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

Part 2 - Outside Access

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Abstract
Part 1 of this 2 part series of papers on nozzle weld inspections by phased-array ultrasound provided background on the types of nozzle configuration and made several recommendations for scanning from the nozzle inner surfaces. Part 2 discusses scanning when access is available from the outer surfaces of the vessel for a set through configuration.
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 made 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 outside surface of either the nozzle or vessel.

Keywords: Phased-array, ultrasound, nozzles, mechanised

1. Introduction

Part 1 of this article (Automated Ultrasonic Inspection of Nozzle Welds using Phased-Array Ultrasonic Testing, Part 1 - Inside Access) presented a description of nozzle inspection by phased-array UT and the limitations and considerations required. This article is a continuation of the coverage of that topic. Whereas Part 1 looked at the inspection considerations and possibilities when scanning access is from the inner surface of the nozzle, Part 2 looks at the considerations when the scanning surface available is from the nozzle outer surface. The same nozzle mock-up used in Part 1 is used here in Part 2.

In Part 1 reference was made to the good practice for angles and surfaces of approach as codified and recommended in such standards as EN 1417. In EN 1417 the degree of inspection is dictated by the level of quality required in the contract documents. As the level of quality required increases more scanning is added. Extra scanning is in the form of scans from multiple surfaces (both nozzle and vessel) and in the form of multiple angles of refraction where possible.

But there are often physical restrictions that prevent scanning from both inner and outer surfaces and the recommendations for multiple angles may be hampered by standoff restrictions (e.g. for set-on nozzles scans from nozzle outer surfaces may not have adequate distance to pull the probe back due to flanges on the nozzle).

When access is available from the outer surface of either the nozzle or the vessel the operator must also look at the geometric configuration of the weld to ensure adequate coverage and good probability of detection of the expected flaws.

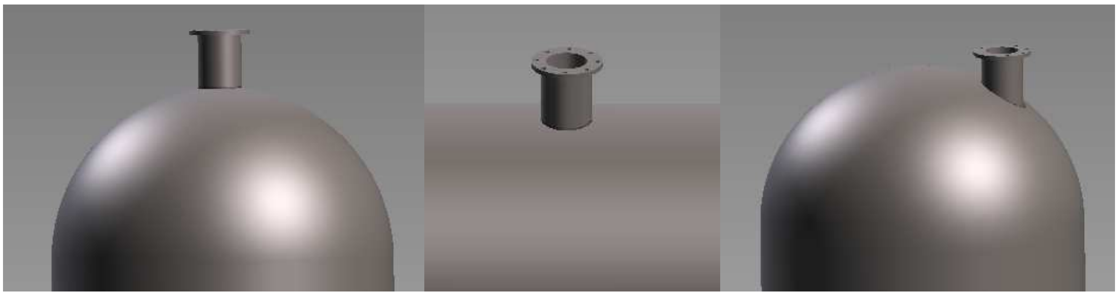
For a vessel constructed in accordance with one of the ASME (American Society of Mechanical Engineers) Code Sections, ultrasonic inspection may be used for weld examination via the ASME Code Case 2235 (for Sections I, VIII and XII vessels). When used, this Code Case requires that the ultrasonic methods use computerised data acquisition. It further assumes some form of mechanisation of the scanning apparatus so that flaw positioning is accurate and repeatable. This extra requirement for mechanisation, in all cases, uses encoded positioning which may need to be further complicated by some form of geometry tracking feature that ensures the probe is at a known position relative to the weld reference or centreline. This knowledge of the probe position relative to the weld reference is critical in order that the computerised equipment be able to correctly plot the data acquired.

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.

