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Ultrasonic Inspection of Pressure Vessel Construction Welds using Phased Arrays

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ABSTRACT

Ultrasonic phased arrays are a new technology that offers considerable potential for inspecting construction welds. Using electronic control of the beam, phased arrays can scan, sweep, steer and focus the ultrasound. Since welds typically produce defects of known character and orientation, phased arrays can be programmed to optimize weld inspections. These inspections include standard ASME-type pulse echo raster scans, zone discrimination, TOFD and "specials", depending on the vessel, weld profile, geometry and specifications.

One advantage of phased arrays is inspection speed: linear travel speeds of up to 100 mm/sec are possible. Sizing is typically performed using diffraction approaches (TOFD and back diffraction), both well suited to phased arrays, as well as by pulse echo. Results can be obtained shortly after welding. Since phased arrays use pre-programmed set-ups, they are inherently flexible for many different weld and vessel configurations. Lastly, ultrasonics generates no safety hazards, so moving personnel or vessels is unnecessary.

This presentation will describe how ultrasonic phased arrays work, what can be done with them, and gives examples of phased array inspection systems for pressure vessels. Examples of inspections on various vessels will include thick-sectioned welds inspected using both electronic raster scans and zone discrimination. Phased arrays are well suited to premium vessel inspections, which require multiple NDE techniques for Fitness-For-Purpose (Engineering Critical Assessment) inspections. Examples will be given of smaller portable phased array weld inspections, with code-compliant procedures.

INTRODUCTION

Ultrasonic phased arrays are a novel method of generating and receiving ultrasound. They use multiple ultrasonic elements and electronic time delays to create beams by constructive and destructive interference. As such, phased arrays offer significant technical advantages over conventional single-probe ultrasonics; the phased array beams can be steered, scanned, swept and focused electronically.

- Electronic scanning permits very rapid coverage of the components, typically an order of magnitude faster than a single probe mechanical system.
- Beam forming permits the selected beam angles to be optimized ultrasonically by orienting them perpendicular to the predicted defects, for example Lack of Fusion in welds.
- Beam steering (usually called sectorial scanning) can be used for mapping components at appropriate angles to optimize Probability of Detection. Sectorial scanning is also useful for inspections where only a minimal footprint is possible.
- Electronic focusing permits optimizing the beam shape and size at the expected defect location, as well as optimizing Probability of Detection. Focusing improves signal-to-noise ratio significantly, which also permits operating at lower pulser voltages.

Overall, the use of phased arrays permits optimizing defect detection while minimizing inspection time.

Phased arrays offer significant advantages over traditional radiography of welds as well:

- No safety hazards
- Inspection as soon as weld is cool
- Better defect detection and sizing
- Great flexibility in parameter range
- Compliant with all known codes
- Many special techniques are possible.

HOW PHASED ARRAYS WORK

Ultrasonic phased arrays are similar in principle to phased array radar, sonar and other wave physics applications. However, ultrasonic development is behind the other applications due to a smaller market, shorter wavelengths, mode conversions and more complex components. Several authors have reviewed applications of ultrasonic phased arrays (1-3), though industrial uses have been limited until the last few years (4, 5).

Phased arrays use an array of elements, all individually wired, pulsed and time-shifted. These elements can be a linear array, a 2D matrix array, a circular array or some more complex form (see Figure 1). Most applications use linear arrays, since these are the easiest to program, and are significantly cheaper than more complex arrays due to fewer elements. As costs decline and experience increases, greater use of the more complex arrays can be predicted.

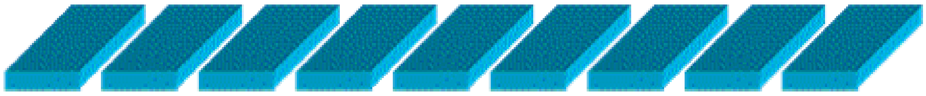

Figure 1: Schematic of 1D linear array.

The elements are ultrasonically isolated from each other, and packaged in normal probe housings. The cabling usually consists of a bundle of well-shielded micro co-axial cables. Commercial multi-channel connectors are used with the instrument cabling.

Elements are typically pulsed in groups from 4 to 32, typically 16 elements for welds. With a user-friendly system, the computer and software calculate the time-delays for a set-up from operator-input on inspection angle, focal distance, scan pattern etc, or use a pre-defined file (see Figure 2). The time delays are back calculated using time-of-flight from the focal spot, and the scan assembled from individual “Focal Laws”. Time delay circuits must be accurate to around 2 nanoseconds to provide the phasing accuracy required.

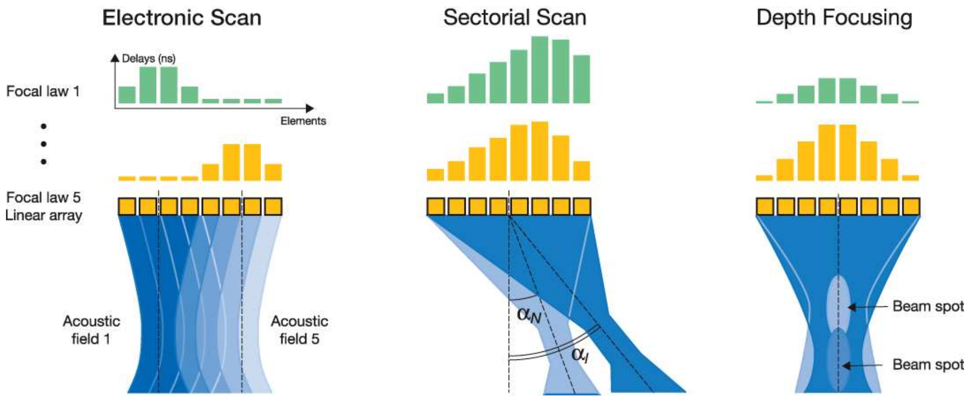

Figure 2: Schematic showing generation of electronic (originally called “linear scans”) and sectorial scans using phased arrays.

