Pressure Vessel Inspection Codes for phased Arrays

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ABSTRACT

Pressure vessel and piping welds require inspection to code worldwide to minimize failures due to the presence of weld defects, and this applies in particular to nuclear reactors. Ultrasonic phased arrays are now commercial cost-effective. In particular, they offer major benefits over traditional radiography for weld inspections. Specifically, phased arrays are rapid, flexible and auditable when encoded scanning is used. In addition, phased arrays have no safety problems, no environmental effects and minimal data storage requirements.

However, all new technologies must follow a set or rules, or codes, to guarantee reasonable and reliable defect detection, and that a suitable process is followed. Arguably, the world leader in pressure vessel codes is ASME, and Section V of ASME for new construction welds has been very active in developing Codes and Code Cases specifically for phased array inspection of pressure vessel and piping welds. This paper describes the evolution of new inspection codes for phased arrays, specifically the issues that arose with introducing phased array codes, such as:

- manual vs. encoded scanning,
- calibration of all beams (particularly for S-scans),
- scanning patterns (linear or raster),
- bevel angle incidence and
- coverage.

In addition, a brief status update is given on other North American ultrasonic inspection codes, such as API, AWS and ASTM.

INTRODUCTION

Ultrasonic phased arrays are now commercially cost-effective, and used extensively for both in-service and construction applications. In particular, they offer major benefits over traditional radiography for weld inspections. Specifically, phased arrays are rapid, flexible and auditable when encoded scanning is used. In addition, phased arrays have no safety problems, no environmental side-effects and minimal data storage requirements.

However, all NDT technologies must follow a set or rules, or codes, to guarantee reasonable and reliable defect detection, and that a suitable process is followed. Pressure vessel and piping welds require inspection to code worldwide to minimize failures due to the presence of weld defects, and this applies in particular to phased arrays. Arguably, the world leader in pressure vessel codes is ASME, and Section V of ASME for new construction welds has been very active in developing Codes and Code Cases specifically for phased array inspection of pressure vessel and piping welds. This paper describes the evolution of new inspection codes for phased arrays, specifically the issues that arose with introducing phased array codes, such as:

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PHASED ARRAYS

Industrial phased arrays are a new technology, but are based on the same principles as other wave physics, plus "phasing". However, phased arrays are behind the development of related technologies like radar, sonar, medical ultrasonics and geophysics since the market is much smaller, and there are also specific issues: smaller wavelengths, different wave modes, wide variety of components and materials.

Phased arrays have been well-described elsewhere (1), so only a brief description will be included here. Essentially, an array of separate elements is individually pulsed, with applied time delays. The software permits the operator to define the angles, focal distances, scan patterns, and other parameters; the software then calculates all the time delays to permit "phasing" and constructive and destructive interference for steering the beam through a range of angles, scanning the beam along axes, focusing the beam and using multiple scan patterns. Figure 1 shows illustrations of electronic scanning (E-scans) and sweeping the beam (S-scans).

