Qualification of Phased Arrays to ASME Section V and Other Codes

Michael MOLES, Olympus NDT, Toronto, Canada

Abstract - Phased arrays offer major advantages over conventional radiographic inspection of welds: no radiation hazard, chemical disposal or licensing requirements; no disruption of production; near real-time inspection results, plus vertical defect sizing for Engineering Critical Assessment. In comparison with conventional ultrasonics, phased arrays are significantly faster, more flexible, reproducible, and can be tailored to the application. Overall, there is a strong interest in phased arrays, especially now that units are competitively priced and software is robust. However, the codes are not as advanced as the technology, as expected.

In general, the codes accept phased arrays as a valid technology, but say little on the technique or procedures. This paper describes a typical process required to approve new inspection techniques for ASME Section V, specifically Olympus NDT's OmniScan unit. The rationale and processes required for Section V, both Article 4 and the new Article 14 for novel techniques, is described. The various processes can be applied to:

1. Encoded electronic scanning (i.e. fixed angle raster scanning or E-scans), as in this case.
2. Encoded sectorial scans (S-scans) where the beam is swept through a range of angles,
3. and manual S-scans. A variety of techniques, procedures and reporting documents have been developed. There will also be updates on developments in other code areas:

1. ASME phased array code cases
2. ASTM recommended practice for phased array set-up.
3. AWS code developments, and
4. API approvals for portable phased arrays.

Background

NDT is described in ASME B&PV Code Section V. There, the traditional methods of ultrasonic application of the various methods are described. Descriptions in Section V are, for the most part, "good practice". When NDT is required in the referencing Code Section, it directs the user to Section V and the traditional methods. However, when a part or component is not typical and/or if a new technology is introduced that requires deviation from the traditional methodology, some of the ASME Code Sections additionally require that the process be "qualified". Examples of where the qualification process has been a requirement include ASME Section VIII Code Case 2235-6 [1] and ASME Section XI [2].

Qualification is a process whereby evaluation of technical, general and performance-based evidence is presented to verify that the examination technique, equipment and written procedure conform to the requirements of the Code, Standard or Specification.

This methodology is usually associated with the nuclear industry; the ASME Section XI, Appendix VIII, commonly referred to as the Performance Demonstration Initiative (PDI) and the European Network for Inspection Qualification (ENIQ) methodologies are probably the best known. Conformance to these programs requires that the special conditions of the test are mocked-up and equipment, techniques and personnel demonstrate efficacy and proficiency.

ASME Section VIII Code Case 2235 is a non-nuclear example of the qualification requirement that provides an opportunity to examine suitability of the traditional manual ultrasonic techniques that may be different from those described in Section V, Article 4.

Until recently there may have been some uncertainties as to the methods in which a qualification should be carried out. In the 2003 revision of Section V, Article 14 was added. This is entitled “Examination System Qualification” and provides ASME users a guideline on the methods and rigor involved in qualification. Article 14 has provided a timely solution to concerns for acceptance of new ultrasonic phased array technology.

A Review of Examination Requirements

Early in 2004 R/D Tech (now Olympus NDT) asked Materials Research Institute and Eclipse Scientific Products to assess the suitability of using a portable phased array instrument, OmniScan [3], on weld inspections. This was not as simple as using a new digital manual ultrasonic A-scan scope. It meant that an entirely new set of parameters needed to be examined. The biggest concern was how users could rationalize deviation from the “tried-and-true” techniques prescribed by the various codes.

After a code review it was concluded that, in North America, ASME Section V seemed to be the most extensively used NDT regulatory document. Consideration was then given to how the provisions of this Code might incorporate the new portable ultrasonic phased array technology. Recent revisions to Section V have incorporated several provisions that open the doors to new advances in ultrasonic technology. These are identified below. Using these provisions, a program was developed to demonstrate examination techniques using the portable ultrasonic phased array apparatus. A set of Standard Practices and Techniques (i.e. a full working Procedure) was developed that, when used, demonstrated conformance to the requirements of the ASME Code.

