ease of analysis is directly related to the quality of the calibration and acquisition.

- Use of Omniscan Displays
- Use of Omniscan Data, Reference, and Measure Cursors
- Use of Omniscan Gate Based Readings
- Use of Omniscan Defect Table Generation of Report

The acquisition was taken as pictured in the scan plan below. 25mm V weld with the probe -24mm from the weld centerline.

---

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Phased Array Analysis on Omniscan MXU

Fig 9.17

Phased Array Offline Analysis - Tomoview

- To perform offline analysis, the data from the flashcard is transferred to the computer for conversion to Tomoview file format.
- Flashcards can be purchased up to 8 Gigabytes and can store hundreds of data files.
- File saving and management is a critical step in the phased array inspections and a source of common errors resulting in wasted time and lost work.
- Tomoview licensing is controlled by a USB Hasp Security Key and enables use of the various versions.

Fig 9.18
Phased Array Offline Analysis- Tomoview

Tomoview is available in 4 versions related to applications.

- **Tomoview Full**: Includes capability to acquire data through an Omniscan MXU or Focus LT and all analysis Features.
- **Tomoview Analysis**: Includes all analysis features without the ability to acquire data.
- **Tomoview Weld LT**: Limited version specifically designed for analysis of Omniscan data files with most common analysis tools and limited customization.
- **Tomoview Viewer**: Free version that can be provided to customers or inspectors for basic data file screening without advanced tools.

![Fig 9.19](image_url)
### Tomoview Family of Products

#### Phased Array Offline Analysis - Tomoview

- The Tomoview Viewer is free. It requires no activation or security key and can be distributed to customers with data if desired.
- The Viewer provides a very simple interface with preset display templates for reviewing data without advanced sizing and analysis tools.

---

| Feature                          | Imperial/metric Units | Data File merge | Multiple channels display | Display phased array and TOFD | Display predefined weld overlay | Binarize Cscan images | Measure SNR on Cscan | Resynchronize Ascan offline | TOFD manager (LW removal, resynch) | Beam Drawing | Open multiple files simultaneously | Create Display layouts | 3D cursor | FFT calculation | Hysteresis correction | Convert Log to linear | Excel exchange | Import PASS files | Data acquisition capability |
|----------------------------------|-----------------------|-----------------|---------------------------|-------------------------------|-------------------------------|---------------------------|-----------------------|-------------------------------|--------------------------|-------------------------|-------------------------|---------------------|-----------------|------------------------|------------------------|------------------------|---------------------|-------------------------|
| Edit Comments                    | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Zoom In/Out                      | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Convert Omniscan data files      | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Adjust soft gain                 | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| One channel display              | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Display conventional UT channel | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Display phased array channel     | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Template display layouts         | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Adjust Color Contrast             | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Display TOFD channel             | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Auto volumetric merge            | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Modify/resize color palette       | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Built-in Report Generator        | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Display rebounds                  | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Modify display layouts            | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Display custom weld overlay (.drf) | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Calibrate sound axis             | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Display/Edit defect table        | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Display specific readings         | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Cscan merge                       | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
| Draw contour box (statistical meas.) | ✓                     | ✓               | ✓                         |                               |                               | ✓                         | ✓                     |                               | ✓                        | ✓                       | ✓                       | ✓                   | ✓                 | ✓                      | ✓                      | ✓                      | ✓                   | ✓                       |
An essential tool used in the offline analysis of phased array data files is the volumetric data merge. The C-scan below is the sum of all focal laws used in the scan plan. In this example over 200 focal laws on 6 linear scan channels from 2 probes. The ability to merge all focal laws into one C-scan allows all focal laws on all channels to be analyzed in seconds in one display.

From the Merged C-scan, individual flaws are analyzed on the relevant channels using B-scans, D-scans and S-scans.

Additionally, every A-scan from every focal law is available on customized views designed for the particular application.

