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Advancements in Non-Destructive Evaluation: A Comprehensive Study on Phased Array Ultrasonic Testing (PAUT)

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Abstract: Phased Array Ultrasonic Testing (PAUT) is an advanced non-destructive testing (NDT) technique that utilizes multiple individually pulsed piezoelectric elements to generate, focus, and steer ultrasonic beams electronically. Unlike conventional single-element probes that require physical movement to scan, PAUT systems enable dynamic electronic scanning, focusing, and steering, allowing for precise imaging and defect detection without mechanical repositioning. By employing complex focal laws and beamforming algorithms, PAUT can create real-time cross-sectional (B-scan), top-view (C-scan), and sectorial images for comprehensive material evaluation. The technique offers enhanced flaw detection, faster inspection speeds, and improved reliability, making it ideal for weld inspections, corrosion mapping, and thickness measurements. Emerging methodologies such as the Total Focusing Method (TFM) and Full Matrix Capture (FMC) further advance PAUT's capabilities by enabling pixel-by-pixel focusing across the inspection region. Compared to radiographic testing (RT), PAUT eliminates radiation hazards, allows inspections during normal operations, and significantly reduces downtime. A case study at Hindalco Mahan demonstrated a three-day reduction in boiler overhaul time by replacing RT with PAUT, validating its advantages in safety, efficiency, and productivity.

Keywords: Phased array ultrasonic testing, Piezoelectric elements, Ultrasonic beams, Full matrix capture, Sectorial images, Reliability, Sectorial images.

I. INTRODUCTION

Phased Array Ultrasonic Testing (PAUT), also known as phased array UT, is an advanced non-destructive inspection technique that uses a set of ultrasonic testing (UT) probes made up of numerous small elements. Each of these is pulsed individually with computer-calculated timing to create the phased aspect of the process, while the array refers to the multiple elements that make up a PAUT system. The beam from a phased array probe can be focused and electronically swept across an inspection piece without moving the probe itself. This differs from single element probes (also known as monolithic probes). These more conventional probes need to be physically moved or turned to cover larger areas, which is not required for PAUT.

Phased array ultrasonic testing is based on the principles of wave physics, which also have applications in areas including optics and electromagnetic antennae.

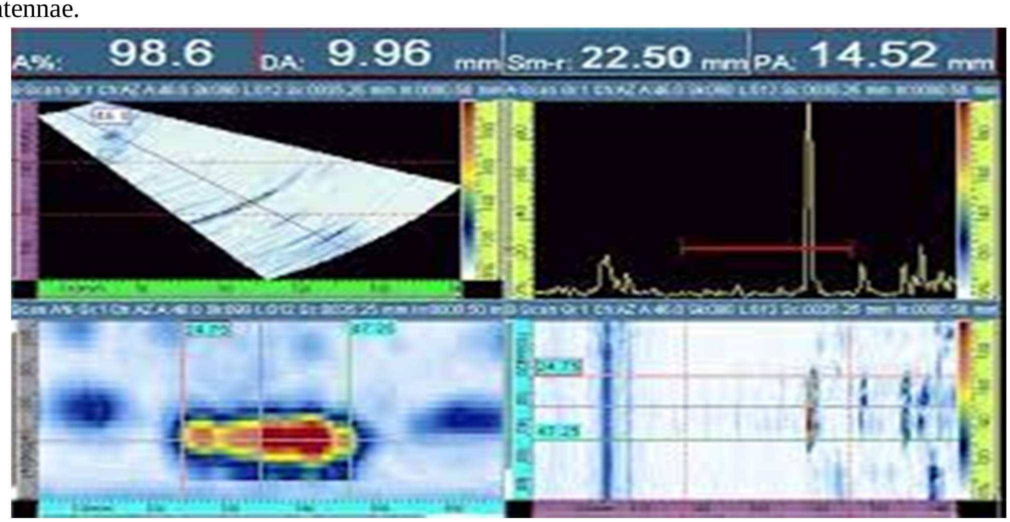

Figure-1: Phased Array Interpretation

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Phased arrays are used for a wide variety of inspection and measurement applications, and they can be used for any job done by conventional ultrasonics. For example, phased arrays are used to detect and image defects including cracks, voids, and pits caused by corrosion. They are used to measure material and coating thickness and to detect changes in material properties. Another common application is to assess the quality of welds and rivets. Phased arrays are also used to inspect joints and interfaces, for example, to detect and map adhesive.

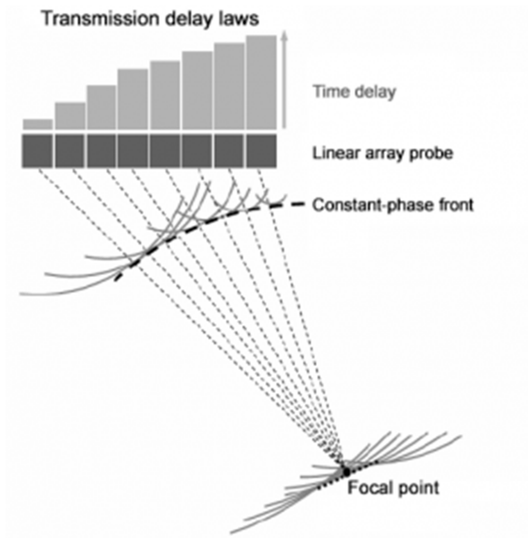

Figure-2: Phased Array ultrasonic beam with multiple array

A. How Does Phased Array Work

As mentioned above, phased array ultrasonic testing probes are made up of several piezoelectric crystals that transmit/receive independently at different times. An ultrasonic beam is focused using time delays Figure-2, which are applied to the elements to create a constructive interference in the wave fronts. This interference allows the energy to be focused at any depth and angle in the test specimen as shown in Figure-3

