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Automated Ultrasonic Inspection of Nozzle Welds using Phased-Array Ultrasonic Testing

Part 1 - Inside Access

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Abstract
Nozzle weld inspections have long been an important function carried out by ultrasonic test methods. When performed using manual techniques the plotting of located defects is a time-consuming ordeal requiring local profiles, wall thickness readings and compensation for curvature effects. The introduction of Code Case 2235 for ASME compliant vessels has allowed many welds in the vessel to be inspected using ultrasonic methods. The computerisation requirement in the Code Case is easily applied to longitudinal and circumferential butt welds. However, complexities of geometry can limit the useful application of ultrasonic methods to nozzle welds unless provision is made for the mechanics to provide adequate tracking to assure full-volume beam coverage.
This paper discusses the options available when phased-array techniques are used with mechanical apparatus that provides encoded motion from the inside surfaces of the nozzle. Modelling provides evidence of the physical parameters that must be considered for full coverage. Actual scan results are provided to indicate how well the models predict the coverage by detecting targets at the edges of the weld zones.
Modelled and actual results indicate that a scan-plan, using a ray-tracing programme, can provide suitable indication of required coverage. In many cases, the mechanical apparatus used to guide the probe can be designed with a minimum of complexity when scanning access is from the inside surface of either the nozzle or vessel.

Keywords: Phased-array, ultrasound, nozzles, mechanised

1. Introduction

Nozzle inspection by UT has long been carried out using manual techniques. Good practice for the angles and surfaces of approach has been codified and the recommended techniques found in international standards (see EN 1417). In some situations the provision for weld inspection of pressure vessel welds has been restricted to radiography as a result of Code requirements (e.g. ASME) while in others the users tend to prefer radiography due to the availability of a permanent record.

ASME Boiler and Pressure Vessel Code has, via the Code Case 2235 (for Sections I, VIII and XII vessels), made provision that all pressure vessel welds (>0.5 inch for these Sections) may be examined using ultrasonic methods. However, the requirements to comply with CC2235 dictate that the inspections use computerised data acquisition methods. In order that the computerised equipment is able to correctly plot the data acquired, the geometric conditions of the nozzle welds must be factored into both the data display software and the mechanical motion used for the probe motion. The degree of complexity of the software and mechanical motion will be in large part based on the physical dimensions of the nozzle and the access available at the time of inspection.

This paper describes some of the considerations of nozzle inspection and demonstrates how modelling can help to address the mechanical and ultrasonic problems of a mechanised inspection.

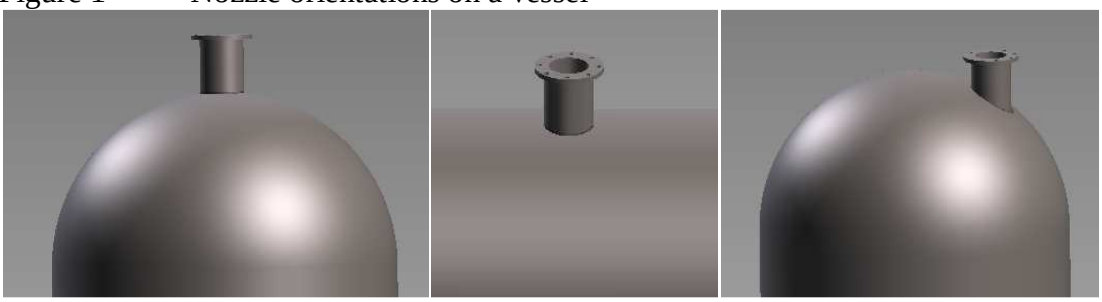
Part 1 of this two part paper will consider general aspects of nozzle inspection s with illustrations from an inspection of the nozzle ID in a set-through nozzle. Part 2 (a separate paper) will look at the modelling aspects involved for inspection of the set-through nozzle when access is from the vessel OD.

2. Nozzle Types

Nozzles are generally speaking a cylindrical inlet or outlet attached to a cylindrical or spherical vessel. The simplest configuration has the nozzle (secondary cylinder) project from the vessel (primary cylinder) at right angles. The cut made in the primary vessel is then a circle. When the secondary cylinder has an angle other than 90° to the primary vessel the cut made in the primary vessel is an ellipse.

Figure 1 illustrates three options of nozzle configurations that are commonly found on vessels.

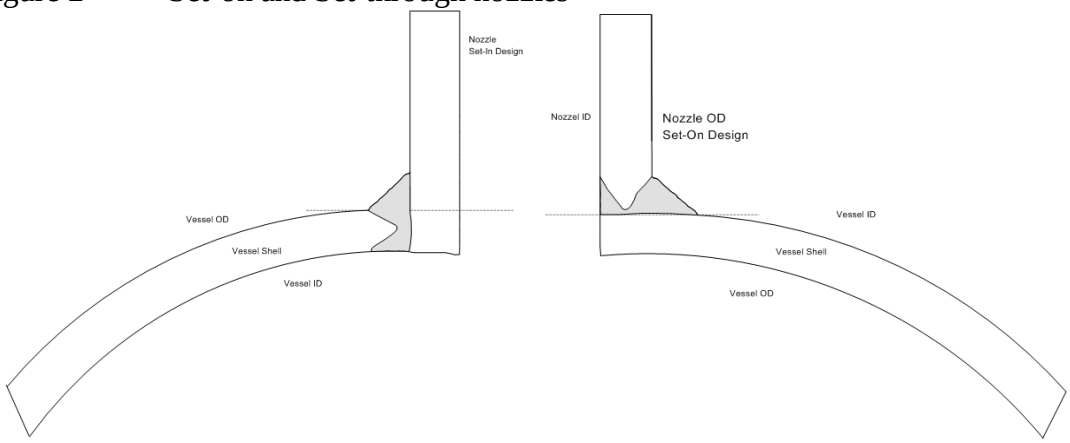
Figure 1 Nozzle orientations on a vessel