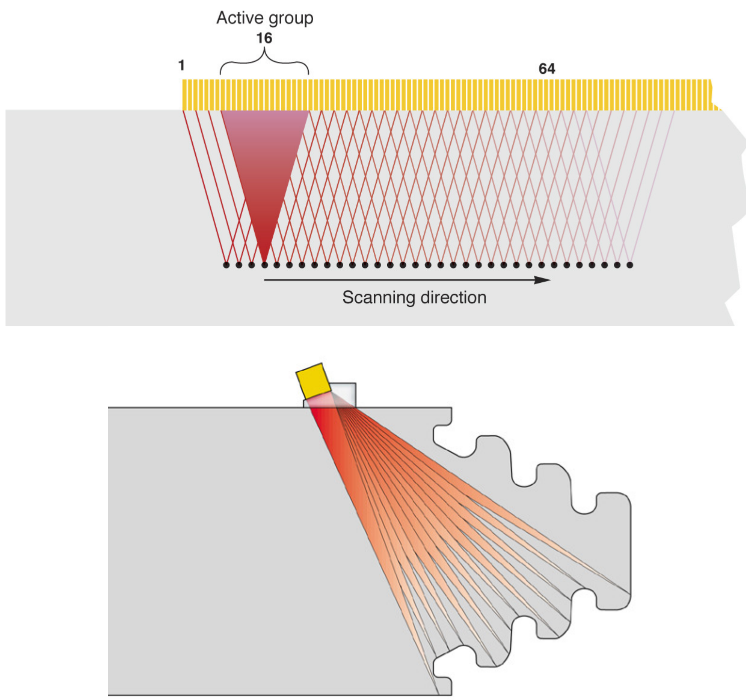

Figure 1 - Top, E-scan to perform corrosion. Bottom, S-scan on turbine blade root.

CODES - American Society of Mechanical Engineers (ASME)

ASME has been the leader in pressure vessel construction regulation for over a century, and is arguably still the leader. ASME has developed a full multi-section Code for pressure vessels, which includes Section V on NDE. Within Section V, Article 4 covers ultrasonic testing, and new techniques and technologies are introduced as Code Cases (initially), followed by Mandatory or NonMandatory Appendices (2). Section V has been successful recently in introducing new regulations for both Time-Of-Flight Diffraction (3) and phased arrays (4), arguably the two most significant developments in weld inspection in the last decades.

The normal procedure for ASME to develop a new or modified code is through the appropriate Working Group (Ultrasonics in this case), which argues the regulations on technical and literary grounds. This draft code case is then passed up to the Main Committee, balloted, negatives accommodated, and finally printed. The whole process typically takes years.

This paper describes some of the main issues that were discussed and resolved for the ASME phased array code cases.

Issues for ASME

Since it became apparent that phased arrays were commercially viable and could provide good quality inspections, ASME moved quickly to work on an appropriate rule set. The fastest way was through Code Cases, with a Mandatory Appendix to follow. This route was followed, with three Code Cases on manual phased arrays (2541, 2557 and 2558) and two on encoded linear scanning (2599 and 2600). The following main issues were discussed:

- calibration of all beams (particularly for S-scans),
- manual and encoded scanning,
- bevel angle incidence
- scanning patterns (linear or raster), and
- coverage.

Calibration of all beams (particularly for S-scans)

This turned out to a remarkably simple decision for the ASME Working Group. Article 4 requires waveforms to be calibrated; therefore, if one has thirty waveforms, all thirty waveforms need calibration. Therefore, all beams in all E-scans and S-scans must be calibrated. This request turned out to be much easier for some manufacturers than others. Figure 2 shows the OmniScan Auto-TCG approach; the beam is scanned over a series of calibration holes at different depths, and the overall gains electronically adjusted to the reference level.

Both time and distance require calibrating, i.e. both ACG (Angle Corrected Gain) and TCG (Time Corrected Gain).

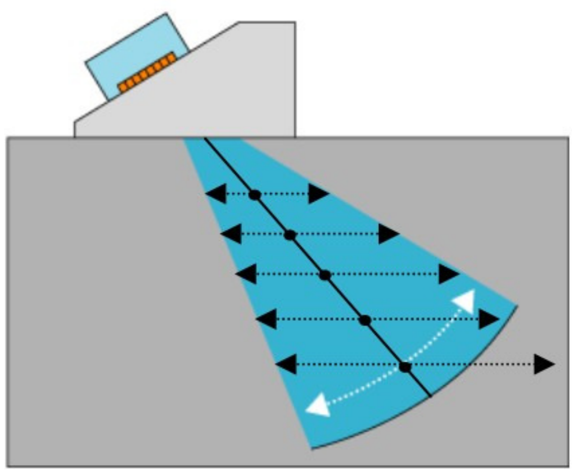

Figure 2 - Schematic showing OmniScan Auto-TCG approach to calibration.

Manual and encoded scanning

Manual scanning is a “no-brainer” as it is largely covered by Article 4, and these coverage provisions apply. For linear scanning, it is possible to perform manual scanning either with or without an encoder. The main differences are that having no encoder effectively does not allow repeatable data collection, and auditing is not possible. After discussion, ASME realized that there were so many problems with un-encoded linear scanning that it should not be acceptable. Therefore, only encoded linear scanning and manual scanning are permitted.