ASME Section V Article 1 T-150 explains how Procedures may be developed that deviate from those described in Section V for special configurations or materials. It also states that these special configurations may require modified techniques that are proved by demonstration to be equivalent or superior to those described in Section V.

According to ASME Section V, Article 1 T-160, calibration aspects of instrumentation are required to meet both Subsection A and B as applicable. Subsection A includes the ASME standards whereas Subsection B includes the ASTM requirements. Of these requirements the screen height and amplitude control linearity checks are listed as the “Mandatory Appendices” in Article 4 of Subsection A. Subsection B items being based on ASTM will typically reference ASTM E-317 as a guide to checking calibration of the instrument parameters, but E-317 is not listed in the Subsection B list of documents.

Since the procedures developed for OmniScan were considered a "special configuration" as allowed for in T-150, it was then up to the "Code User" to specify what calibrations are required and when. The Standard Practices developed for the OmniScan identified what calibration verifications are to be checked in the field. These include the requirements for the mandatory ASME checks for screen height and amplitude control linearity.

Special consideration for the fact that the instrument is based on phased-array technology has resulted in deviations from standard practices that might be used with single element pulse-echo probes and instrumentation. These are considered to be in accordance with the instructions of ASME V Article 1 T-160.

ASME Section V Article 4 T-421.2 specifically states that Computer Imaging Techniques (CITs) may be used. This paragraph references Non-mandatory Appendix E as a list of described CITs that are permitted. Phased array systems are specifically stated within this list.

Sensitivity settings for the "traditional" manual UT are based on responses set to a Distance Amplitude Correction curve using side drilled holes (or ID and OD notches) in what is called a "Basic Reference Block". However, when reading ASME Section V Article 4 T-434.1.1 it is clear that use of the Basic Calibration Blocks is not actually mandatory but a recommended practice. T-434.1.1 states that "Known reflectors (i.e. side drilled holes, flat bottom holes, notches, etc.) shall be used to establish primary reference responses of the equipment". Provided the changes from the basic calibration techniques for sensitivity can provide an equivalent or superior performance, ASME specifically allows deviation from the basics (see Article 1, T-150 (a)).

ASME Section V Article 4 Table T-422 identifies the "Requirements" of an ultrasonic procedure and identifies which are considered essential variables and which are considered nonessential variables. These are reproduced here in Table 1; in practice, most variables are considered "essential".

Table 1 List of Essential and Nonessential Variables

Requirement	Essential variable	Nonessential variable
Weld configuration (thickness, product form)	X	
Personnel qualification requirements		X
Personnel performance when required	X	
Surface of examination	X	
Surface condition		X
Couplant brand		X
Technique (straight, angle, immersion, contact)	X	
Angles and wave modes in the test piece	X	
Probe type, frequency, size, shape	X	
Special wedges, adaptors, etc	X	
Ultrasonic instruments	X	
Calibration blocks and techniques	X	
Directions and extent of scanning	X	
Automatic alarm or recording when used		X
Scanning (manual vs. automatic)	X	
Method for discriminating flaw and geometry	X	
Method for sizing flaws	X	
Computer enhance acquisition when used	X	
Records (including minimum calibration data recorded)		X
Scan overlap (decrease only)	X	

The procedure developed for OmniScan identified all the items in the table above and described the extent to which they are applicable. Variables pertinent to ensure that all phased array software controls that could affect the amplitude response or data acquired (e.g. time base range, gated region, sampling, etc.) were identified on the technique information sheets developed for each configuration.

Definitions

As with any new technology, phased arrays have their own unique terminology and definitions. Some selected definitions are listed here.