Nozzles on the hemi-head of a vessel provide a symmetrical access from all directions when approached from either the vessel surface or the nozzle surface. Nozzles that are perpendicular to the cylindrical form of the vessel repeat the shape in every quadrant with a mirror symmetry. Nozzles set at an angle to the vessel or offset on the hemi-head have a mirror symmetry with each half of the nozzle repeating the curvature on the opposite side of the axis of symmetry.

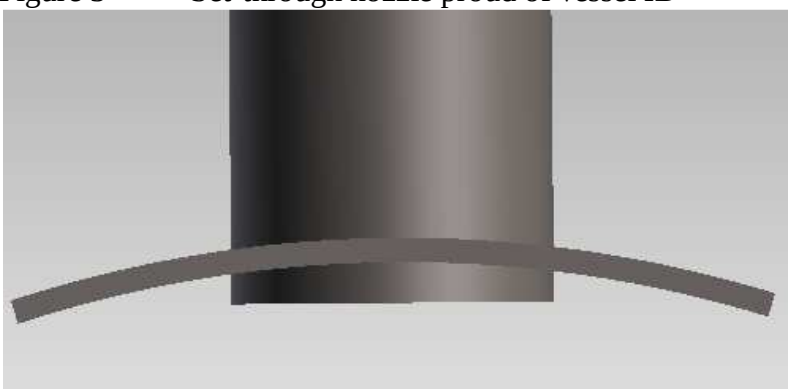
Ultrasonic inspection of nozzle welds is primarily done from the surface of the component where the weld bevel is made. Nozzle types can be identified as either “set-on” or “set-in” (or “set-through”) nozzles. Set-on nozzles have the secondary cylinders (i.e. the nozzle) prepared with the weld bevel, while set-in nozzles have the primary vessel prepared with the bevel. Examples of the nozzle types are illustrated in Figure 2.

Figure 2 Set-on and Set-through nozzles



A variation on the set-through nozzle exists where the nozzle is not contoured to match the vessel curvature but instead protrudes into the vessel. This is illustrated in Figure 3.

Figure 3 Set-through nozzle proud of vessel ID



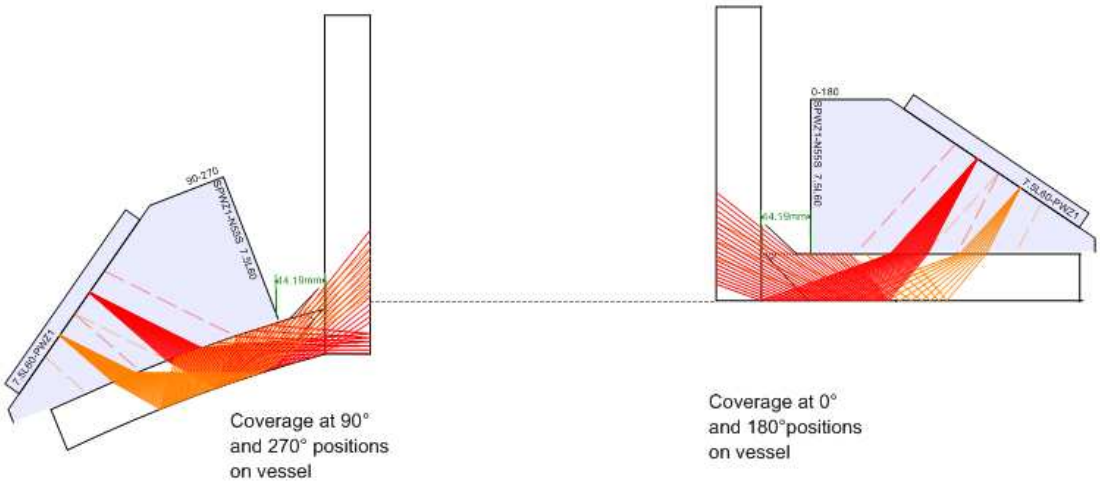
3. Scan Plans

In all cases there are subtle geometric considerations to address in constructing a useful scan plan for nozzle inspections. These considerations would relate to the effect of curvature of the weld or the curvature of the probe's scan surface. In addition to the effect on the beam that a constantly changing curvature can have, the operator must also be aware of the fact that the probe or beam elevation may need to move relative to the vessel apex, and some probes may require that the wedges be contoured to allow proper coupling to the test surface..