Bevel angle incidence

This issue has concerned ASME for some years, and rightly so. The concept is quite simple for E-scans (usually called "linear scanning" in the nuclear industry), which are fixed angle electronic scans. These can be defined much as any manual or AUT scan, by using "appropriate" angles, or choosing angles to produce incidence on the subsurface bevel approximately of normal incidence.

However, the issue is different for S-scans, where the beam is swept through the weld. Depending on the location of the array, the contours of the weld bevel, geometry, thickness etc, beams will strike the weld bevel at a wide range of angles (5); some of these angles may be appropriate and some inappropriate. The problem can be seen schematically in Figure 3, where a single S-scan is apparently "appropriate" near the cap, but obviously inappropriate in the root area. For manual scans, this is not an issue; however, it is of major concern with encoded linear scans.

First, there has been discussion on what is an "appropriate" angle; the jury is still out on this while some R&D is being finalized. Second, a single encoded S-scan may not be adequate in all cases; in fact, a single S-scan is really only satisfactory for thin-walls, typically less than ~10 mm (6). The solution today is to require appropriate angles using a Scan Plan which shows coverage, and is a required part of the report package. More functionally, there are now economical ray tracing packages on the market such as ESBeam (7), which specifically are targeted at defining Scan Plans for phased array and TOFD inspections of welds. Figure 4 shows a sample Scan Plan on a 10 mm wall using two 45^o-70^o S-scans (6). Depending on the weld profile etc., multiple S-scans may be needed for coverage and angles.

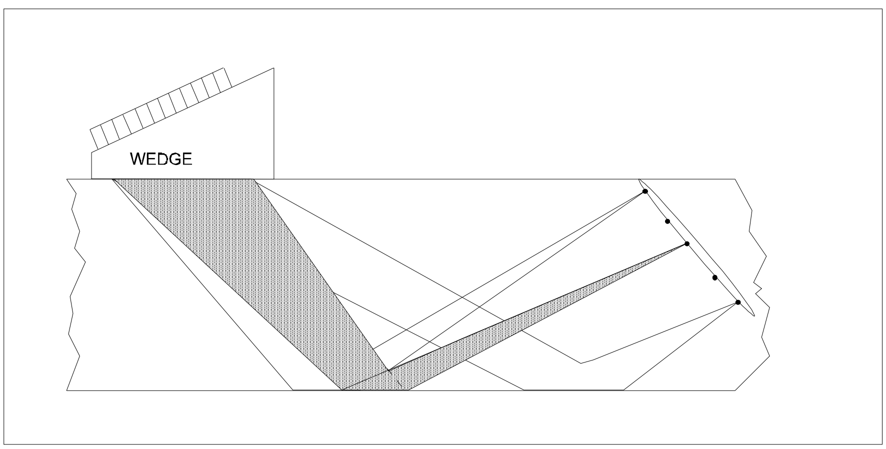

Figure 3 - Schematic showing single S-scan coverage of weld

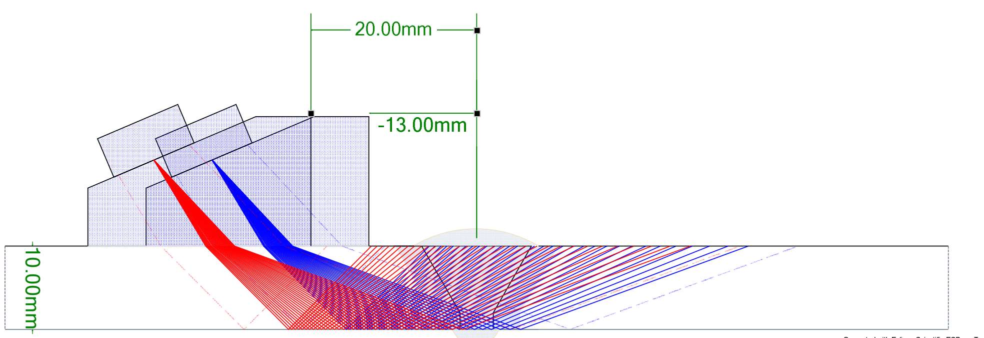

Figure 4 - Typical Scan Plan for butt weld.