Each element generates a beam when pulsed; these beams constructively and destructively interfere to form a wavefront. (This interference can be seen, for example, with photo-elastic imaging, 6). The phased array instrumentation pulses the individual channels with time delays as specified to form a pre-calculated wavefront. For receiving, the instrumentation effectively performs the reverse, i.e. it receives with pre-calculated time delays, then sums the time-shifted signal and displays it. This is shown in Figure 3.

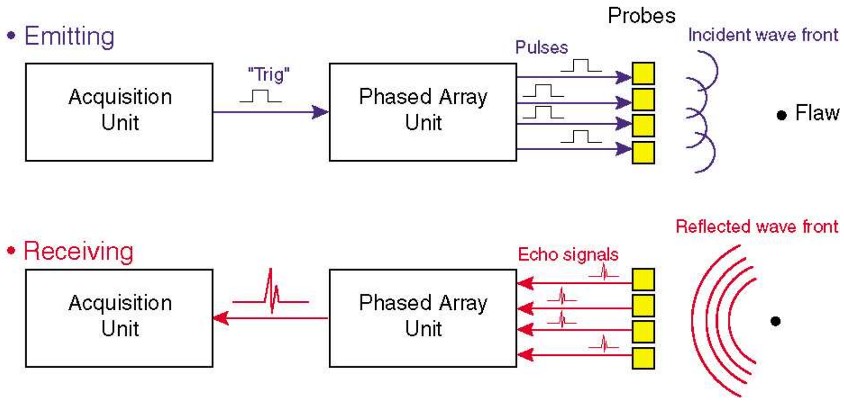

Figure 3: Beam forming (above) and receiving (below).

The summed waveform is effectively identical to a single channel flaw detector using a probe with the same angle, frequency, focusing, aperture etc.

PRACTICAL APPLICATION OF PHASED ARRAYS

From a practical viewpoint, ultrasonic phased arrays are merely a method of generating and receiving ultrasound; once the ultrasound is in the material, it is independent of generation method, whether generated by piezoelectric, electromagnetic, laser or phased arrays. Consequently, many of the details of ultrasonic inspection remain unchanged; for example, if 5 MHz is the optimum inspection frequency with conventional ultrasonics, then phased arrays would typically start by using the same frequency, aperture size, focal length, and incident angle.

While phased arrays require well-developed instrumentation, one of the key requirements is good, user-friendly software. Besides calculating the Focal Laws, the software saves and displays the results, so good data manipulation is essential. As phased arrays offer considerable application flexibility, software versatility is highly desirable. Phased array inspections can be manual, semi-automated (i.e. encoded) or fully automated (see Chapter 6), depending on the application, speed, budget etc. Encoder capability and full data storage are usually required.

Though it can be time-consuming to prepare the first set-up, the information is recorded in a file and only takes seconds to re-load. Also, modifying a prepared set-up is quick in comparison with physically adjusting conventional probes.

TYPES OF SCANS

Electronic Scans

Electronic pulsing and receiving provide significant opportunities for a variety of scan patterns, as shown in Figure 4 below.

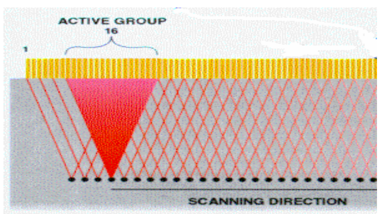

Figure 4: Schematic illustration of electronic scanning.

Electronic scans (originally called linear scans) are performed by multiplexing the same Focal Law (time delays) along an array. Typical arrays have up to 128 elements. Electronic scanning permits rapid coverage with a tight focal spot. If the array is flat and linear, then the scan pattern is a simple B-scan. If the array is curved, then the scan pattern will be curved. Electronic scans are straightforward to program. For example, a phased array can be readily programmed to perform corrosion mapping, or to inspect a weld using 45^o and 60^o shear waves, which mimics conventional ASME manual inspections.

Sectorial Scans (S-scans)

This type of scan is unique to phased arrays. Sectorial scans use the same set of elements, but alter the time delays to sweep the beam through a series of angles (see Figure 5). Again, this is a straightforward scan to program. Applications for sectorial scanning typically involve a stationary array, sweeping across a relatively inaccessible component like a turbine blade root (7), to map out the features and defects. Depending primarily on the array frequency and element spacing, the sweep angles can vary from $\pm$ 20^o up to $\pm$ 80^o.

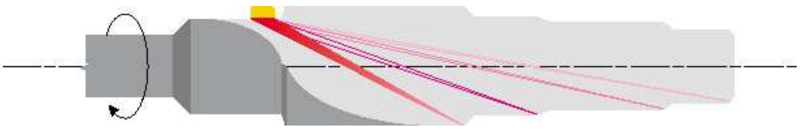

Figure 5: Schematic showing sectorial scanning used on turbine rotor.