Modelling can be used to assist in all of these commonly encountered situations in the ultrasonic examinations of nozzles.

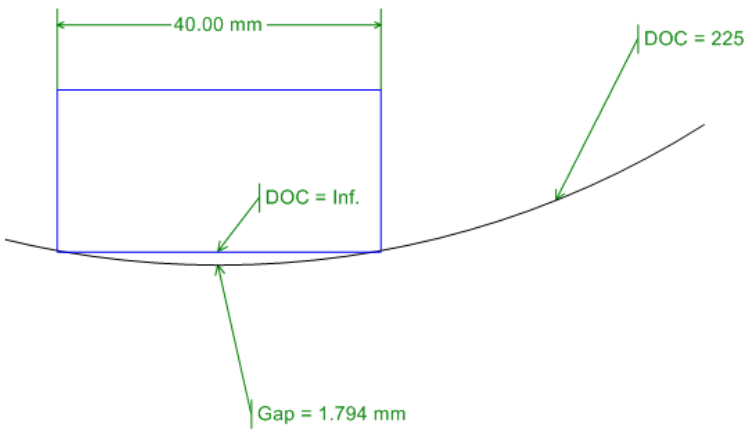
Ray-trace modelling programmes allow probes to be virtually placed on geometric profiles and predict the centre rays of the beam. Figure 4 illustrates an example of ray-tracing phased-array focal laws to address a set-through nozzle weld, using a popular commercial programme.

Figure 4 ESBeamTool scan plan showing coverage for set-through nozzle from vessel OD



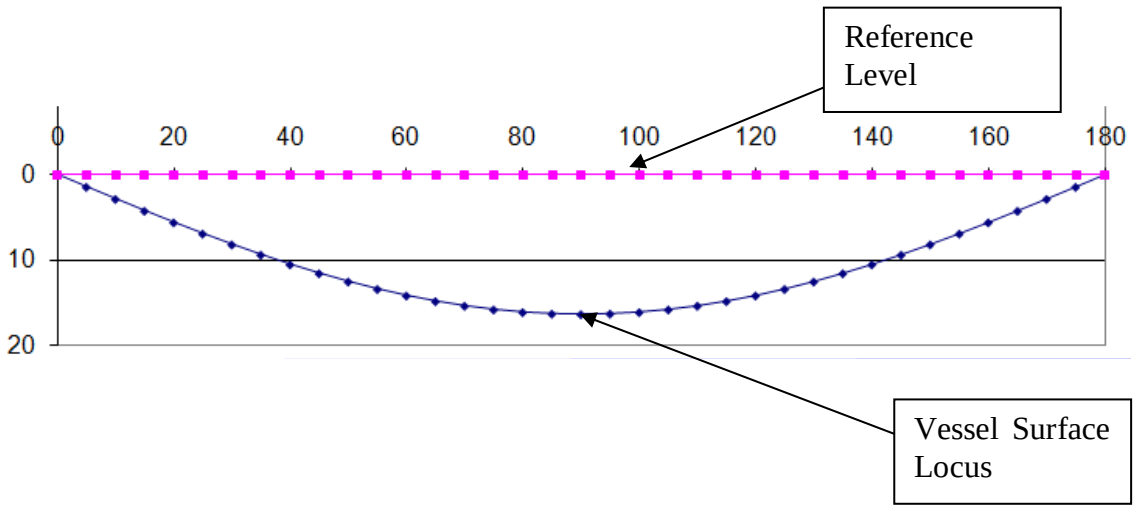
Further modelling with simple graphics can indicate whether or not the probe wedge should be contoured. EN-1714 is one of the few standards in NDT that indicates when contouring is required, . stating that if a gap of more that 0.5mm exists between the bottom of the wedge and the test surface, the wedge is to be contoured to match the curvature. This can be calculated given the probe wedge dimension in the direction of the curvature and the specimen diameter (free downloadable software is available to compute this requirement at http://www.eclipsescientific.com/Software/ESWedgeGap/info.html).
An example of the need for curved wedges would be when performing a scan with a linear phased- array probe from the inside surface of a nozzle. Figure 5 illustrates that using the standard 40mm wide wedge used for mechanised UT in a nozzle with a 225mm (10 inch) inside diameter, leaves a 1.8mm gap, more than allowed in EN 1714.

Figure 5 Gap consideration for flat probe on 225mm inside diameter



Further modelling of the scanning conditions can be done to compensate for the variation of the probe position relative to the weld elevation. Change in elevation of the weld and probe is seen in Figure 4. The high point is at the vessel axis (0° and 180°) and the low points at 90° and 270° relative to the vessel axis. This is indicated in Figure 6. which plots the difference between the contact surface of the vessel to the nozzle from its origin (0mm at 0°) to the maximum displacement at 90° around the nozzle. The contact point then retraces its path to the apex of the vessel at 180° and the process repeats again for the other half of the circle around the nozzle, i.e. the maximum displacement distance is achieved at 270° and then the displacement decreases until the origin is reached at 0°.

Figure 6 Plot showing weld and probe elevation change



The equation to estimate the surface displacement that will be encountered for a cylindrical nozzle placed at right angles to a cylindrical vessel is

$$d = R - \sqrt{R^2 + r^2}$$

Where d is the maximum displacement, R is the radius of the vessel and r is the radius of the nozzle.