The typical application would use 2 or 4 phased array channels from probes on both sides of the weld combined with 1 or 2 TOFD channels.

Tomoview enable to view more than one file at a time when both files are MERGED using the Software.
Chapter 10: Phased Arrays Code Compliance

Code Compliance

- The overwhelming majority of applications are for replacement of radiography in the fabrication of pipelines, vessels, and welded structures.
- To replace RT the customer and the relevant code require permanent records and the ability to analyze data offline after the inspection through the instrument or computer based software.
- Some of the most common codes that govern these activities are the ASME Sec III, Sec V, and Sec VIII, AWS D1.1, API 1104, and API RP2X. There are many others as well.
- Compliance with these codes is not solely a function of the instrument but rather a total process to include equipment, calibration block and technique, scan plan design, inspection procedure, qualification of the process or technique, personnel certification, and many other parameters specified in the applicable code.
- Scanners and Instruments are not inherently code compliant. They are one part of an overall procedure or process that is written to comply with the various codes. They contain features such as scan speed, encoder capability, instrument linearity, software features, data recording that make up the equipment portion of the over-all process.
Code Compliance

The ASME has been particularly proactive in updating their codes to maximize the benefits of Phased Array through the release of specific Code Cases.

- Case 2235 Use of Ultrasonic Examination in Lieu of RT for ASME Sec VIII Pressure Vessels
- Case 2600 Use of Linear PA S-scan per Art. 4 Sec V
- Case 2557 Use of Manual PA S-scan per Art. 4 Sec V
- Case 2599 Use of Linear PA E-scan per Art. 4 Sec V
- Case 2541 Use of Manual PA per Art. 4 Sec V
- Case 2558 Use of Manual PA E-scan per Art. 4 Sec V
- Case 181 Use of Alternative UT Examination Accept Criteria for ASME B31.3
- Case 179 Use UT in Lieu of RT for B31.1 Applications < ½ inch in Thickness

Code Compliance

When used by certified personnel, Phased Array Systems shall meet the basic requirements of any code with respect to all the following parameters.

- Vertical and Horizontal Linearity
- Time of Flight (Velocity & Wedge Delay) Calibration
- Sensitivity Calibration
- ACG (Angle Corrected Gain as defined by the ASME)
- TCG Calibration
- DAC Calibration

Fig 10
Code Compliance

- It is not practical to calibrate individual Focal Laws (A-scans) one at a time as there can be up to 256 in some applications. For this reason the software must have tools or “Wizards” to make these functions fast and easy, repeatable, and in compliance with the codes for Sensitivity, TCG, Velocity, etc.

![Fig 10.1](image1)

![Fig 10.2](image2)

The Phased Array equipments are capable of generating many focal laws (in case of omniscan 256 focal laws (A-scans)) simultaneously divided in up to 8 channels. All calibrations are performed per channel and any individual focal law (A-scan) can easily be verified using standard references such as an IIW block or similar. This is verbatim compliance with the requirements of ASME, AWS, API, and similar.

- Exit Point
- Refracted Angle
- Sensitivity
- Velocity
- Time of Flight (Wedge Delay)
- TCG or DAC
- Surface Distance

![Fig 10.3](image3)
Code Compliance

- In addition to compliance with the codes and regulations, the quality of the calibration is directly related to the probability of detection, a reject rate in line with the applicable code, and ease of analysis for the operator.
- A quality calibration would allow the same size and type of reflector to be detected at the correct time of flight and amplitude, regardless of angle and sound path.
- This results in a consistent color palette throughout the digitized range and allows high probability of detection and accurate consistent flaw characterization.

![Fig 10.4]

**Mechanical Engineering Books**
**Code Compliance**

- The Omniscan and Focus LT software use cursors, gates, and digital readings to make sizing and characterization of flaws fast and efficient.
- The required reading are configured and saved as part of the set up for different code requirements. This typically includes Depth (DA), Height (Um-r), Length (Sm-r), Volumetric Position (Via), etc.