Combined Scans

Combining linear scanning, sectorial scanning and precision focusing leads to a practical combination of displays (see Figure 6). Optimum angles can be selected for welds and other components, while electronic scanning permits fast and functional inspections. For example, combining linear and L-wave sectorial scanning permits full ultrasonic inspection of components over a given angle range, e.g. $\pm$ 20^o. This type of inspection is useful when simple normal beam inspections are inadequate, e.g. for titanium castings in aerospace where defects can have random orientations. A related approach applies to weld inspections, where specific angles are often required for given weld geometries; for these applications, specific beam angles are programmed for specific weld bevel angles at specific locations.

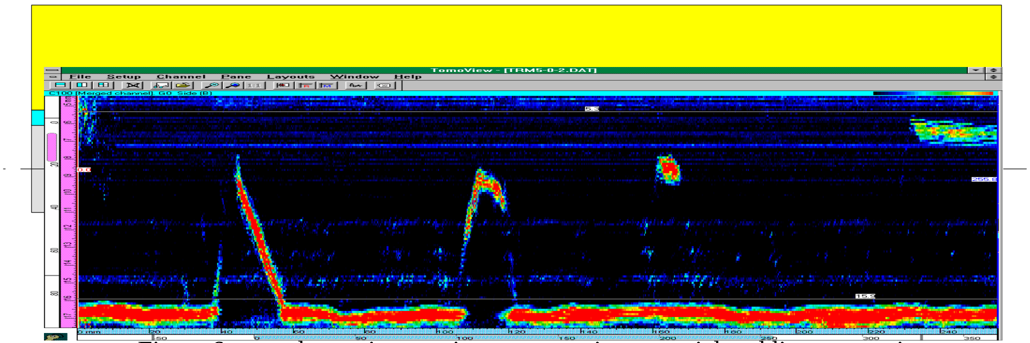

Figure 6: top, ultrasonic scanning pattern using sectorial and linear scanning; bottom, ultrasonic image using all data merged together.

Linear scanning of welds

Manual ultrasonic weld inspections are performed using a single probe, which the operator "rasters" back and forth to cover the weld area. Many automated weld inspection systems use a similar approach (see Figure 7a), with a single probe scanned back and forth over the weld area. This is time consuming, since the system has dead zones at the start and finish of the raster.

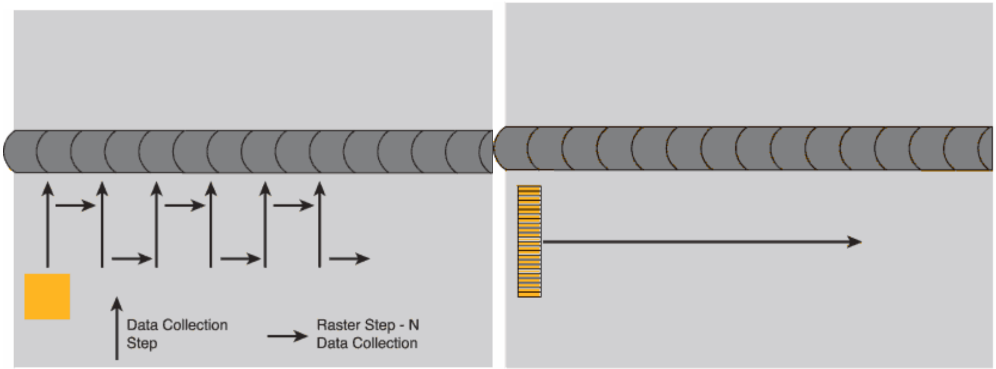

Figure 7a (left), conventional raster scanning; 7b (right), linear scanning.

In contrast, most multi-probe systems and phased arrays use a “linear scanning” approach (see Figure 7b). Here the probe pan is scanned linearly round or along the weld, while each probe sweeps out a specific area of the weld. The simplest approach to linear scanning is found in pipe mills, where a limited number of probes inspect ERW pipe welds (8).

Phased arrays for linear weld inspections operate on the same principle as the multi-probe approach; however, phased arrays offer considerably greater flexibility than conventional AUT. Typically, it is much easier to change the set-up electronically, either by modifying the set-up or reloading another; often it is possible to use many more beams (equivalent to individual conventional probes) with phased arrays; special inspections can be implemented simply by loading a set-up file.

TYPICAL APPLICATIONS

Realistically, there is no “typical application” for phased arrays; phased arrays are very flexible and can address many types of problems. Consequently, ultrasonic phased arrays are being used in a wide variety of industries, where the technology has inherent advantages. These industries include: aerospace, nuclear power, steel mills, pipe mills, petrochemical plants, pipeline construction, general manufacturing and construction, plus a selection of special applications. All these applications take advantage of one or more of the dominant features of phased arrays:

- **Speed**: scanning with phased arrays is much faster than single probe conventional mechanical systems, with better coverage;
- **Flexibility**: set-ups can be changed in a few minutes, and typically a lot more component dimensional flexibility is available;
- **Inspection angles**: a wide variety of inspection angles can be used, depending on the requirements and the array;
- **Small footprint**: small matrix arrays can give significantly more flexibility for inspecting restricted areas than conventional probes
- **Imaging**: showing a “true depth” image of defects is much easier to interpret than a waveform. The data can be saved and re-displayed as required.

Each feature generates its own applications. For example, “speed” is important for pipe mills and pipelines, plus some high volume applications. “Flexibility” is important in pressure vessels and pipeline welds due to geometry changes. “Inspection angles” is the key for pipelines, some pressure vessel and nuclear applications. “Small footprint” is applicable to some turbine applications. “Imaging” is useful for weld inspections.