For a 250mm diameter nozzle placed on a 1m diameter vessel the displacement of the vessel surface at the 90° and 270° positions is about 16.4mm.

Detail of the scanning considerations from the vessel outer surfaces is the subject of Part 2 of this series of two papers. The remainder of this paper will present a description of how modelling tools were used to design an inspection of a nozzle weld where access was from the inner surface of the nozzle for a set-through weld.

4. Nozzle Inner Surface Scanning - Set-through Nozzles

4.1 Nozzle Flush

Figures 2 and 3 illustrate the standard welded configurations for nozzles. For set-through nozzles, as in Figure 3 where the nozzle is projected proud of the vessel ID, inspection using a single element probe rastered up and down to near the limit of the nozzle projection edge allows for a simple mechanical solution with the old mono-element technology. However, for the condition where the nozzle is flush with the vessel ID a mechanical tracking system would always be required to prevent the probe from falling off the edge of the nozzle because the raster length is constantly changing around the nozzle.

A linear array phased-array probe can be configured to ride at a fixed position around the nozzle inside surface and provide an electronic scan of the weld. Using the equation to estimate the surface displacement around the nozzle (described in Section 3) the probe can be selected to ensure that the array can remain at a fixed depth while the beam coverage of the electronic scan is adequate to follow the sinusoidal contour made by the weld contact locus. (Note that for very thick welded sections it may not be possible to place the probe in a single position and cover the entire range of interest).

For the purposes of this paper, a set-through nozzle mock-up was fabricated. Details of the nozzle are listed in Table 1:

Table 1 Nozzle mock-up details

Item	Value
Vessel Diameter	1000mm
Vessel Wall Thickness	13mm
Nozzle Diameter	250mm (ID)
Nozzle Wall Thickness	13mm
Materials	Carbon Steel
Welding	Single V SMAW

To evaluate the efficacy of the modelled focal laws for detection, four EDM notches were made in the weld zones and two areas were made with clusters of porosity in the weld.

Figure 7 illustrates the nozzle configuration and Figure 8 identifies the nature and location of the embedded flaws.

Figure 7 Nozzle mock-up

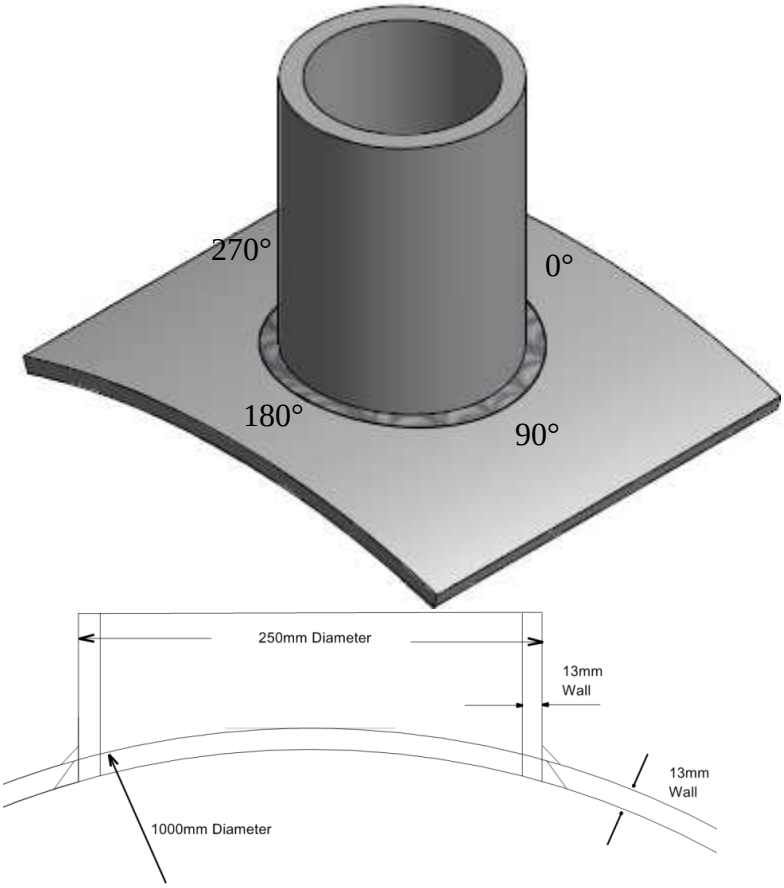
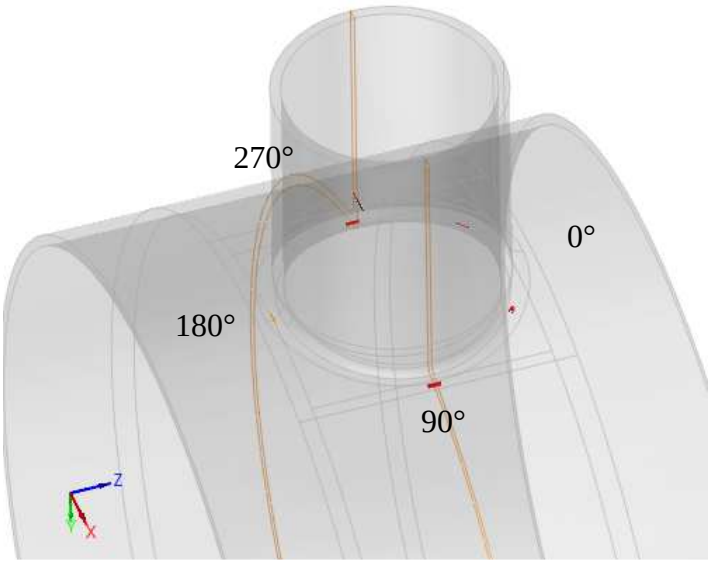