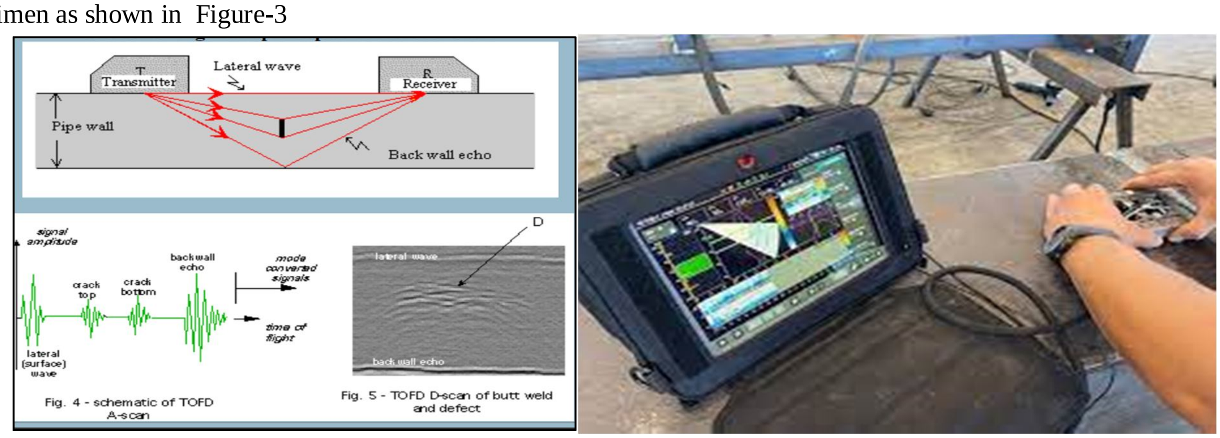

Figure-3: Phased Array ultrasonic principle and testing

Each element radiates a spherical wave at a specified time, creating waves that converge and diverge to create an almost planar wave front at the specified location. Changing the progressive time delay allows the beam to be steered electronically and swept through the test material like a searchlight. When multiple beams are put together it creates a visual image that shows a slice through the test object.

B. A-Scan Data

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

Distance = velocity x time

The most basic presentation of ultrasonic waveform data is in the form of an A-scan, or waveform display, in which echo amplitude and transit time are plotted on a simple grid with the vertical axis representing amplitude and the horizontal axis representing time. The example below shows a version with a rectified waveform; unrectified RF displays are also used. The red bar on the screen is a gate that selects a portion of the wave train for analysis, typically measurement of echo amplitude and/or depth as shown in Figure-4.

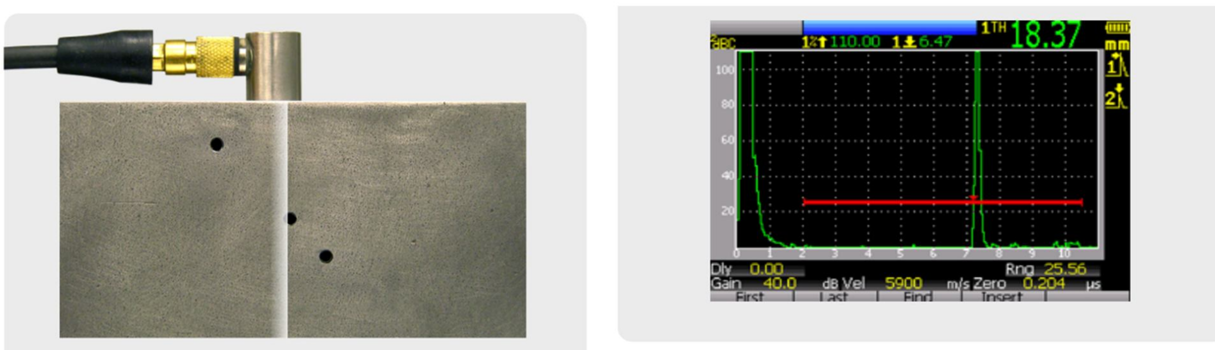

Figure-4: PAUT A Scan interpretation

C. Single Value B-Scans

Another way of presenting this information is as a single value B-scan. A single value B-scan is commonly used with conventional flaw detectors and corrosion thickness gauges to plot the depth of reflectors with respect to their linear position. The thickness is plotted as a function of time or position while the transducer is scanned along the part to provide its depth profile. Correlating ultrasonic data with the actual transducer position enables a proportional view to be plotted and enables the ability to correlate and track data to specific areas of the part being inspected. This position tracking is typically done using electromechanical devices known as encoders. These encoders are used in fixtures that are either manually scanned or in automated systems that move the transducer by a programmable motor-controlled scanner. In either case, the encoder records the location of each data acquisition point with respect to a desired user-defined scan pattern and index resolution as shown in figure-5.