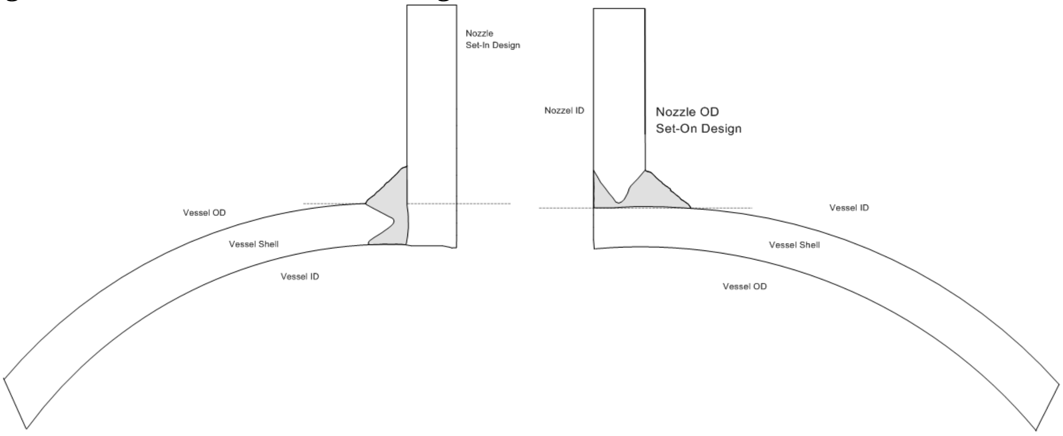
Nozzle configurations were addressed in Part one. Figure 1 re-iterates the basic geometries that might commonly be found on vessels.

Figure 1 Nozzle Orientations on a vessel



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-through” nozzles. Set-on nozzles have the secondary cylinders (i.e. the nozzle) prepared with the weld bevel, and set-through have the primary vessel prepared with the bevel. Examples of these two nozzle types are illustrated in Figure 2.

Figure 2 Set-on and Set-through Nozzles



3. Scan Plans

The nozzle mock-up fabricated for this demonstration project was a set-through nozzle with a nominal 250mm (10 inch) diameter nozzle through a 1000mm diameter vessel. Both the nozzle and vessel had 12.5mm (0.5inch) wall thicknesses.

Considerations for inspection of a set-through nozzle from the vessel outer surface will be considered in this paper. It will be assumed that the access is unimpeded (e.g. no re-enforcement pad is present).

Beam paths to provide full volume coverage of the weld and HAZ are required. This can be facilitated using ray tracing drawings of the extremes along the scan path. Of particular concern is the vertical displacement of the probe from the high-points on the vessel apex to the low-points at 90° to the apex.

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. This drop is not as critical to the scanner and probe placement when scanning from the vessel outer surface as it is when scanning from the nozzle inner surface. The critical aspect of this elevation change comes in the plotting of the beam position as the elevation change has associated with it variations in the skip angle due to the change in curvature.

Scanning from the vessel outer surface for a set-through nozzle must provide a means of constantly directing the beam at the centre of the nozzle and it must also consider the drop that results as the probe moves from the apex (along the vessel long axis at the vessel-to-nozzle connection) down to the low points perpendicular to the vessel long axis. Shaping the probe wedge is not feasible because the curvature contact-point is constantly changing as the probe moves on the vessel around the nozzle. This will mean that the probe size (via the wedge footprint) will be a consideration for coupling efficiency.

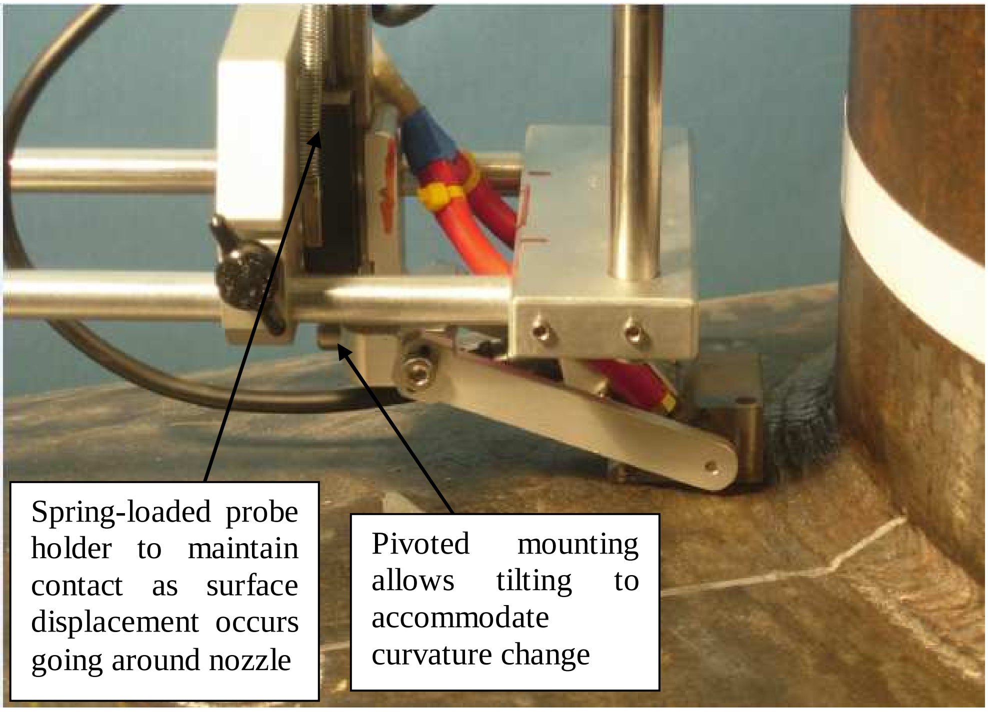
Unlike the scan from the nozzle inner surface where a custom scanner was constructed, scanning from the outer surfaces can be simplified using off-the-shelf scanners. Depending on the degree of surface and the footprint of the phased array probe selected, the probe holder may require only a small spring action for this displacement.