![Fig 10.5](image)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DA/ (%)</td>
<td>135.0</td>
</tr>
<tr>
<td>Um-r (mm)</td>
<td>14.50</td>
</tr>
<tr>
<td>Sm-r (mm)</td>
<td>7.26</td>
</tr>
<tr>
<td>Via (mm)</td>
<td>-6.30</td>
</tr>
</tbody>
</table>

**Code Compliance**

In addition to tools for sizing Depth, Height, Length, etc., the Omniscan MXU software also contains the standard readings that you would expect in any modern conventional flaw detector including:

- AWS Defect Ratings
- Amplitude Drop Sizing Tools
- Volumetric Positions in 3 Axis
- Code Calibration Reference Level Comparisons
- Probe and Surface Parameters
- And many, many more

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWS-D A</td>
<td>Indication level for AWS-D1.3.A</td>
</tr>
<tr>
<td>AWS-D B</td>
<td>Zero reference level for AWS-D1.5.B</td>
</tr>
<tr>
<td>AWS-D C</td>
<td>Attenuation factor for AWS-D1.5.C</td>
</tr>
<tr>
<td>AWS-D D</td>
<td>Indication rating for AWS-D1.5.D</td>
</tr>
<tr>
<td>AWS-D 4G</td>
<td>Discontinuity Severity Class for AWS-D1.5 4G</td>
</tr>
<tr>
<td>AWS-D 6G</td>
<td>Discontinuity Severity Class for AWS-D1.5 6G</td>
</tr>
<tr>
<td>AWS-D 7G</td>
<td>Discontinuity Severity Class for AWS-D1.5 7G</td>
</tr>
<tr>
<td>AWS-D CL</td>
<td>Discontinuity Severity Class for AWS-D1.5 CL</td>
</tr>
<tr>
<td>Scale</td>
<td>Scale factor</td>
</tr>
<tr>
<td>%U1/4v0</td>
<td>Signal amplitude at reference ultrasonic cursor position</td>
</tr>
<tr>
<td>%U1/4v0</td>
<td>Signal amplitude at measurement ultrasonic cursor position</td>
</tr>
</tbody>
</table>
Code Compliance

API 1104 requires Zone Discrimination Weld Inspections. Phased arrays are not supportive to this, There are other products (some using phased array) supporting API 1104.

In addition to the calibration requirements and hardware parameters, the codes also regulate the required area of coverage, probe parameters, and the overall inspection.

Use of the ES Beam Tool, Olympus Beam Simulator or similar software allows the operator to design and document correct probe position, channels and angles used for proper coverage, and over all inspection strategy using Phased Array, TOFD, and Conventional UT techniques.

The information obtained from the scan plan software is programmed into the Omniscan using Group Wizards and Calibration Wizards allowing the operator to manage hundreds of Focal Laws (A-scans) simultaneously.
References

- Presentations issued to training members of Olympus IMS.
- Advances in Phased Array Ultrasonic Technology by Olympus
- Introduction to phased array ultrasonic technology applications by Olympus
Chapter 11: Equipment, Probe performance Check

**Equipment performance Check**

- All the Performance checks explained here are only for linear array probes
- Performance check can be done in Active and Passive plane (preferred to explain only in active plane)
- Applicable to both linear and Sectorial Scan – normal and angle beam- contact and immersion also (preferred only contact here)

**This course covers the Following Topics**

- Beam Profile
- Steering
- Focusing
- Element Activity
- PA computer control of parameters and data display
- Wedge delay and Wedge attenuation compensation
- PA instruments Linearities.
Beam Profile

- Use a side drilled holes block of various depths (flaw free sample)
- Generate Linear focal (for 0° and any angle) – using linear scan feature of PA system, the beam is passed over the targets of various depths
- Collect the data. Use B-scan for display. This is Beam Profiling for 0° in Active Plane
- Repeat the same steps for Linear scan of any Particular angle using the PA Wedge
- Collect the data and display it as B-scan
- This is Beam Profile for angle beam Shear wave