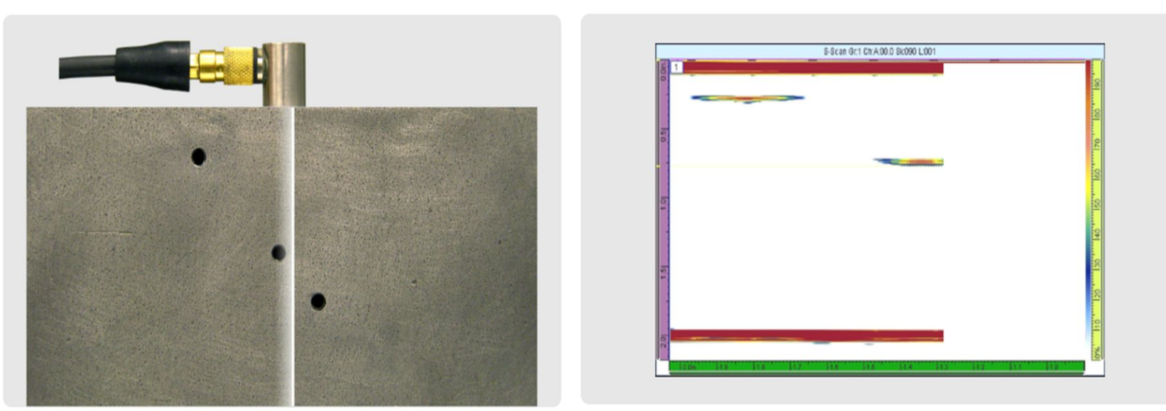

Figure-5: PAUT B Scan interpretation

In the case below, the B-scan shows two deep reflectors and one shallower reflector, corresponding to the positions of the side-drilled holes (SDHs) in the test block

D. C-Scan Mapping

Another presentation option is a C-scan, a two-dimensional presentation of data displayed as a top or planar view of a test piece, similar in its graphic perspective to an X-ray image, where color represents the gated signal amplitude or depth at each point in the test piece mapped to its position. Planar images can be generated on flat parts by tracking data to the X-Y position or on cylindrical parts by tracking axial and angular position. For conventional ultrasound, a mechanical scanner with encoders is used to track the transducer's coordinates to the desired index resolution. The following images conceptually show C-scans of a reference block made with a conventional immersion scanning system using a focused immersion transducer, as shown in figure-6

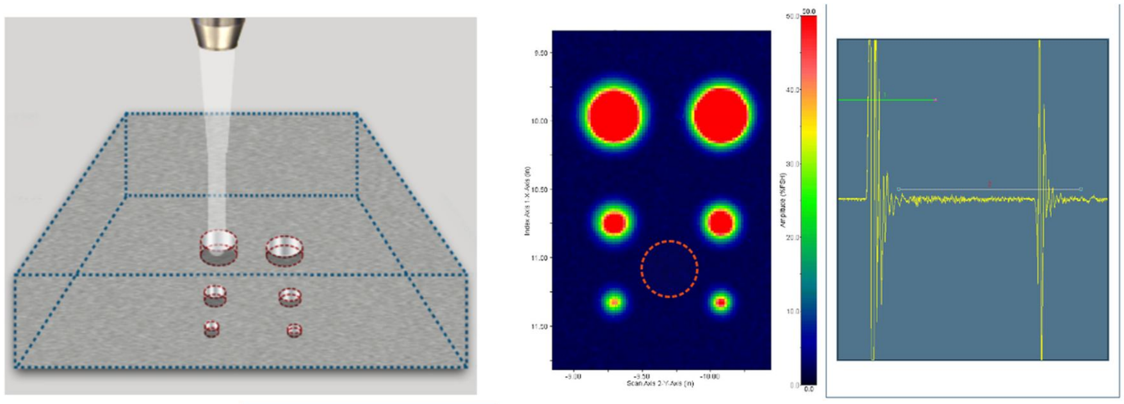

Figure-6: PAUT C Scan mapping

E. Phased Array C-Scan

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

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

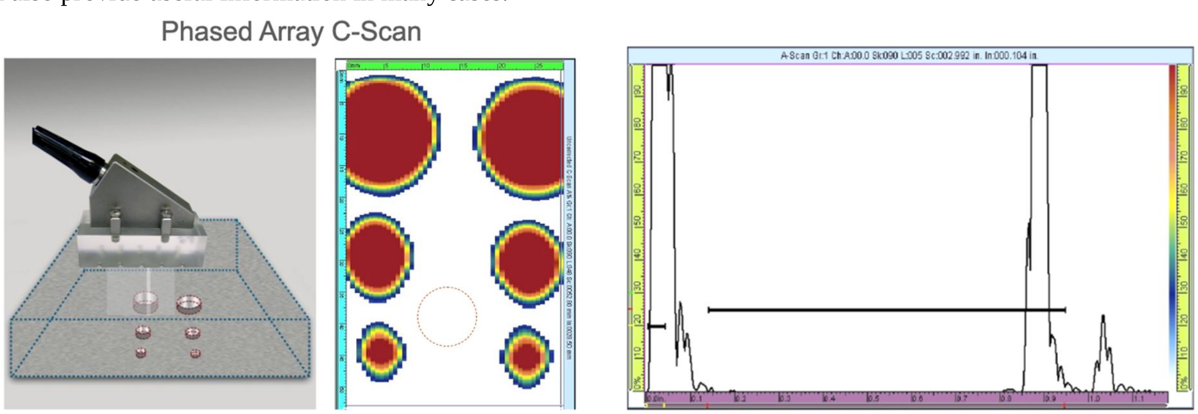

Figure-7: Phased array C scan

While the graphic resolution is not fully equivalent to the conventional C-scan because of the larger effective beam size, there are other considerations. The phased array system is field portable, which the conventional system is not, and costs about one-third the price. Additionally, the phased array image was made in a few seconds, while the conventional immersion scan took several minutes. Real-time generation of the C-scan is shown at the bottom.