1. ***Electronic scan**:* Also termed an E-scan or electronic raster scanning. The same focal law is multiplexed across a group of active elements; E-scans are performed at a constant angle and along the phased array probe length. E-scans are equivalent to a conventional ultrasonic probe performing a raster scan.
2. ***Sectorial scan**:* Also termed an S-scan, sector scan or azimuthal scan. This may refer to either the beam movement or the data display. As a data display, it is a 2D view of all A-scans from a specific set of elements corrected for delay and refracted angle. When used to refer to the beam movement, it refers to the set of focal laws that sweeps through a defined range of angles using the same set of elements.

3. **Angle Corrected Gain**: also called ACG. This is compensation for the variation in signal amplitudes received from fixed depth SDH's during S-scan calibration. The compensation is typically performed electronically at multiple depths. Note that there are technical limits to ACG, i.e. beyond a certain angular range, compensation is not possible.
4. **Array Probe Terminology***:*
    a. ***Grating Lobe****:* Undesirable lobes of ultrasonic energy caused by the regular, periodic spacing of array elements.
    b. ***Active Aperture****:* The dimensions of the active acoustic elements.
    c. ***Passive Aperture****:* The dimension of an array element's length.
    d. ***Elevation****:* The same as Passive Aperture.
    e. ***Virtual Probe****:* A group of individual array elements, pulsed simultaneously or at phasing intervals to generate a larger acoustic aperture.
    f. ***Axial (or Vertical) Resolution****:* The ability to distinguish closely spaced reflectors that lie in a plane perpendicular to the ultrasonic beam's direction of propagation.
    g. ***Lateral Resolution****:* The ability to distinguish closely spaced reflectors that lie in a plane parallel to the ultrasonic beam's direction of propagation.
    h. ***Cross-Coupling:*** An undesirable condition where array elements are activated, electrically or acoustically, by adjacent elements.
    i. ***Element Width:*** In a rectangular element, the acoustic element's short dimension.
    j. ***Element Length:*** In a rectangular element, the acoustic element's long dimension. See Passive Aperture.
    k. ***Element Pitch:*** The distance between the centers of two adjacent array elements.
5. **Phased Array Wedge Parameters***:*
    a. ***Wedge Velocity:*** The longitudinal wave speed of the wedge material.
    b. ***Wedge Angle:*** The incident angle of a wedge as referenced to the normal longitudinal axis.

With phased arrays, there are many possibilities for different scanning and imaging. For example, welds can be inspected using E-scans or S-scans, in manual, encoded (semi-automated) or fully automated scanning. In this approval, encoded E-scans were used.

The Qualification Process

The "Qualification" was made using unique capabilities of phased array ultrasonic technology. For the performance demonstration the techniques were a limited departure from traditional manual techniques. Expectations needed to be defined that would allow easy comparisons between the "pre-qualified" manual techniques as described in ASME Section V and the new technology.

The process involved detection, length sizing, depth and location measurements of embedded flaws of known sizes (typical NDT qualification welds were used "as manufactured"). Expectations were defined as detection over the reference level of all relevant imbedded flaws. These were then compared against the responses seen using the manual techniques described in ASME Section V. A limited range of test piece thicknesses and geometries was used to establish the performance demonstration protocol. These are listed in Table 2.

Table 2 Thicknesses and Geometries used for Qualification

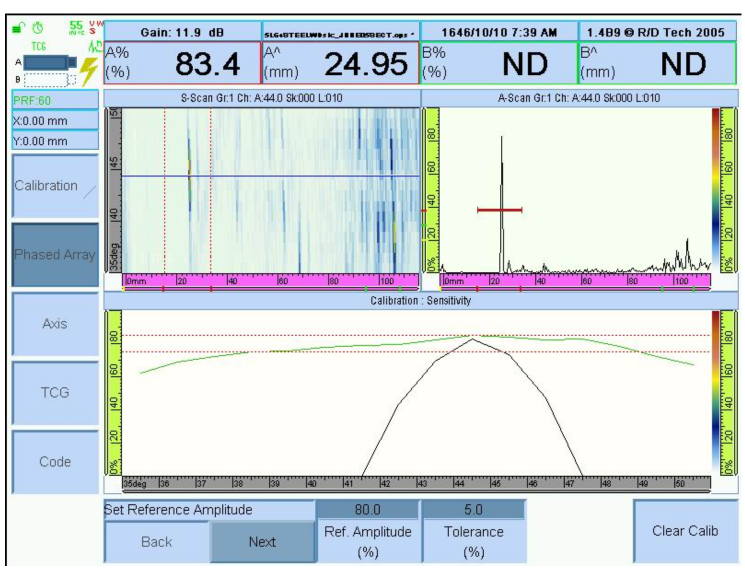
Thickness	Form
13mm	Plate
13mm	Pipe 4.5 inch diameter
18mm	Pipe 12 inch Diameter
25mm	Plate