If the nozzle was a set-on configuration the probe might be capable of simple mounting on a holder typically used for butt welds and may be able to "reach" the weld extents via the beam positioning in the focal laws as the probe is placed on the nozzle outer surface.

However in our case of a set-through nozzle, the scanner needs to be fitted with a spring loading actuator that can ensure that the probe is pushed down on the vessel surface as the surface moves further from the high-points at the vessel apex.

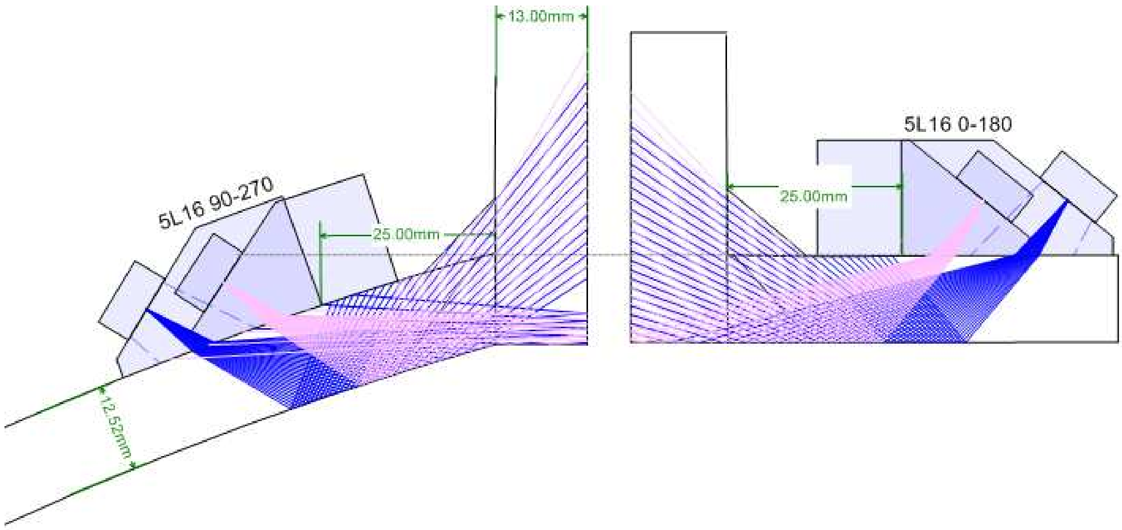
The probe holder mounted on the nozzle for this demonstration is illustrated in Figure 3.

Figure 3 Nozzle scanner for scanning a set-through nozzle from the vessel OD



Volume coverage of the weld in the various positions, as the probe moves around the nozzle, can be estimated using popular software. Figure 4 illustrates the beam selections and probe details for the weld examination from the vessel OD for the mock-up used for this demonstration.