NDE phased array technology is relatively new and still requires some set-up effort, especially for complex 3D applications. 2D set-ups are generally straightforward, provided the software is user-friendly. For example, automated set-up procedures have been developed for weld inspections. At this stage of development, phased array systems are often more costly than single channel systems; however, the higher speed, data storage and display, smaller footprint and greater flexibility can often offset the higher costs, especially with the newer portable instruments.

INSPECTION TECHNIQUES

Since they are very flexible, phased arrays can fulfill many different inspection techniques from standard ASME to zone discrimination to TOFD to "specials".

ASME Raster Scans

Figure 8 shows a phased array set-up for standard ASME raster scans using two separate angles in pulse-echo. The arrays are angled on wedges to optimize energy as well as reduce wear and damage. Phased arrays can perform inspections at multiple angles, plus TOFD.

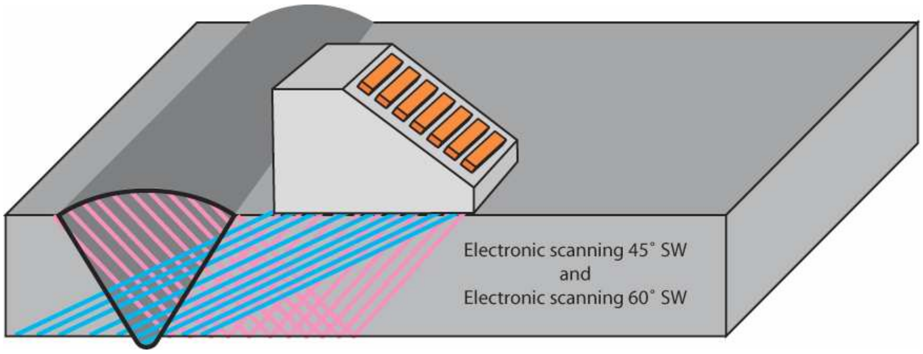

Figure 8: Schematic showing phased arrays performing ASME raster scans.

Zone Discrimination

Similarly, phased arrays can perform zone discrimination (9) as performed in pipeline AUT, similar to conventional multiprobe systems. However, phased arrays can generate twice the number of pulses at a given speed. Figure 9 shows a schematic of an array performing zone discrimination. One advantage of arrays is that they couple much better than a multitude of smaller conventional transducers.

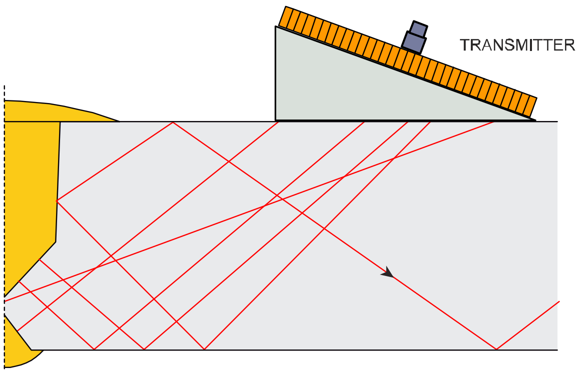

Figure 9: Schematic showing phased array performing zone discrimination.

TOFD

Phased arrays can also perform TOFD (Time-Of-Flight Diffraction) just like conventional UT (see Figure 10). Often the same array is used for pulse-echo and for TOFD since this saves scanning time and cost, and provides a better inspection using both combined. Normally TOFD frequencies are slightly higher than pulse-echo, and TOFD transducers are more highly damped, so there is a small resolution loss. Otherwise, the technique is the same; the phased arrays use a small aperture to generate a broad L-wave, and an RF display.

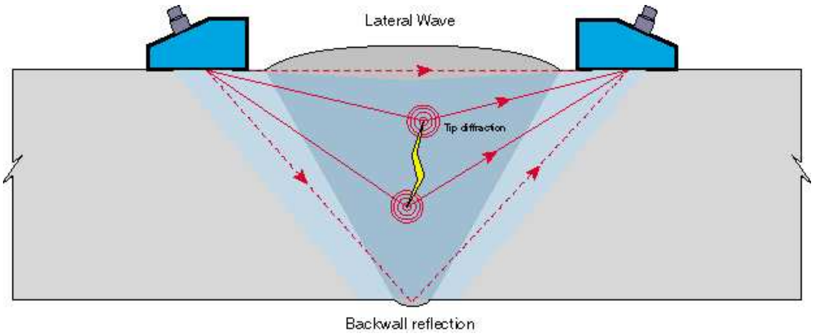

Figure 10: Schematic of TOFD set-up.

Back Diffraction

Phased arrays also work well with back diffraction for accurate sizing, better than conventional UT since the arrays do not move and coupling is more constant. Figure 11 shows the back diffraction technique, and Figure 12 typical results on an internal defect (10).