The purpose is to understand the beam spread of the probe and implication of beam spread in defect over sizing

Focusing

- Couple the PA block with SDH holes as mentioned Previous slide.
- Compression mode with or with out delay, shear wave with wedge can be assessed.
- Single angle focusing can be accessed by this method. When several angels are to be assessed, do it for each angle separately.
- Use E scan, collect data- display in B-scan.
- Assess by Sizing the hole on 6dB drop and compare with actual machined diameter of the SDH.
- Working range can be defined as the depth or sound-path distance that the B-scan can be maintain the 6-dB to less that twice the actual diameter.

The significance of this is to find the maximum focal depth in which the inspection can be carried out.
Beam Steering

- Prepare a series of SDH holes as illustrated in fig 1.
- Holes are at 5° intervals are 25mm and 50mm distance from the centre where the probe is located.
- When a set of focal laws arrange in plane instead of beam path, the block is as illustrated in fig 2.
- Use a probe without wedge or delay, align the mid point of the aperture with central line.
- Assessment of steering limit shall be made using the DB diff between the max and minimum signal amplitudes of two adjacent SDH.
- For example a pair of SDHs which achieve 6dB diff shall be the maximum steering capability of probe.
- Can be performed for both S and E scan.
- The significance of this is to find out the maximum steering capability of probe so that the maximum angle the probe can give better results.

Element Activity

- PA probe with out wedge & delay line shall be coupled to 25mm thickness of an IIW block with uniform layer of couplant.
- Generate focal law with 1 element and stepping 1 element at a time for the total no of elements in array.
- Set the pulser parameters (gain) to optimize the max response.
- Establish the back wall echo to 80% of the display for each element in the probe.
- Record the results in table format.
- No 2 side by side elements are inactive.
- A total of more than 25% inactive element probe may affect sensitivity, steering etc.

- The significance of this is to find the inactive (damaged) and no of such individual or consequent elements.
PA computer control of parameters and data display

- Linear array probe having at least 16 elements with a pitch not greater than 1mm.
- Generate Two S-Scans one at ±30° with a focal distance of 25mm and other at ±30° with a focal distance of 50mm.
- For both sets of Focal laws, the angular step interval is 5° and all focal laws use 16 adjacent elements.
- Couple the probe to a series of SDH holes drilled (as mentioned in Beam steering) such that the center of the element array aligns with the central line of hole pattern.
- Scan and scan the S-scan for 25mm and 50mm focal distance.
- Using the co-ordinate cursors, Record the depths, offsets from the central line and angles to the side drilled hole in tabular column.
- Compare the values with physical positions of the holes in block.
- ±0.5mm tolerance is allowed for sound path, depths and offset positions.
- ±1.0° tolerance is allowed for all angles of the holes.

- The purpose of this test is to make sure the accuracy of the measurement parameters such as depth, angle, sound path, offset positions etc.

Wedge attenuation compensation

- Configure the PA systems for the Focal Laws to be used in this application.
- Couple the probe to 1.5mm SDH hole in IIW block.
- A dynamic assessment would simply require to move the probe back and forth over the SDH ensuring that all the focal laws used have the SDH target moved through the beam.
- The Amplitude of SDH by each focal law would be adjusted to same amplitude ensuring that the wedge attenuation compensation is calculated.
- Similar process can be used for S-Scan using the radius in IIW Block.
- Delay or wedge shall have variations in path distance with in the wedge will results in some focal laws require more or less amp gain.
- This is a method to compensate for gain variations & normalize all laws.
Wedge Delay Compensation

- Sound path in the wedge material varies from one focal law to the next in E-Scan, S-Scan with refracted wedge and S-Scan Delay line.
- Compensation for this delay time diff is required to ensure that indications detected are correctly positioned i.e, depth and angle with in the test piece is correctly plotted.
- Couple the probe to radius in IIW block and move back and forth over the radius assuring that all focal laws used have the center of beam ray peak on the radius appropriate for their angle
- When a PA Probe is used on delay or wedge, beam steering and projection displays depends on fermats principle.
- Requires to identify the position in space of the probe elements
- This ensure the path length to wedge steel interface in turn gives correct depth of indications.