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F. Phased Array Linear Scans

A phased array system uses electronic scanning along the length of a linear array probe to create a cross-sectional profile without moving the transducer. As each focal law is sequenced, the associated A-scan is digitized and plotted. Successive apertures are "stacked" creating a live cross-sectional view. An animated representation of this sequence using a 16-element linear probe is shown below.

In practice, this electronic sweeping is done in real time so a live cross section can be continually viewed as the transducer is physically moved. Below is a real-time image using a 64-element linear phased array probe.

This highlight phrase references the animation below (using a 16-element probe), but then the paragraph below talks about a "real-time image using a 64-element probe" and references again an image below, but I'm confused where that image is because there seems to only be one image (in Fig-8).

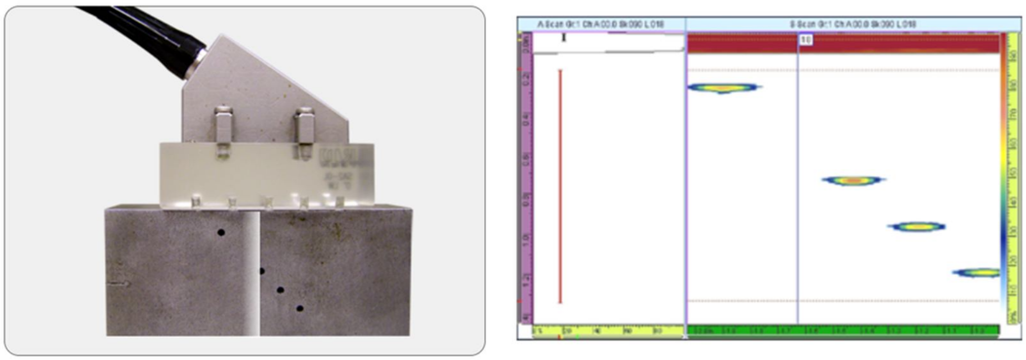

Figure-8: Linear Straight Scan, The focal law to use 16 elements to form an aperture and sequenced the starting element increment by one.

It is also possible to scan at a fixed angle across elements. As discussed later this is very useful for automated weld inspection. Using a 64-element linear phased array probe with a wedge, shear waves can be generated at a user defined angle (often 45, 60, or 70 degrees). With aperture sequencing through the length of the probe, full volumetric weld data can be collected without the need for physically increasing distance to the weld center line while scanning. This enables single pass inspection along the weld length.

G. Phased Array Sectorial Scans

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

Two main forms are typically used. The most familiar, very common in medical imaging, uses a zero-degree interface wedge or shoe to steer longitudinal waves at relatively low angles, creating a pie-shaped image showing laminar and slightly angled defects (in Fig-9).

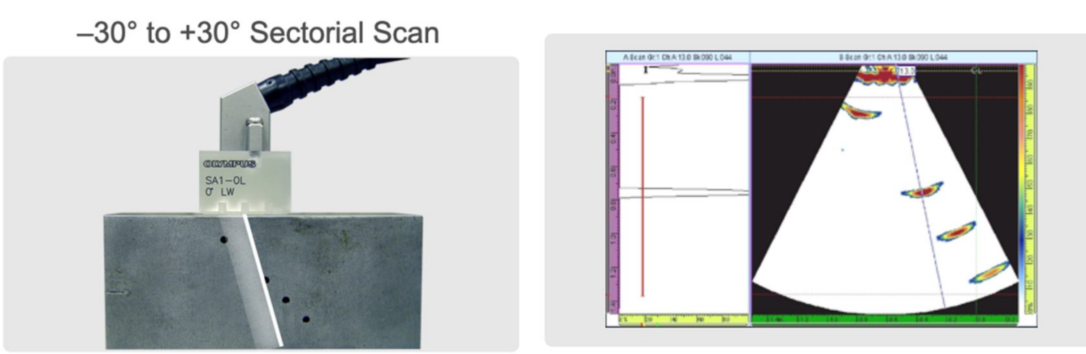

Figure-9: Phased array sectorial scan -30° to +30°

The second format employs an angled plastic wedge to increase the incident beam angle for the generation of shear waves, most commonly in the refracted-angle range of 30 to 70 degrees. This technique is similar to conventional angle beam inspection, except that the beam sweeps through a range of angles rather than a just single fixed angle determined by a wedge. As with the linear scan, the image presentation is a cross-sectional picture of the inspected area of the test piece(In Fig-10).