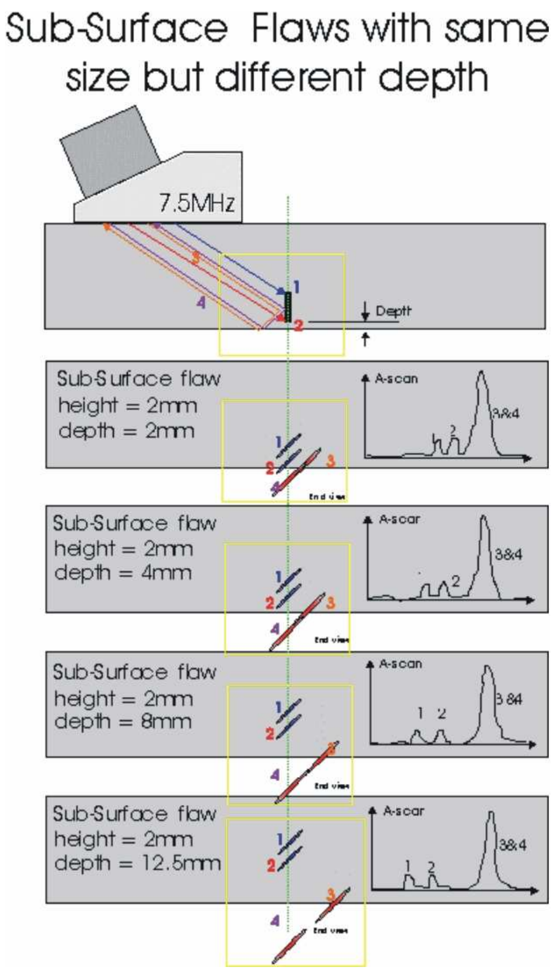

Figure 11: Schematic showing the back-diffraction concept.

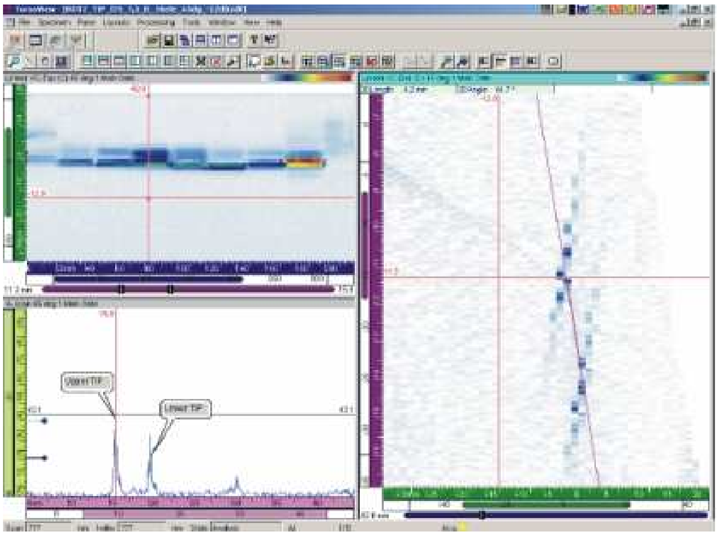

Figure 12: Typical back-diffraction scan results. Top left, C-scan; right, B-scan, bottom left, A-scan.

ASME CC 2235

Phased arrays can fulfill ASME Code Case 2235 (11) using pulse-echo, TOFD or a combination of pulse-echo and TOFD. This opens the door for pressure vessel inspections.

Specials

With their inherent flexibility, phased arrays are ideal for special applications. For example, weld roots can be inspected at multiple positions and angles to optimize defect detection, all with the same array in the same pass at high speed.

SOME DO’s and DON’Ts WITH PHASED ARRAYS

Calibration

Unlike conventional transducers, arrays need calibrating along the entire length for reproducible results. The best solution is to perform a scan over the calibration reflector, then “compensate” using a software program. This process is essential for raster-type inspections.

Weld Overlays

These are extremely useful for determining the location of defects in the weld. Much recommended, though there are possible position errors.

3D Images

With TomoView software and AutoCAD, it is possible to project 3D images of defects, rather than the standard ”top, side, end” views. An example is shown in Figure 13 below (12); these 3D images show very good representation and location of actual defects. However, 3D images are of limited value in practice for engineering assessments since the ASME (and other) codes require a box drawn around the maximum defect dimensions.

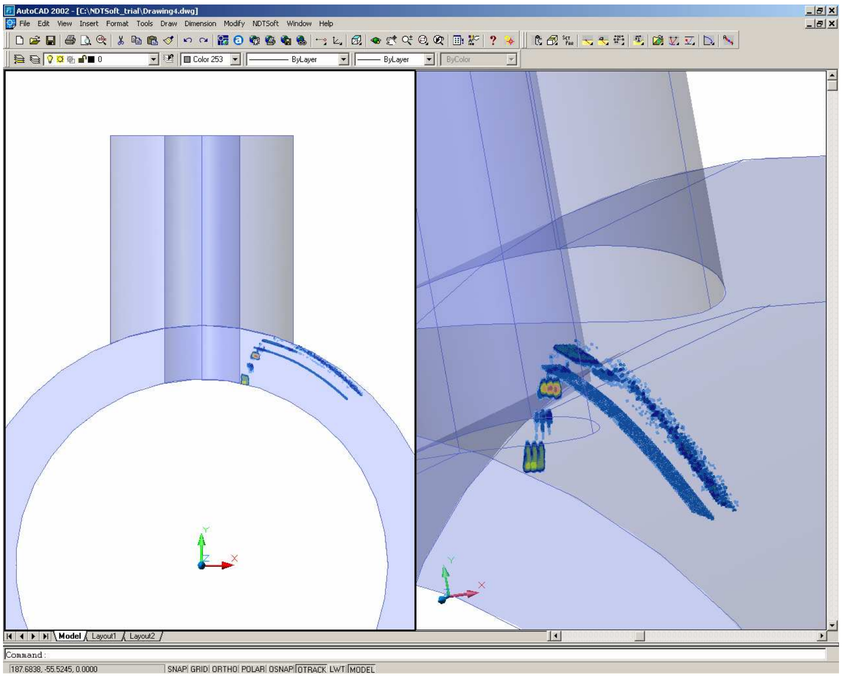

Figure 13: 3D data reconstruction of defects in nozzle (Courtesy of Zetec).