Figure 4 Scan Plan indicting beams and coverage for vessel OD scanning



The probe and focal law details selected for this examination included:
Probe 5L16linear array (5MHz, 16 element, 10mm passive aperture, 0.6mm pitch)
S-scan 16 element active aperture
Start element 1
Range 40-70° transverse mode
In order to provide the recommended angular redundancy of voxel coverage, the technique used two passes; the first with the wedge 15mm from the nozzle (effectively at the toe of the weld) and the second 25mm from the nozzle (these are illustrated in Figure 4).

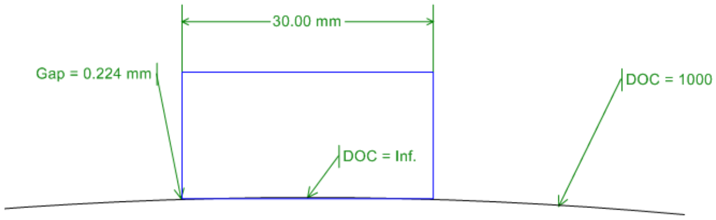
The smaller footprint provided by the 16 element probe ensures that the "wobble" and coupling issues are minimised. This is required since there is a continuously changing curvature so the wedge cannot be contoured for a particular curvature.

Unlike the condition where the weld was scanned from the inner surface and the weld moved further away from the initial surface level, the weld surface remains at approximately the same elevation relative to the front of the probe for the scan from the vessel outer surface with a fixed standoff to the nozzle. The item that changes is the refracted and reflected angles that result due to the curvature.

When the scanning is made from the nozzle inner or outer surface, wedge curvature matching can be made because the nozzle contact geometry will be constant for all points around the scan surface. This is not the case for scanning from the vessel surface so a suitable small wedge size must be selected that minimises any loss of coupling contact surface. Using the selection of standard wedges and linear array probes from the probe manufacturer's catalogue, a combination was selected using the WedgeGap software which indicated a modelled gap less than 0.5mm at the wedge edge.

Figure 5 indicates that the 5L16 probe on the 60° nominal refracting wedge would provide about 0.2mm gap when placed at either the vessel apex (0°) or the shoulder positions (90° to the scan start).

Figure 5 Gap considerations for flat probe on 1000mm outside diameter



When the probe is placed on the vessel outer surface and the beam directed at the nozzle weld of a set-through nozzle, the bevelled edge of the vessel weld prep is generally approached with a constant perpendicular incidence. However the fusion line of the weld to the nozzle changes both angle and elevation. For pulse-echo angle beams there is no practical refracted angle that can provide perpendicular incidence to the nozzle fusion line. Since the angle that the beam is incident at the nozzle fusion line is constantly changing around the nozzle, even a single tandem path is not practical. As a result, only diffracted signals and corner effects are practical detection options for the nozzle fusion line when access is limited to the vessel outer surface.

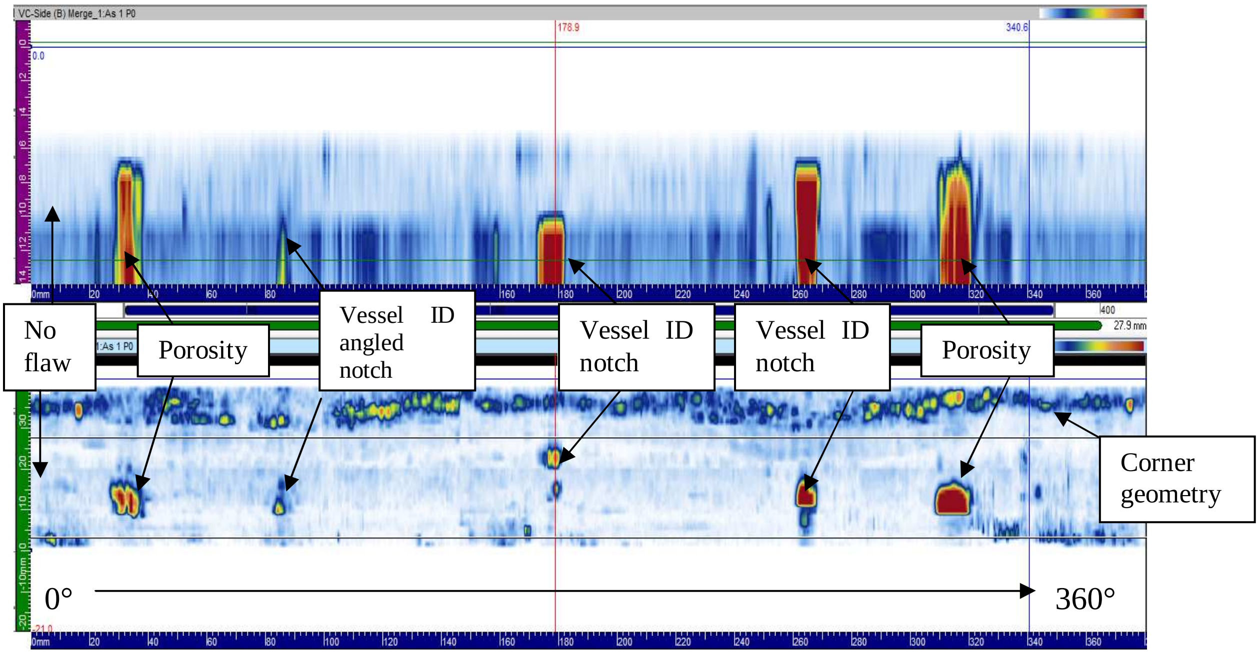
These concerns for the nozzle fusion face make it clear why, ideally, if access is available to provide both the vessel outer surface and the nozzle inner surface, both scans should be carried out.