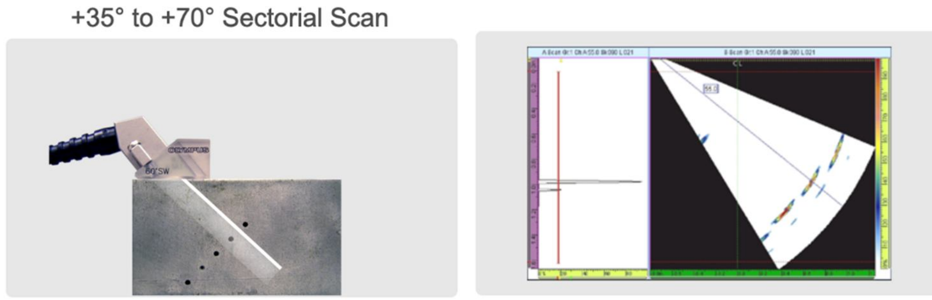

Figure-10: Phased array sectorial scan +35° to +70°

In actuality, the sectorial scan is produced in real time, offering continuous dynamic imaging with the probe's movement. This is very useful for defect visualization and increases probability of detection, especially with respect to randomly oriented defects, because many inspection angles can be used at once.

H. Total Focusing Method (TFM)

The non-destructive testing (NDT) industry is experiencing an important technological advancement, as total focusing method (TFM) capable inspection devices are making their entry into the market. The TFM approach represents a significant step forward for phased array ultrasonic testing (PAUT) technology. However, some PAUT practitioners may still be confused about TFM and its relation to full matrix capture (FMC), as well as the differences between conventional PAUT and TFM/FMC processing. This application note provides a basic understanding of TFM imaging for people who are familiar with PAUT imaging. For conciseness and clarity, aspects related to ultrasound propagation modes are set aside.

This method involves the application of the basic phased array focusing principle at a defined region of interest. The inspection region is segmented into a grid of positions, or pixels, with beamforming applied to each pixel in the grid.

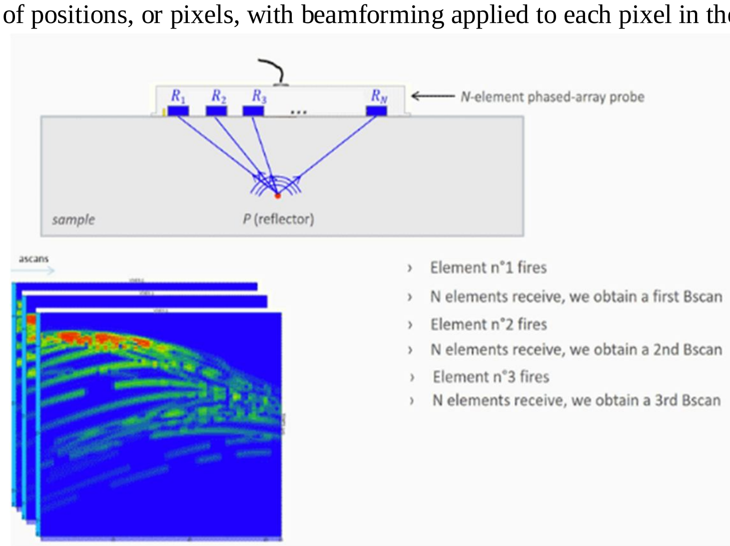

Figure-11: Total focusing method

The Total Focusing Method (TFM) is an ultrasonic array technique which is used to synthetically focus at every point of a region of interest (Fig-11).

The total focusing method (TFM) is the systematic application of the basic focusing principle of phased array in a defined region of interest (ROI) in an inspected part. The ROI is segmented into a grid of positions, or "pixels," and focusing through phased array beamforming is applied to every pixel in that grid. To date, TFM is the most efficient method to generate this ROI image that is focused everywhere and at every depth.

However, if the PAUT acquisition strategy through physical beamforming acquisition were used for the total focusing method, the time to generate a single TFM image would prohibit any deployment for most NDT applications.

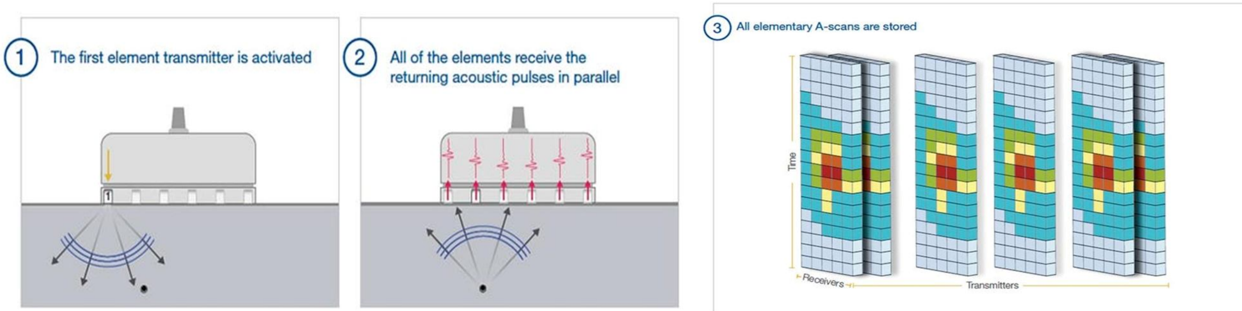

Figure12a: Full Matrix capturing Strategy

With the TFM, the number of pixels constituting an image is much higher, for instance, than the number of discrete angles required to generate an S-scan covering the same region of interest. An S-scan that is swept through 100 angles requires 100 acquisitions through physical beamforming, whereas a TFM image of 100 × 100 pixels would require 10,000 physical beamforming acquisitions (in Fig-12).