S-scans

Sectorial scans can be used to calibrate in any position on ASME-type side drilled holes, but may not be the best inspection technique since inspection angles will inherently be non-optimum for some defects. This means that under some conditions, particularly larger walls with a single pass, probability of defect detection is low (13). Figure 14 shows a typical simulation of an S-scan in a thick weld; the reflections from the midwall defect are minimal under these conditions.

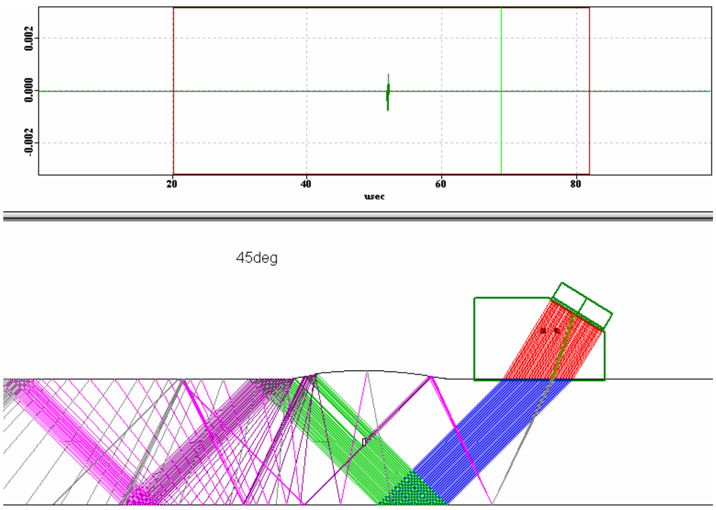

Figure 14: Imagine3D simulation of S-scan inspecting 25 mm plate with LOF midwall defect.

It should be noted that it is possible to "pass" the ASME CC 2235 Performance Demonstration using single S-scans and three defects, provided array position etc. is worked out. However, this does not necessarily mean that defect detection will be optimal.

INSPECTION SYSTEMS

Portable Phased Arrays

This system uses 16/128 format, i.e. 16 pulsers and a total of 128 elements. OmniScan is the entry system for phased arrays, and can perform electronic and sectorial scans, to comply with ASME CC 2235 and other codes. OmniScan can operate fully automated scanners and encoders, record all waveform data, use DAC and TCG. It can perform pulse-echo and TOFD, and display A-scans, B-scans, S-scans, TOFD scans and combinations. However, OmniScan is limited in that it can only perform one type of scan per pass, unless controlled by TomoView. The instrument is shown in Figure 15 below. OmniScan uses highly user-friendly software.

Figure 15: OmniScan portable phased array equipment

TOFD and Pulse-Echo (PV-100)

Time-Of-Flight Diffraction (TOFD) offers great potential for rapid scans with limited equipment. Essentially, wide angle longitudinal wave beams fill the whole wall with sound, and low amplitude diffracted signals from defect tips are collected and displayed in gray scale waveforms. This technique works very well for mid-wall defects, but has dead zones at the OD and ID. For this reason, R/D Tech firmly recommends using both pulse-echo and TOFD for coverage: pulse-echo for the near surfaces and TOFD for the midwall. Figure 16 below shows typical TOFD/pulse-echo equipment, and Figure 17 a typical display based on combined PE-TOFD. This type of inspection will fulfill ASME CC 2235. (The PV-100 is not a phased array system.)

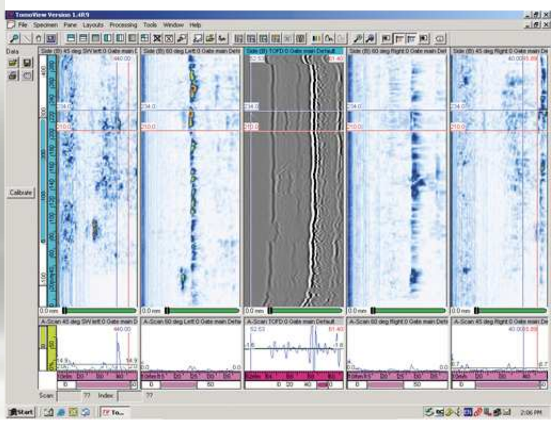

Figure 16 (left): PV-100 instrumentation. Figure 17 (right): typical PE-TOFD display.

General Phased Array Systems (PV-200)

These systems are based on the Tomoscan III (or FOCUS LT), a high speed, high data transfer rate, phased array instrument (see Figure 18). In comparison with OmniScan, these TomoView-based systems can perform multiple scans simultaneously, including TOFD, electronic and sectorial. Tomoscan III can perform detailed defect imaging using the Tomoview software, such as "top, side, end" views or "top, side, TOFD" views. Weld overlays can be used, and multiple and 3D cursors for accurate defect analysis (see Figure 19). The PV-200 system can be configured to pass essentially any code.