4. Phased Array Scanning Results

With the apparatus assembled and the focal laws calibrated on the 1.5mm SDH 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 6 is a "merged" B-scan and 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. The C-scan (lower half of image) correctly illustrates the flaw locations relative to the inside corner geometry signal seen along the top of the view. However the B-scan does not image the correct depths for all flaws due to the effects of curvature changing the actual depths relative to the computed depths. Figure 7 will illustrate that using CIVA modelling the porosity indications are correctly plotted in the volume of the weld away from the surfaces.

Figure 6 Merged B-scan and C-scan of nozzle mock-up



5. Modelling Phased Array Nozzle Scans from Outer Surface Access

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 ray-trace modelling process, a modelled nozzle was configured in the CIVA Simulation software. This included placement of representative flaws and the use of a modelled phased array probe and wedge with the same parameters as was used for the real scanning.

Results of detection can be seen for several of the modelled targets.

Use of CIVA defect interaction simulations in this application is something of a second-stage qualification validation. Having demonstrated that the ray-tracing provided suitable coverage and detection on a limited selection of targets, the use of CIVA simulation to demonstrate that the modelled detections were similar to the actual detections provided some confidence that CIVA could be used with the same ultrasonic technique to determine detectability of other flaws in other locations and orientations. This would be the rationale for a cost saving by reducing the number of fabricated flaws and relying on modelled simulations to assess detections.

The associated video illustrates the scanner setup, probe actuator details and how the CIVA simulation is configured to mimic the actual scanning.

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Figure 7 Porosity at 40° and 325°