Figure 8 indicates a “see-through” view identifying the locations of the fabricated flaws in the nozzle mock-up.

Figure 8 Flaw locations in nozzle mock-up



EDM notches (4x15mm 1mm wide) are located at 90°, 180° and 270°. The porosity clusters are located near the 40° and 330° positions.

4.2 Modelling Items in the Nozzle Scan

4.2.1 Displacement Calculation

Preparation for the set-through nozzle inspection, from the nozzle inside surface, began with assessing the weld displacement between the 0° and 90° positions. The values were in fact those seen in Figure 6 so the estimated displacement was 16.4mm.

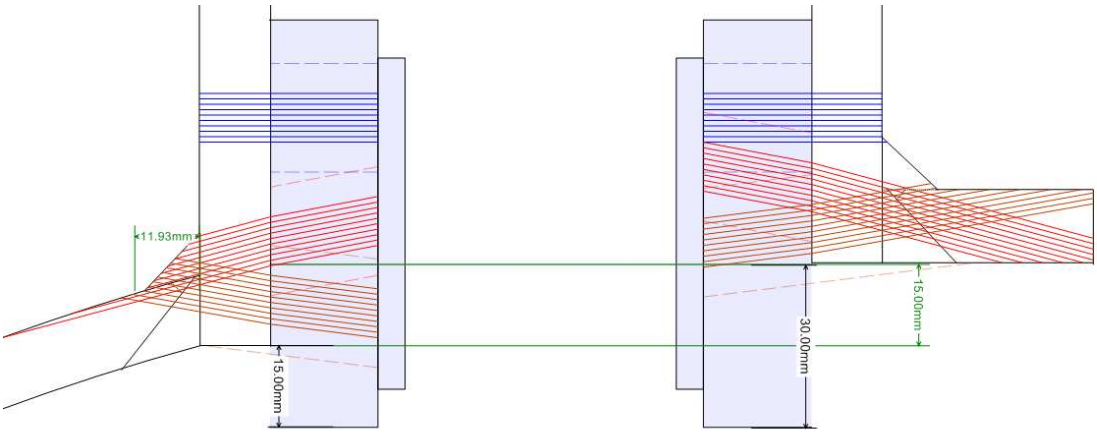
4.2.2 Probe Selection and Placement

Next, a ray-trace model was used to determine a suitable probe and wedge and the position in which it could be placed to accommodate the weld displacement. A commercially available linear array probe was selected along with a 0° wedge. (7.5MHz 60 element array with 1mm pitch and 10mm passive aperture on a 20mm thick polystyrene delayline). Using the ray-trace software the probe was placed on the nozzle ID surface at the 0° profile and a suitable depth positioning was established such that the weld could still be inspected with the same coverage at the 90° position where maximum displacement occurs.

4.2.3 Focal Law Selection

With the probe positioned to allow mechanical tracking around the nozzle inner surface a suitable selection of focal laws was configured that would provide the volume coverage of the weld and Heat Affected Zones. The selected focal laws are illustrated in Figure 9.

Figure 9 Linear Scan sets for set-through nozzle



To provide redundancy of volume and increased detections using multiple angles three sets of electronic scans (E-scans) were configured, and 0°, 10° and -15° compression

modes were used. These were configured with a 12mm aperture (i.e. 12 adjacent elements per focal law) and each was stepped one element along the entire length of the probe.

Figure 9 illustrates how the probe position with the wedge overhanging the edge at the 0° position (right side image) by 30mm allowed the focal laws to provide coverage with all three angles when the maximum displacement point was reached. At the 90° (and 270°) positions of the nozzle the edge of the probe wedge was still 15mm from the vessel ID.

4.2.4 Probe Curvature

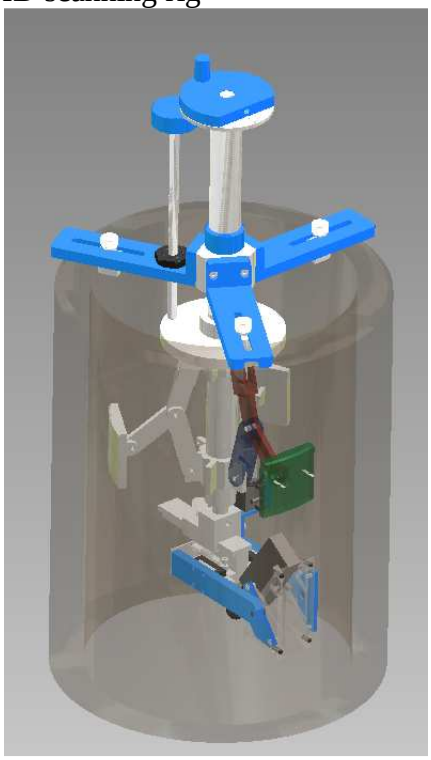
Since the probe wedge would start with a flat surface, the curvature modelling software was used to establish the gap (1.8mm) and the need to adapt the wedge to the nozzle ID surface.