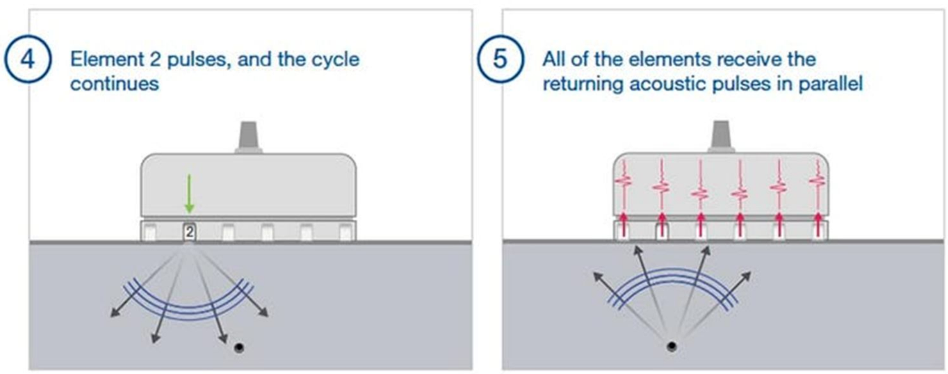

Figure12b: Full Matrix capturing Strategy

To avoid this problem, another acquisition strategy is used, in which the amplitude values in the grid are calculated through synthetic beamforming for both the transmission and reception phases. This strategy requires a set of focal laws corresponding to each pixel position over the ROI grid, and a set of raw, fundamental waveforms, or elementary A-scans. An efficient way to obtain this set of elementary A-scans is full matrix capture (FMC) data acquisition.

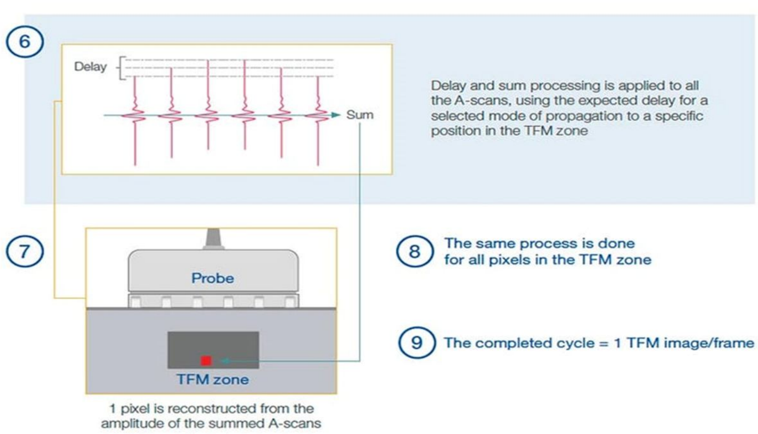

Figure12c: Full Matrix capturing Strategy

Full matrix capture (FMC) is an acquisition process that obtains all the A-scans (amplitude time series) between all individual pairs of transmitter and receiver probe elements. These elementary A-scans are stored in the FMC data set. To achieve the best focusing result, all of the elements constituting the full aperture of a probe should be used to generate the FMC data set through synthetic beamforming. In this case, the number of acquisitions required to build the FMC data set is equal to the number of elements of the probe. The FMC data set contains all the sound propagation information between each element of the probe, including reflections at interfaces and scattering by flaws. Any type of PAUT acquisition can be reconstructed from the FMC data set using adequately chosen delays, including a sectorial scan, plane wave imaging (PWI), dynamic depth focusing (DDF), total focusing method (TFM), etc.

I. Electronic Scanning

Electronic scanning reproduces the inspection performed by manually moving a standard UT probe. An ultrasonic beam is electronically translated across the entire probe, allowing for faster inspection while limiting mechanical displacement. The technique can be performed with an S or and L wave and can be combined with beam focusing and beam steering.

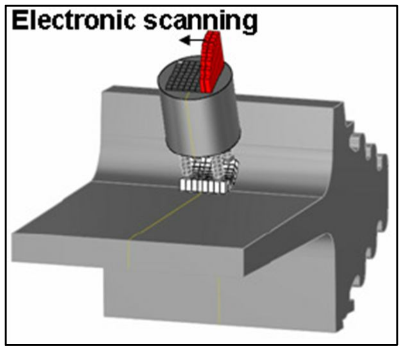

Figure13 : Electronic Scanning

The core principle lies in the ability to electronically control the transmission and reception of ultrasonic waves from multiple elements, Multi-element Probe: A PAUT probe contains numerous small, independent piezoelectric elements (typically 16 to 256) arranged in an array.

Sequential Pulsing: Instead of using all elements at once, the system selects a small group (an aperture) of adjacent elements, pulses them with a specific sequence of time delays (focal law), and then moves to the next adjacent group, and so on (Fig-13).

Beam Translation: The delay laws for each sequential group are designed to generate an ultrasonic beam at a constant angle (often a straight beam for linear scans) and a fixed focal depth.

Image Formation: Each pulse sequence generates a single A-scan (waveform) corresponding to a specific location. These A-scans are then "stacked" in software to create a real-time, cross-sectional image (B-scan) that emulates the raster scan of a conventional single-element probe.

II. ADVANTAGES

The advantages of phased arrays over conventional ultrasonic probes include improved portability, convenience, inspection speed, and safety. A phased array is more robust and easier to use than conventional single-element probes, providing improved efficiency, capturing hundreds of signals at once, and reducing the number of false alarms. PAUT inspection strategies can be optimised to improve flaw detection when used alongside simulation, while data recording and traceability are also greatly improved.