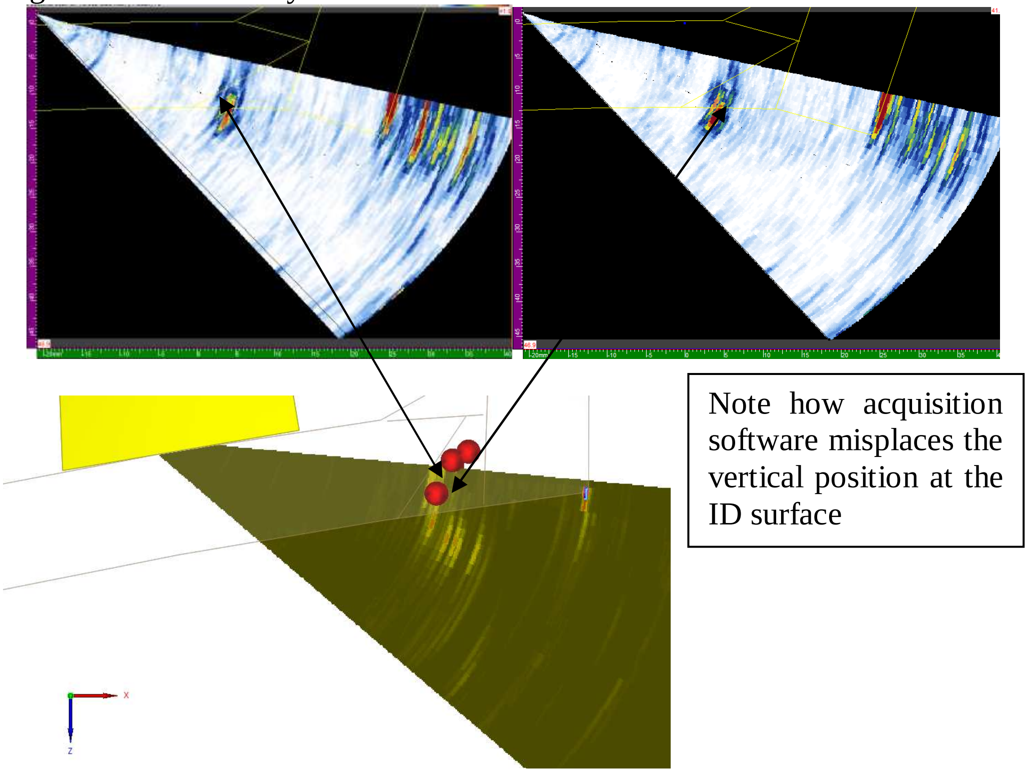


Figure 8 Angled Surface notch at 90°

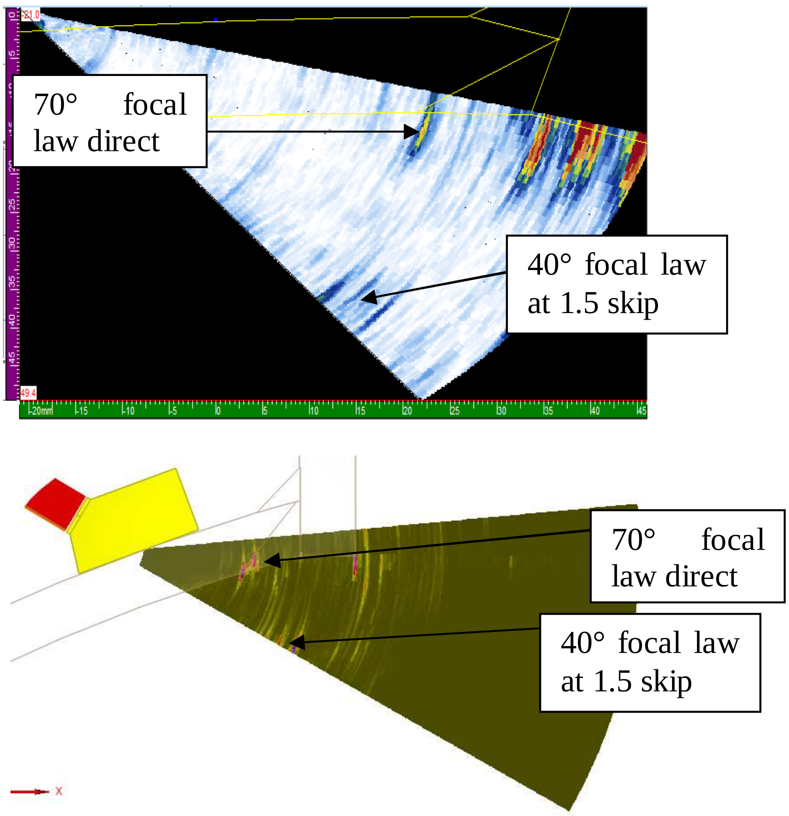


Figure 9 Perpendicular