At the time of writing, encoded linear scanning code cases are published (CC 2599 and 2600). However, there is still discussion on the final text and requirements of the Mandatory Appendix.

Scanning patterns (linear or raster) and coverage

Manual scanning patterns were not an issue, as they are covered in Article 4. Encoded scans were essentially covered by the introduction of Scan Plans to show coverage. For example, the array has to be long enough to provide full weld coverage using multiple beams, or multiple passes used. Other details, like how often the data need to be collected axially (every 1 mm on thinner material) and how many data points can be dropped before re-scanning, were derived from other AUT codes.

One difference for E-scans is that it is possible to step electronically every element, or jump elements to save time and data storage, i.e. to optimize scanning. This was covered in the code case by requiring a minimum of 50% coverage (6 dB). Stepping every element with a typical array gives ~90% coverage, i.e. significant over-scanning.

A similar situation arises with S-scans, where the beam sweep gives redundant coverage at a 1^{o} increment (as frequently practiced). Here, the code case proposes using a minimum of 50% coverage again, though the issue has not been finalized for the Mandatory Appendix.

Other issues

Several other issues required little discussion: reporting (including all the Essential Variables plus special variables for phased arrays); full data storage with encoded scanning; displays.

OTHER CODE ACTIVITIES

API

A recent trial using American Petroleum Institute QUTE procedure was very successful. No changes were required to API procedure UT2 for OmniScan. OmniScan is now regularly used on API work on e.g. API 1104 and RP2X. In general, API is quite philosophically advanced and has adopted phased arrays without a lot of problems.

AWS

The American Welding Society is a different story, and is well locked into their D1.1 code. Here, requirements for manual inspections are closely specified, and OmniScan M (manual) has been adapted to them. Alternative techniques, e.g. AUT, require special approval through Annex S, which requires the Engineer’s approval. In 2005, special approval was obtained by a Los Angeles company through Performance Demonstration, but this is an exception. A linear encoded AUT Annex is being developed, but AWS has been reluctant to accept this concept until recently as the probe is not oscillated as required by D1.1.

ASTM

The American Society for Testing and Materials has published a Recommended Practice for setting up phased arrays - E-2491-06 (8). This RP requires both Angle Corrected Gain (ACG) and Time Corrected Gain (TCG) for calibration, which limits the range of beam sweeping possible with phased arrays. Figure 5 shows an example of an S-scan which definitely could not be calibrated and would also generate both shear and longitudinal waves.

Figure 5 - From Insight, photo of phased array weld inspection using S-scan.

A Standard Practice for phased array is currently being drafted (essentially a procedure for manual and encoded PA).

CONCLUSIONS

1. ASME in particular has worked hard to develop several codes and code cases for phased array inspections of welds in pressure vessels.
2. The ASME manual and encoded linear scanning Code Cases are published. A Mandatory Appendix is in process.
3. Overall, ASME has addressed: calibration, coverage, bevel angle incidence, scanning procedures, Scan Plans, plus manual vs. encoded scanning.
4. Other North American codes bodies, specifically ASTM, have been active in writing codes and practices.

DISCLAIMER

These opinions are those of the author, and may or may agree with those of ASME.

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2) ASME Section V Article 4, "*Ultrasonic Examination Methods for Welds*," American Society of Mechanical Engineers, 2007 Edition, July 1, 2007.
3) ASME Section V Article 4 Mandatory Appendix III – "*Time of Flight Diffraction (TOFD) Technique*"
4) ASME Section V Article 4, Code Cases 2541, 2557 and 2558 for manual inspections; 2599 and 2600 for encoded linear scanning.
5) M. Moles and J. Zhang, "Construction weld inspection procedures using ultrasonic phased arrays", *Materials Evaluation*, January 2005, page 27.

6) E. A. Ginzel and M. Moles, "S-scan Coverage with Phased Arrays", *Materials Evaluation*, August 2008, page 810.
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