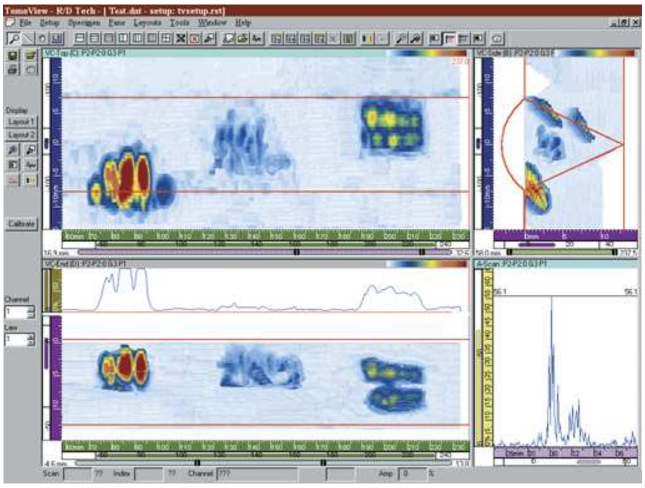

Figure 18 (left): Tomoscan III system. Figure 19 (right): "Top, side, end" view with weld overlay.

Premium Phased Array Systems (PV-300)

These systems are custom-designed for the application, and are primarily targeted at Fitness-For-Purpose applications where defect detection and sizing are critical. In contrast to the PV-100 and PV-200 systems, the PV-300 systems use multiple NDE techniques to give 200% coverage of the weld areas. Depending on the application, this coverage may include: pulse-echo; multiple TOFD channels; transverse defect detection using multiple angles and scanning; oblique defect detection; surface and near-surface defect detection using eddy current arrays. These systems are larger and heavier (and more expensive) then the PV-100 and PV-200 systems, and require full automation. The PV-300 systems are based on the Tomoscan III, but may use an increased number of elements for improved focusing, signal-to-noise etc. Figure 20 shows an example of a scanning head containing multiple phased arrays, TOFD transducers and eddy current arrays.

Figure 20: Typical PV-300 inspection head.

MECHANICS

There are multiple options for inspection, ranging from hand-held encoded devices (semi-automated) to fully robotic systems.

Hand Held Arrays

The simplest solution is a hand held array with encoder for linear scanning, which can collect full waveform data using the correct instrumentation (see Figure 21). However, this approach has limitations: poor positioning, no TOFD capability, but can image welds at multiple angles using Tomoscan III and is very flexible and cost-effective. This semi-automated approach has been demonstrated to be ASME code-compliant for plates and pipes up to 25 mm wall.

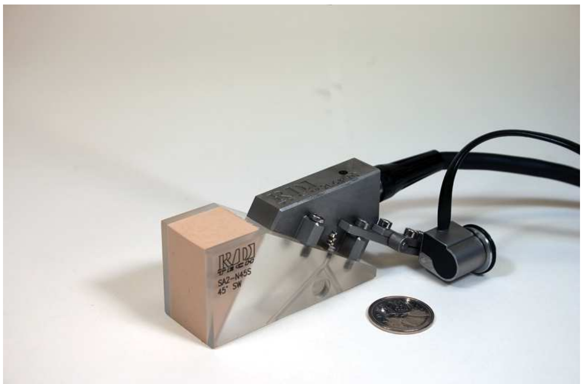

Figure 21: Typical array on wedge with mini-encoder.

Handscanners

Figure 22 below shows a typical handscanner inspecting a weld in a large pipe. This type of scanner is cheap and easy to use, and can hold conventional transducers, phased arrays, TOFD transducers etc. Provided allowance is made for operator positioning error, the system works faster and better than hand scans. Normally, water is pumped for the coupling.

Figure 22: Handscanner in action.

Welding Band

This technique uses a welding band for travel, and is particularly applicable to pipes. The advantages are quick and easy to use, as well as accurate. However, there are physical limitations to the diameter of the vessel to be inspected (around 1.5 m). Figure 23 shows a scanner on a welding band.

Figure 23: Pipe scanner on welding band.

Rotate the Vessel

This technique, shown schematically in Figure 24, is the simplest solution for large vessels. Many fabricators need to rotate to weld, so rotating is a simple option. This minimizes the mechanics and cost. The ultrasonics can be performed rapidly after welding to detect defects without delay, with no safety hazard. Any position errors can be compensated for with the scan pattern.

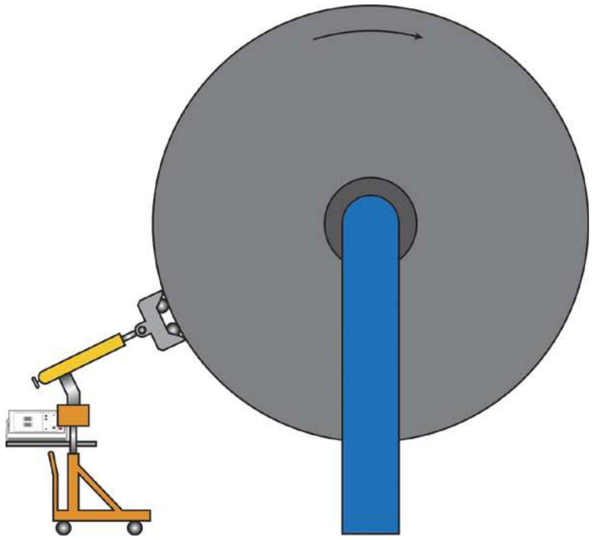

Figure 24: Rotating vessel for automated inspection.

Magnetic Wheel Scanners

These scanners run over a vessel as programmed. Some scanners simply run in a straight line, while others can be controlled by a joystick or other device. The TRAKER (shown in Figure 25 below) follows a magnetic strip so can inspect almost any shape of vessel, including nozzles.

Figure 25: Magnetic wheel TRAKER inspecting vertical weld.