surface notch at 270°

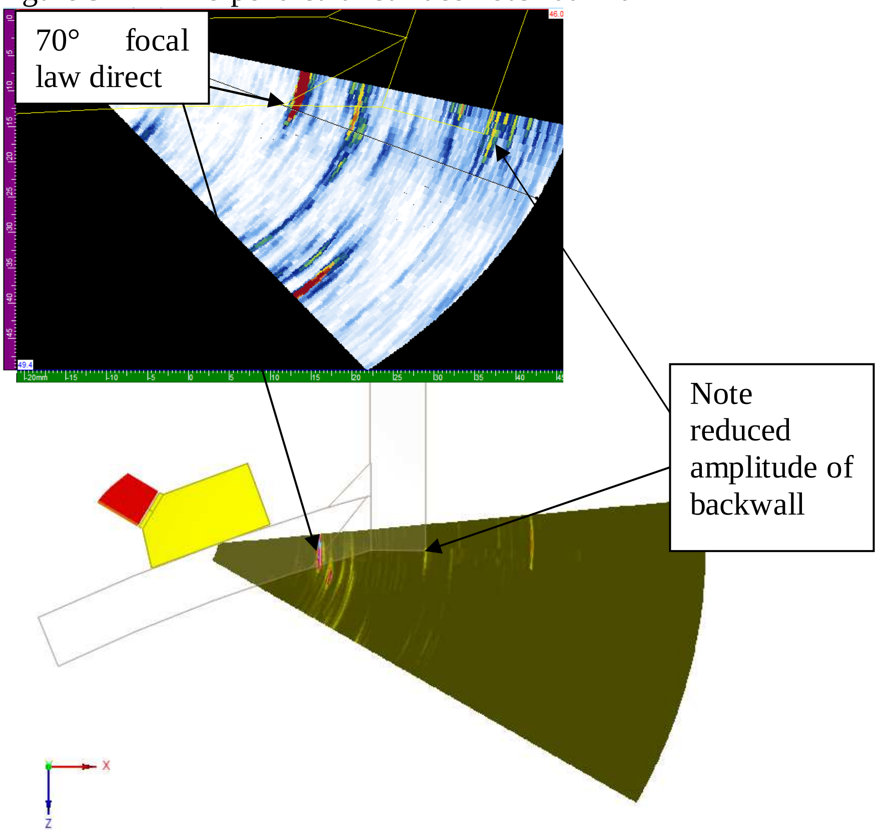
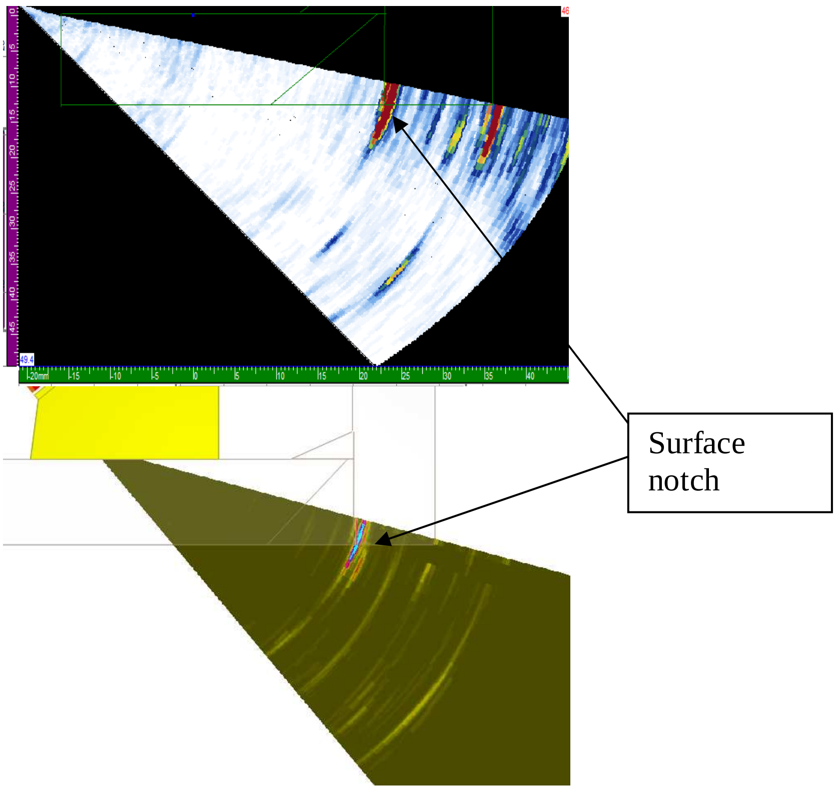
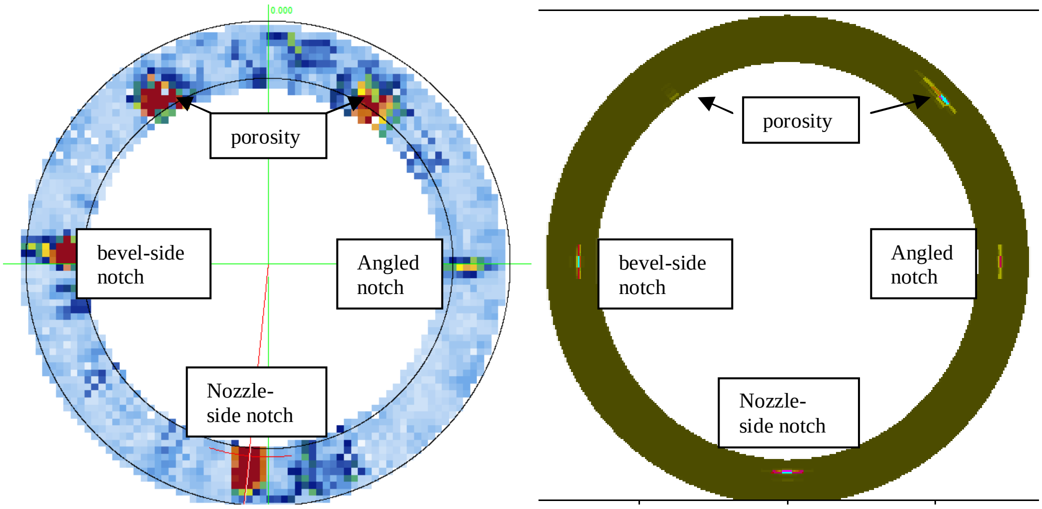