Phased array Instrument linearities

Display height linearity

- A PA instrument connected to a probe and coupled to any block that will produce two signals as show here.
- Adjust the probe such that the amplitude of the two signals are 80% and 40% of the display screen height
- Adjust gain to obtain 100% of FSH of the larger response.
- The height of the lower response is recorded at this gain as % of FSH
- Reduce the height of higher response in 10% steps to 10% of FSH and height of the second response is recorded for each step
- For acceptable tolerance, the response from the two reflectors shall bear a 2:1 with in ±3% of FSH for all values.
Amplitude control linearity

- Select the Probe with as many elements as the pulser.
- Couple the Probe to a suitable surface -25mm of IIW, to obtain a pulse each response from each focal law.
- Select channel 1, monitor the response from the selected target.
- Adjust the gain to bring to 40% of screen height.
- Add gain to the received in increments of 1 dB, 2 dB, 4 dB & 6 dB.
- Remove the gain added after each increment to ensure that the signal had return to 40% display height.
- Record the actual height of signal as % of screen height.
- Signal amplitude should fall within range of ±3% of actual screen height.
- Repeat the sequence for all the Pulser receiver channels.

Time base linearity (Horizontal)

- Couple the Probe to a suitable surface -25mm of IIW, to obtain a pulse each response and choose a range to display 10 multiple back wall echoes.
- With probe coupled to block, the display software is used to assess the interval between the back wall signals.
- With proper velocity entering into software, the echoes will be configured to readout in distance.
- Use the reference and measurement cursors determine the interval between the each multiple and record the interval of first 10 echoes.
- Typically the errors on the multiples should not be exceed ±0.5mm for the steel plate.
- Sample recording table of all linearity check is indicated in next slide.

This Test is to find the non linearity (amplifier, and time base scale) of the multiple pulser receiver channel in the PA equipment.
## LINEARITY VERIFICATION REPORT FORM

<table>
<thead>
<tr>
<th>Large Out</th>
<th>Small Allowed Range</th>
<th>Small Actual (%)</th>
<th>Ind. Height</th>
<th>dB</th>
<th>Allowed Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>w1</td>
<td>67-80</td>
<td>-2</td>
<td>66</td>
<td>32</td>
<td>62-73</td>
</tr>
<tr>
<td>w2</td>
<td>80</td>
<td>-6</td>
<td>69</td>
<td>35</td>
<td>62-43</td>
</tr>
<tr>
<td>w3</td>
<td>90</td>
<td>-6</td>
<td>60</td>
<td>44</td>
<td>40-44</td>
</tr>
<tr>
<td>w4</td>
<td>97-50</td>
<td>-5</td>
<td>49</td>
<td>45</td>
<td>40-55</td>
</tr>
</tbody>
</table>

### Amplitude Control Linearity Channel Results: (Note any channels that do not fall in the allowed range)

<table>
<thead>
<tr>
<th>Channel</th>
<th>(Add notes if required for 10s or AV gain issues, etc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
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<tr>
<td>5</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

### Time Base Linearity (for 2x even U/W markers)

<table>
<thead>
<tr>
<th>Multiple</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
<td>125</td>
<td>150</td>
<td>175</td>
<td>200</td>
<td>225</td>
<td>250</td>
</tr>
</tbody>
</table>

Measured Interval

Allowed Deviation ±0.5 mm (Yhic/Hz)

---

Thankyou