4.2.5 Probe Motion Mechanical Modelling

Access to the inside of a nozzle can significantly restrict the operator from moving the probe so as to ensure repeatable encoded results. Therefore the project took on another modelling aspect when the probe holder was designed. CAD is the acronym for Computer Assisted Design and CAD was used in this application to design a probe holder that also afforded an ease of position encoded motion.

Positioning the probe at the appropriate depth and then providing encoded motion was made possible with the design seen in Figure 10.

Figure 10 Nozzle ID scanning rig



The scanner consists of three spring-loaded centring feet, top-surface holders, a lead screw to adjust the depth of the probe, the probe holder (an angled wedge is illustrated but any wedge or probe can be mounted in the unit) and a rotational axis controlled from the crank at the top. Irrigation lines for couplant and electrical lines for the probe and encoder are not illustrated but feed through the openings between the centring springs.

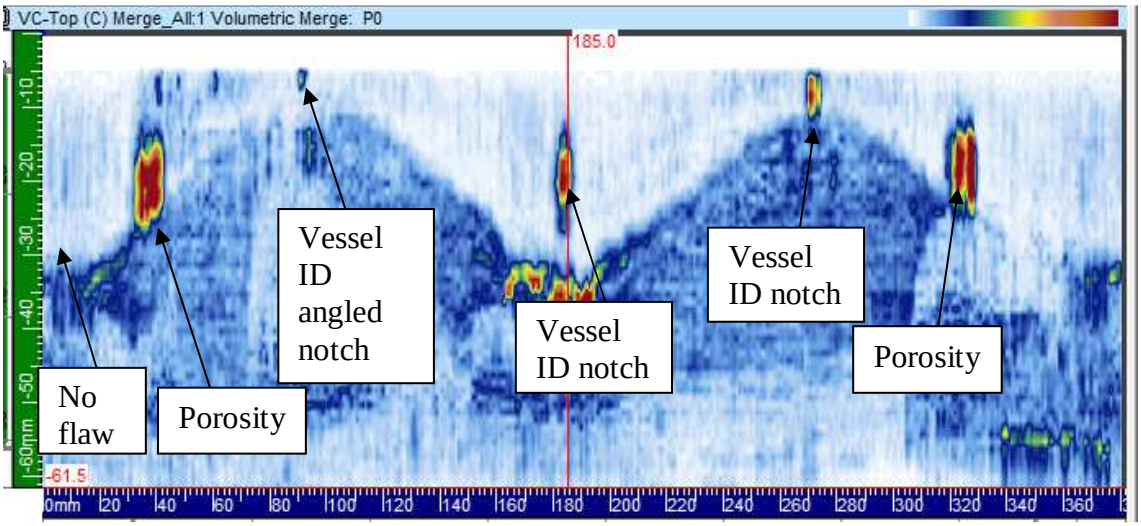
Solid CAD models can be animated (link to video http://www.ndt.net/search/docs.php3?id=9612&content=1) and the potential for mechanical interference or problems with geometry (such as the weld displacement locus) may be identified before the system is even placed in a nozzle.

5. Scanning Results

With the apparatus assembled and the focal laws calibrated on the 1.5mm SDHs in the IOW block to establish a TCG-based sensitivity level, the weld was inspected using the focal laws established by the ESBeamTool modelling.

Figure 11 is a "merged" C-scan of the results indicating the flaws detected in a scan of the nozzle. The scan axis is conveniently labelled in units of degrees.

Figure 11 Merged C-scan of nozzle mock-up



6. CIVA Modelling Results

Construction of full scale mock-ups of welded nozzles can be very expensive. In order to save some of the time and effort required for such detailed scanning, modelling has become a popular and acceptable option for several codes.

As a validation of the modelling process, a modelled nozzle was configured in the CIVA Simulation software. This included placement of representative flaws (as seen in

Figure 8) and the use of a modelled phased-array probe and wedge with the same parameters as used for the real scanning.

Results of detection can be seen for several of the modelled targets. It is interesting to see that the CIVA model predicts a faint mode converted shear component between the backwall and backwall multiple.