Weld Inspection with Phased Array UT

Part of the deviations from "normal" practice using single element techniques is the requirement to calibrate the phased array system for delay and attenuation differences due to different path lengths in the wedge that the various focal laws require.

Figure 1 illustrates an example of the special screen feature used to ensure that the amplitude response from each focal law provides a uniform amplitude response to the calibration reflector. The operator moves the probe back and forth as the portable phased array unit automatically adjusts gain to the prescribed amplitude (80% is indicated on Figure 1). The horizontal scale is the virtual probe aperture which defines the group of elements ("focal law") that is sequenced in the scan. These may be linear steps or angles, depending on whether E-scans or S-scans are being calibrated. Once the amplitude response is seen to be the same for all the virtual probe apertures, the operator enters the calibration as part of the configuration.

Figure 1 Sample pane in calibration sequence of phased array system



Calibration for reference sensitivity was made using the known calibration reflectors described in ASME Section V Article 4 and a time corrected gain (TCG) applied. Figure 2 illustrates the probe positioned on a standard calibration block used for pipe weld inspections. The probe is equipped with two small irrigation lines for couplant and an encoder.

Figure 2 Phased Array Probe on 12"
Diameter Standard Calibration Block

For the thicknesses examined, a single linear scan was required. The operator has the option to display several views simultaneously and in real time, as illustrated in Figure 3. More recently, multichannel scans and displays have been developed. Thus an operator could use two arrays, one on either side of the weld, with multiple E-scans or S-scans, to scan the weld to code in a single linear scan.

Figure 3 Real time Data Display

The critical aspect of qualification is detection of all pertinent flaws. ASME has provided for a generic sensitivity and angle beam coverage in Section V requirements for manual ultrasonic testing. Carrying out ultrasonic inspections to these guidelines precludes any need to qualify the techniques. However, the detection of all pertinent flaws over the required reference level at the required sensitivity need not always occur when following the "pre-approved" ASME manual UT techniques due to the variability of parameters that affect signal amplitude. This has made such a qualification process somewhat onerous.

Section V manual techniques are geared towards the "traditional" treatment of weld inspections; that being as a workmanship assessment tool instead of a critical flaw assessment tool for fracture mechanics. Selecting qualification specimens with "typical flaws" could conceivably result in the traditional techniques not detecting the embedded flaws over the reference level. This is an important factor because many of the acceptance criteria used in ASME Code Sections require that the flaw exceed the reference level before its length is assessed for accept or reject.

The qualification process used in this program made the requirement that all flaws detected would need to exceed the reference level in order to qualify the technique. Various ASME acceptance criteria exist and not all use signals exceeding the reference level to assess acceptability. Section III and Appendix 12 of Section VIII require that all signals originating from flaws that produce a response greater than 20% of the reference level shall be investigated. However, indications characterized as cracks, lack of fusion or incomplete penetration are unacceptable regardless of length (the wording suggests regardless of amplitude if over 20% reference).

In addition to simply detecting flaws over a threshold, several of the ASME Code Sections require flaw height assessment. The Procedure demonstrated used a tip diffraction sizing for flaw height assessment. It should be noted that ASME Section V Article 4 does not specify which vertical sizing method must be used. The non-mandatory appendices describe a method for planar reflectors in Appendix D. This is just one option that may be used. As configured for the qualification, the data display also allows for a straightforward "front-centre-back" of beam to the minus 6dB drop points typically used as described in ASME Section V, Article 4, Appendix H.