Full Robotics

A full robotic system can be used for complex heads, as shown in Figure 26 below. Typically, robotics are the most expensive and flexible solution.

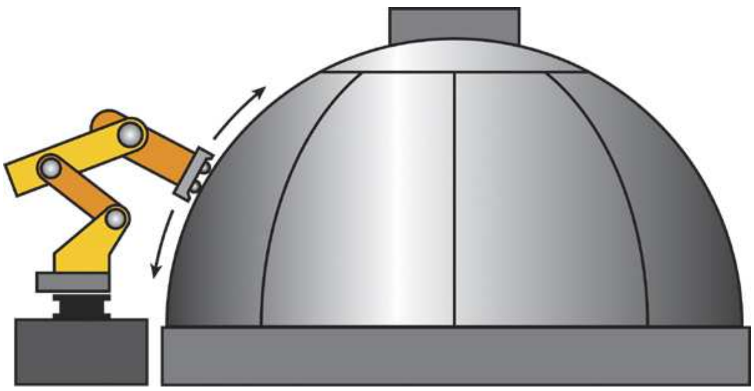

Figure 26: Schematic showing robotic scanner on curved head.

DISCUSSION

Phased arrays offer considerable potential for weld inspections due to their flexibility and versatility. Scan patterns can be tailored to the code, the component and the customer's requests. Once set-up, the scan can be re-loaded and used indefinitely. Phased arrays offer other advantages for pressure vessels: no safety hazards, "immediate" inspections, digital archiving, advanced imaging, better defect detection and improved sizing.

Compared with, say, pipelines, ASME Code Case 2235 permits a wide variety of inspection techniques, provided they all use full data collection and encoded positioning. This variety is compounded by the broad spectrum of pressure vessels to be inspected: small and large, simple and complex. To further complicate the issue, there is a huge number of welds profiles that can be used. All in all, the total number of inspection possibilities is almost unlimited, so flexibility is a major key. Not surprisingly, phased arrays can be code-compliant with every requirement to date.

R/D Tech has developed a spectrum of systems, from TOFD to portable phased arrays, to general phased arrays to premium systems, with a variety of mechanics: handscanners, welding bands, vessel rotation, robots, magnetic wheel scanners. All these systems can be configured to fulfill ASME 2235 and other codes. What is used where will depend on the customer's specific requirements (speed, detection capabilities, sizing accuracy), budget and knowledge.

CONCLUSIONS

1. Many different systems can be used to fulfill pressure vessel inspection codes and inspection requirements, from portable phased arrays to TOFD kits to advanced phased arrays.
2. There are as many possibilities for delivery systems: handscanners, welding bands, magnetic wheel scanners, rotate the vessel, robotics.
3. The customer's choice should be dictated by component requirements, budget and knowledge.

REFERENCES

1. Clay A.C., S-C. Wooh, L. Azar and J-Y. Wang, "Experimental Study of Phased Array Beam Characteristics", Journal of NDE, vol 18, no. 2, June 1999, page 59.

2. Wüstenberg H, A. Erhard and G. Shenk, "Some Characteristic Parameters of Ultrasonic Phased Array Probes and Equipments", NDT.net, vol 4, no. 4, http://www.ndt.net/article/v04n04/wuesten/wsuesten.htm

3. Lafontaine G. and F. Cancre, "Potential of Ultrasonic Phased Arrays for Faster, Better and Cheaper Inspections", NDT.net, vol 5, no. 10, October 2000 http://www.ndt.net/article/v05n10/lafont2/lafont2.htm

4. Lareau J.P and R.M. Plis, NDT.net, May 2002, Vol. 7, No. 5, "Phased Array Imaging First Use Qualification Effort: BWR Feedwater Nozzle Inner Radius Inspection from Vessel OD for a US Nuclear Power Plant", http://www.ndt.net/article/v07n05/plis/plis.htm

5. Whittle A.C., "Phased arrays – panacea or gimmick?", Insight Vol. 46, No. 11, November 2004, p. 674-676.

6. E.A. Ginzel and D. Stewart, "Photo-Elastic Visualisation Of Phased Array Ultrasonic Pulses In Solids", 16th World Conference on Nondestructive Testing, Montreal, Canada, August 31-Sept 4, 2004.

7. Ciorau P., D. MacGillivray, T. Hazelton, L.Gilham, D. Craig and J.Poguet, "In-situ examination of ABB l-0 blade roots and rotor steeple of low-pressure steam turbine, using phased array technology", 15th World Conference on NDT, Rome, Italy, October 11-15, 2000.

8. Dubé, N., "Electric Resistance Welding Inspection", 15th WCNDT, Rome, Italy, October 2000.

9. Standard Practice for "Mechanized Ultrasonic Examination of Girth Welds Using Zonal Discrimination with Focused Search Units", ASTM E-1961-98, publ. American Society for Testing and Materials, September 1998.

10. F. Jacques, F. Moreau and E. Ginzel, « Ultrasonic backscatter sizing using phased array – developments in tip diffraction flaw sizing", Insight vol. 45, no. 11, November 2003, p. 724.

11. ASME Code Case 2235-4, "Use of Ultrasonic Examination in Lieu of Radiography: Section I and Section VIII, Divisions 1 and 2", November 30, 2001, American Society of Mechanical Engineers.

12. Private communication – Guy Maes, Zetec, January 2005.

13. M. Moles and J. Zhang, "Construction weld inspection procedures using ultrasonic phased arrays", Materials Evaluation, January 2005, p. 27.