Figure 12 Flaw at 270°

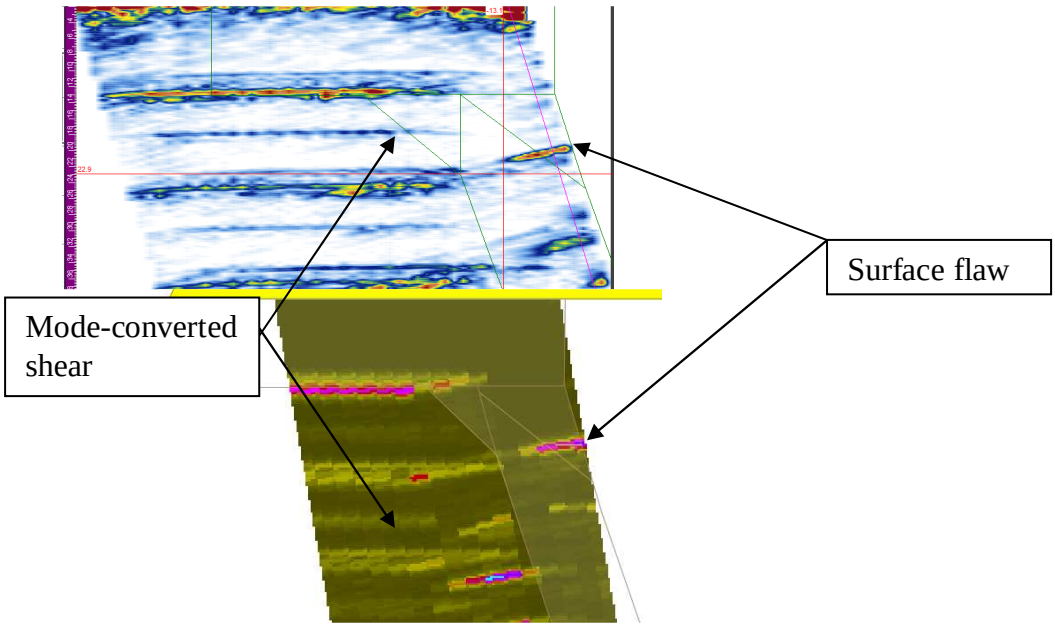


Figure 13 Flaw at 180°

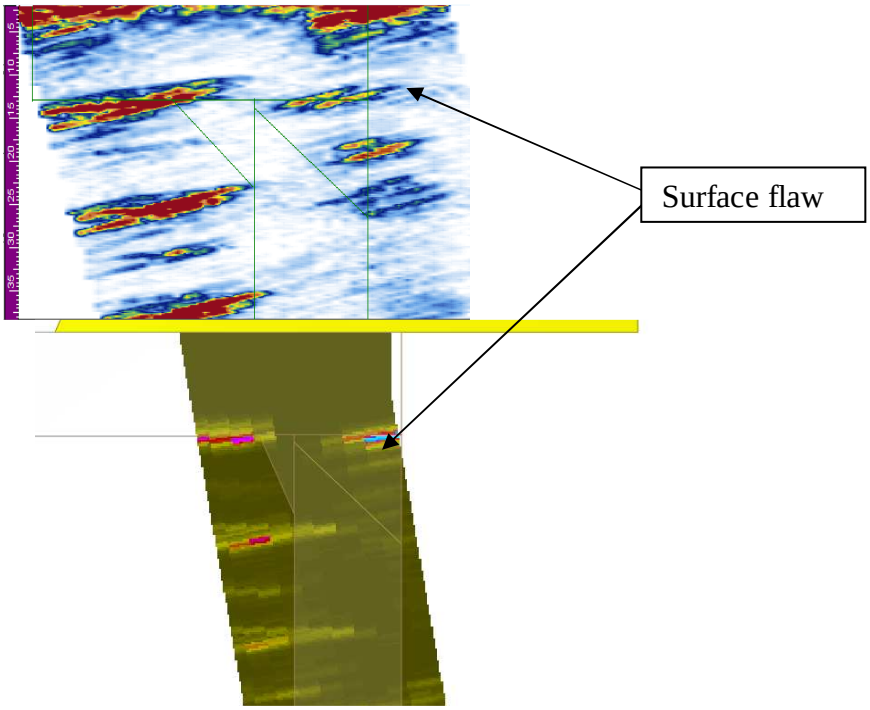


Figure 14 Flaw at 90°

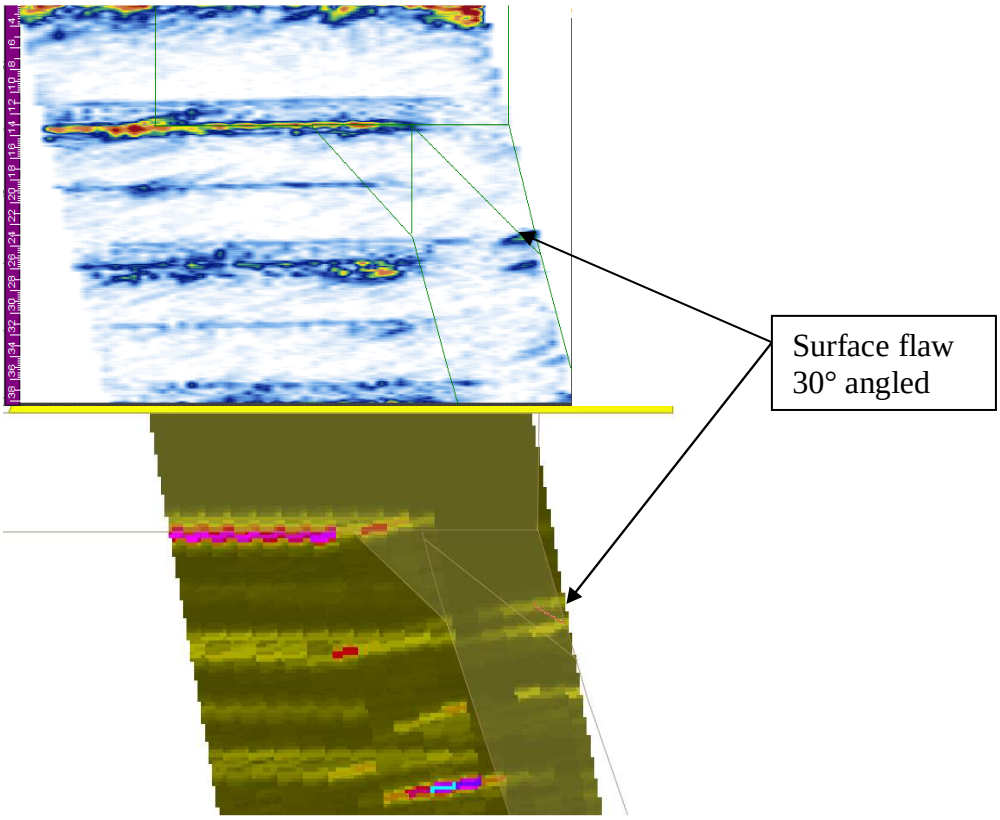
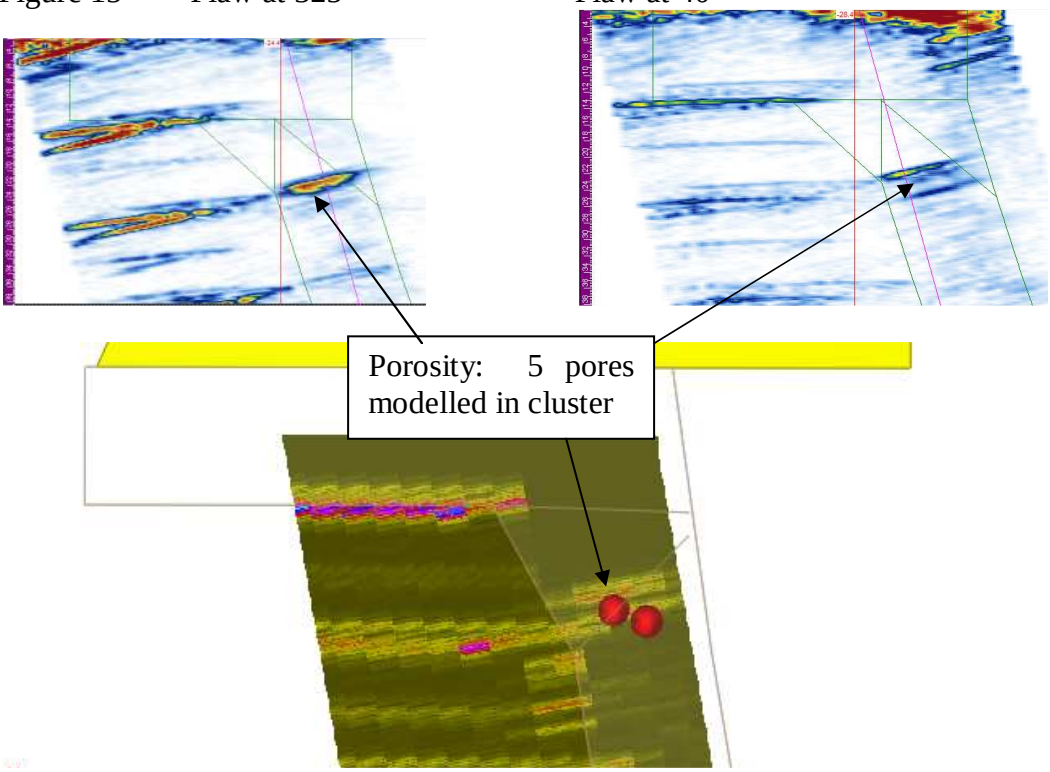


Figure 15 Flaw at 325° Flaw at 40°



6. Conclusions

1. Modelling was used throughout the design and inspection validation of a set-through nozzle.
2. Physical displacement of the contour surface of the weld was modelled by equation and confirmed by physical scanning.
3. Probe and wedge selection, in addition to focal law selection, was established to provide volume coverage based on modelling (ESBeamTool ray-tracing).
4. The requirement for wedge contour adapting was established by modelling (ESWedgeGap software).
5. CAD modelling was used to design the scanner apparatus and to provide visual confirmation of the geometric interaction with the weld contour locus.
6. CIVA semi-analytical modelling was used to simulate flaws in locations similar to those in the nozzle mock-up and proved to be a good indicator of the detection capabilities of the technique.

Based on these results it is expected that other flaws of different orientation and size could be modelled for detection based on a comparison of responses with the CIVA models.

7. Acknowledgements

We would like to thank Darrel Johnson for providing the detailed scans and analyses of the phased-array results. We would also like to thank Steve McCarley for providing the CAD animation and the many useful cross–sections used in the analysis of the data and modelling.
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