Phased array ultrasonic testing provides a permanent record, doesn’t produce radiation and can be used for several applications. Because PAUT can detect defects at the surface and into the volume of a weld (with no dead zone), it also gives information about the lateral position of a defect (depth and height).

The main advantages of phased array ultrasonic testing include:

1) Simplified Inspection and Interpretation: A phased array probe can replace several conventional ultrasonic probes, making complex procedures simpler and removing the need for setting up and calibrating multiple probes. This also allows for simplified functionality, including real-time imaging.
2) Increased Flaw Detection: Because a probe is used to control the direction and shape of the beam, the surface can be scanned at diverse angles. This allows for increased coverage for flaw detection as well as the inspection of complex geometries. PAUT is also effective for determining material thickness, which is useful for ultrasonically determining corrosion or erosion of a test piece.

3) Faster Inspection Speeds: By using electronic scanning to fire successive groups of elements in an array, PAUT reduces the need for mechanical scanning and reduces inspection times. Inspection speeds are also improved compared to conventional probes as the phased arrays allow for the user to change the shape and focal point of the ultrasonic beam to optimise each inspection. This means there is no need for manual set-up and reconfiguration for each unique testing. In addition, dynamic-depth focusing allows measurements to be made at several depths in the same amount of time as it takes to complete a single depth measurement using a conventional probe. Furthermore, because digital feedback can be received instantaneously, flaw identification and weld quality assessments can be completed faster.
4) More Reliable Results: Reducing or eliminating mechanical scanning not only improves inspection times, but also increases the reliability of the measurements by eliminating changes in or the loss of coupling, which is a risk whenever a probe is moved. This also means that phased array probes provide test results with excellent repeatability.

III. APPLICATIONS

Phased arrays can perform any job done by conventional ultrasonics and are used for a wide range of inspection and measurement applications, including those for medical imaging and industrial non-destructive testing (NDT).

Ideal for non-invasive material examinations, for finding flaws in welds and assessing the quality of rivets, PAUT can also detect cracks, voids and pits caused by corrosion. The technology can measure material and coating thickness, detect changes in material properties and inspect joints and interfaces, including adhesive mapping.

As an advanced NDT method, it is used to detect discontinuities to determine component quality, making it ideal for:

Weld Inspections
Thickness Measurements
Corrosion Inspection
PAUT Validation/Demonstration Blocks
Inspection of Rolling Stock Wheels and Axles
PAUT and TOFD Standard Calibration Blocks
Pressure Vessels

IV. CASE STUDY

Practical Case Study for Choosing PAUT in Place of Radiography for Boiler Tube Inspection at Hindalco Mahan

Background: As boiler tube inspection is major job for boiler maintenance during AOH work for boiler tube inspection RT is the main testing for boiler tube welding joints as per our earlier practice we do approx. 1500 joints RT for weld joints and there is limitation of RT due to RT was planned only in Night shift after 2 am to 6 am, so after 2 am all the other AOH activities in Boiler & Auxiliaries area were stopped due to radiation hazards. Timely RT, RT duration, RT Retake, Film development, film interpretation were the main reasons which promoted idle manhours, which directly impact our overhauling durations.

Overhauling of Boiler & auxiliaries took around 30 plus days. If any abnormalities may happen to any running unit, then it will be a great threat to plant production. So, the overhauling period is a crucial period and management always put pressure on team to complete the task ASAP and kept unit ready as stand by.

Analysis: As we were facing the problem for timely completing the AOH jobs by RT this was very challenging for us to complete job in given time lines so we explore the new technology for welding joints inspection through internet and vendors so finally it was suggested by our team that we will take the new initiative of PAUT(phased array ultrasonic testing), We have analyzed that time taken in AOH through RT was more and we were facing 3 days delay in internal hydro and all the time management was not happy due to this delay so we convinced the management for doing this and saved 3 days in internal hydro and we have also improved the safety culture by implementing PAUT and our other jobs will not be hamper due to waiting time for RT.

A. Challenges

We were facing many challenges in RT during tubes weld joints inspection.
No time flexibility in RT inspection (RT was used to plan in night hours only).
It was more time-consuming inspection.
Safety is the main concern in RT due to radiation hazard.
Other mechanical job was hampered due to area was blocked for safety concern.
Idle man hours during RT job process was more.

There is handling issue of RT source because radiation hazard is there.

Solution achieved with Methodology:

During brainstorming, 4W 1 H and consultation with OEM and other NDT agencies we have explored the new technology for inspection of weld joints that give us the better result and time saving job.

We have explored new technology in the field of NDT as PAUT (phased array ultrasonic testing) for boiler tubes weld joints inspection this technology is reliable, safe and less time consuming for NDT inspection, No need to stop any work we can continue all work in parallel with the PAUT, PAUT instrument handling and storage hazard is nil.

B. Expected Benefits from Practice/Idea

People Development/Sustainability/Cost Saving
/Productivity Improvement/Innovation

We have achieved some benefits as under; -

1) No hazardous radiations
2) Easy to use & interpretation
3) NO special precaution in PTW, barricading and work stoppage near by radiation zone as like RT
4) Fast result
5) No time bound (where as RT cane be done in Night time as per plant requirement)
6) Overall 3 days time saving in internal hydro.