Other Code Activities

ASME

A preliminary code case for phased arrays to cover single angle scanning has been submitted through the Ultrasonics Working Group, and initially accepted. Four more code cases are being prepared to cover: manual S-scans, manual E-scans, encoded E-scans, and encoded S-scans. Associated companies are also working on ASME approval for manual S-scans.

The E-scan code case is essentially the same as current automated scanning using conventional equipment. S-scans are less known, and there are issues such as number of passes, bevel incidence angle etc. These are being addressed separately.

A cautionary paragraph about the use of single S-scans on thick-section welds has been proposed for Section V. Once the code cases are published, a comprehensive Mandatory Appendix for phased arrays will be started.

ASTM

A Recommended Practice for phased array set-up has been sent to committee vote. This RP will require full angular gain compensation (ACG) and TCG over the side-drilled hole calibration range for S-scans. If full ACG and TCG are not possible, then the angular range must be reduced.

API

A code demonstration was performed with Davis NDE and Olympus NDT using many API-evaluated weld samples. This approach uses API QUTE UT 1 and UT 2 procedures for new technology/techniques.

AWS

A couple of companies are currently working on demonstrating AWS D1:1 compliance via Annex K. These approvals will be “specials” due to Annex K and “Engineer”; the requirement is that each case meet the “Engineer’s” approval. The best approach is to wait until 2006 version, where new technology/technique approvals will be codified.

Conclusions

The techniques developed for weld flaw-detection using the OmniScan phased array ultrasonic instrument may be considered to be derived from codified techniques. However, they are a deviation from the codified techniques in that it is an examination using a computer imaging and semi-automated phased array system instead of the “traditional” manual techniques, which use only an A-scan presentation. Since the techniques are derived from codified technique, it is considered a general qualification. Scans developed for the Techniques are essentially those described for manual ultrasonic testing but carried out using electronic rastering.

It is worth noting that a parallel project was carried out for a PDI qualification of the OmniScan instrument [4]. Whereas the Section V qualification used a simple linear array, the PDI qualification used a 2D 5x3 array. This provided the simultaneous collection of three different skew angles for circumferential flaws (0^o, $\pm$ 15^o), and five angles for axial flaws, in addition to a sectorial sweep and multiple passes. The Performance Demonstration Initiative qualification was carried out on both ferritic and austenitic samples and thicknesses from 17mm to 70mm.

It may be concluded therefore that the provisions of ASME to allow for changes by qualification will expedite the transition from traditional manual ultrasonic testing to manually assisted phased array ultrasonic testing. Qualifications carried out should not be considered generic to all equipment and all techniques. However, with sufficient preparation and a well documented qualification plan, confidence in the new technology should ease the acceptance by phased array systems.

Formal certification with associated technical justification reports should be the evidence that a user of inspection services should expect that the system used on their project will provide as good or better results than the traditional manual techniques.

Acknowledgements:

Several people and companies assisted with this code qualification, including Ed Ginzel of Materials Research Institute, Robert Ginzel of Eclipse Scientific Products, Simon Labbé of Olympus NDT Canada, Mark Davis of Davis NDE and Chris Magruder of Olympus NDT.

References:

[1] ASME Boiler and Pressure Vessel Code, Code Case 2235-6, May 21, 2003, “Use of Ultrasonic Examination in Lieu of Radiography”

[2] ASME Boiler and Pressure Vessel Code, 2001, 2003 rev., American Society of Mechanical Engineers, New York

[3] Olympus NDT, http://www.rd-tech.com/omniscanpa.html, 2004.

[4] G. Maes, J. Berlanger, J. Landrum and M. Dennis, “Appendix VIII Qualification of Manual Phased Array UT for Piping”, 4th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components in London, UK - December 6-8, 2004.