V. CONCLUSIONS

Phased Array Ultrasonic Testing (PAUT) represents a significant advancement in non-destructive testing, offering precise, efficient, and safe inspection capabilities across a wide range of industrial applications. By electronically controlling multiple ultrasonic elements, PAUT enables focused and steerable beams that provide high-resolution imaging without the need for mechanical probe movement. This technology enhances defect detection, improves data accuracy, and reduces inspection time compared to conventional ultrasonic and radiographic methods.

Its versatility in inspecting welds, detecting corrosion, and assessing material integrity makes PAUT an indispensable tool in modern maintenance and quality assurance processes. Furthermore, its radiation-free operation ensures greater safety and allows simultaneous work in adjacent areas, increasing overall productivity. As demonstrated in the Hindalco Mahan case study, adopting PAUT not only improves inspection reliability but also leads to substantial time savings, cost efficiency, and enhanced workplace safety. In essence, PAUT combines the principles of advanced wave physics with modern digital imaging to deliver faster, safer, and more reliable non-destructive evaluation—making it a cornerstone of today's industrial inspection technologies.

VI. ACKNOWLEDGE

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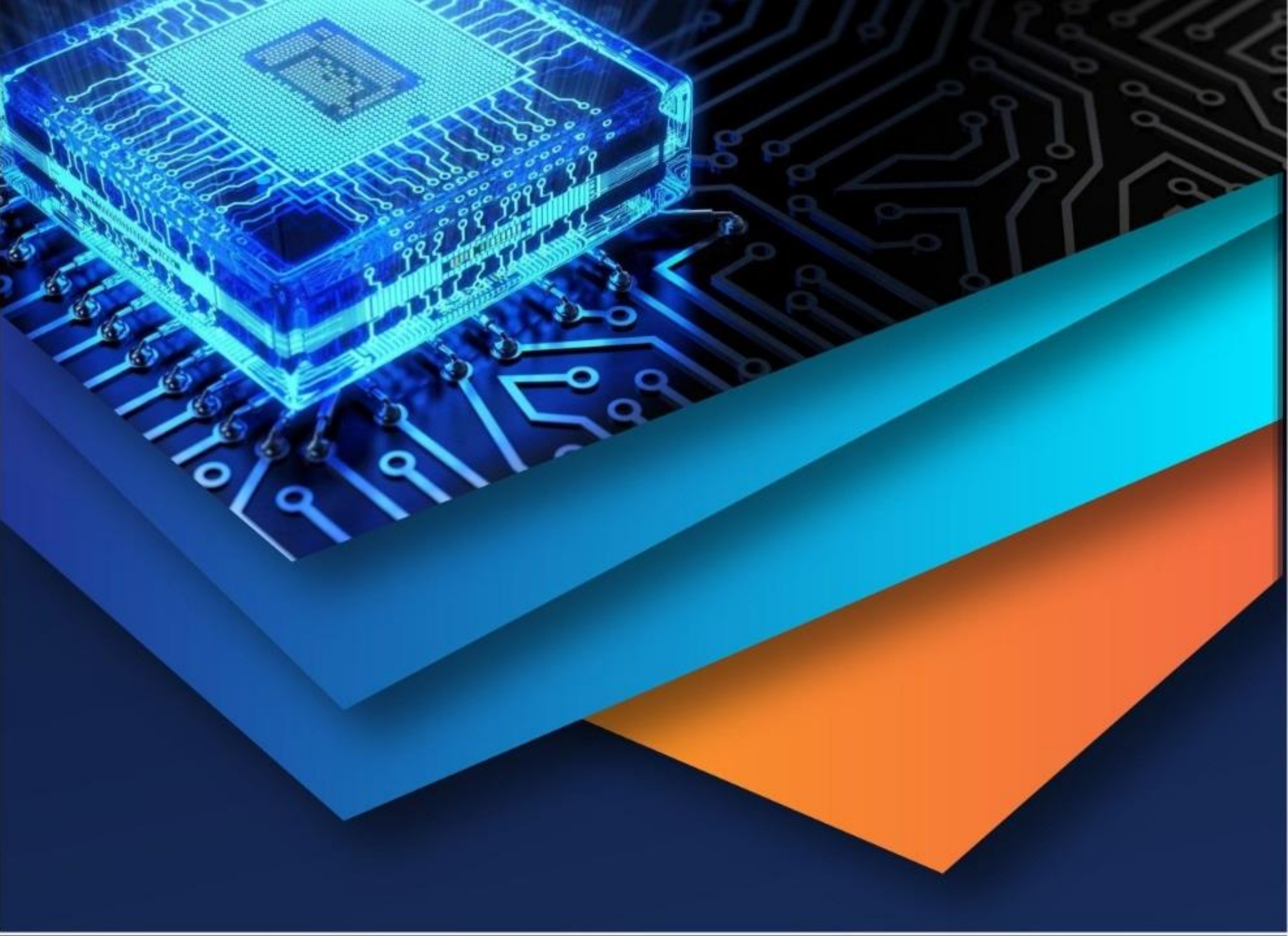
REFERENCES

[1] Advanced NDT Training Presentation, Trainer: Mr. Sushil Sharma.
[2] Literature on PAUT and advance NDT Method by kint.nl/assets
[3] Baker Hughes blogs on Advance NDT methods and PAUT vs Conventional UT.
[4] Bureau of Transportation Statistics literature Comparative Testing of Radiographic Testing, Ultrasonic Testing and Phased Array Advanced Ultrasonic Testing Non-Destructive Testing Techniques.



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