Figure 10 Surface notch at 180°



A polar plotted B-scan can be made with both the acquisition and CIVA modelling software. Figure 11 illustrates a close similarity of the detections in the polar plots. Only the cluster of porosity on the 325° position shows as weaker (this could be remedied by arranging pores with sufficient density to duplicate the same conditions).

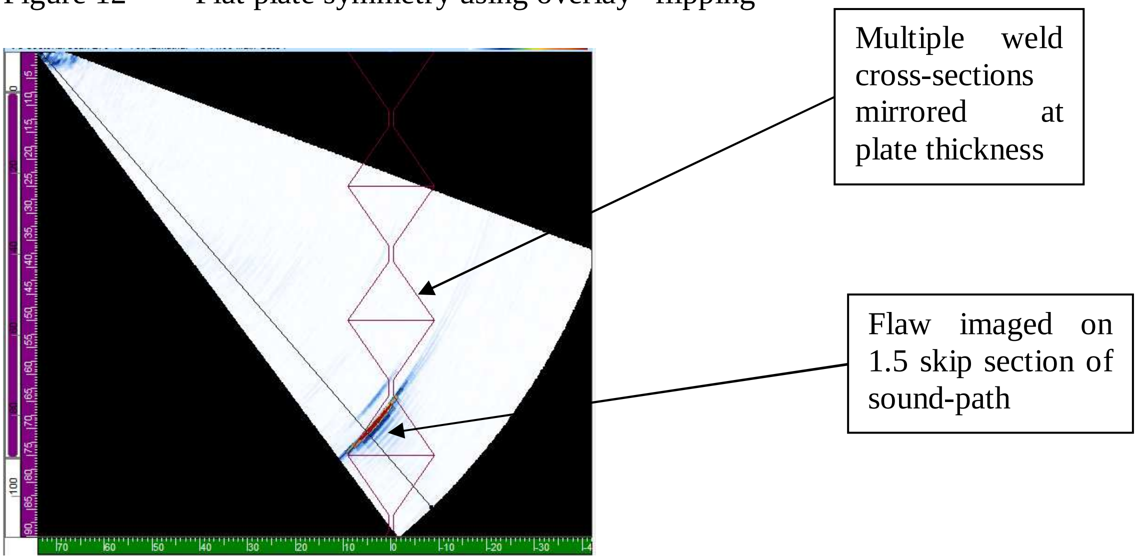
Figure 11 Comparing real and simulated Polar Plot B-scans



6. Overlay Plotting Considerations

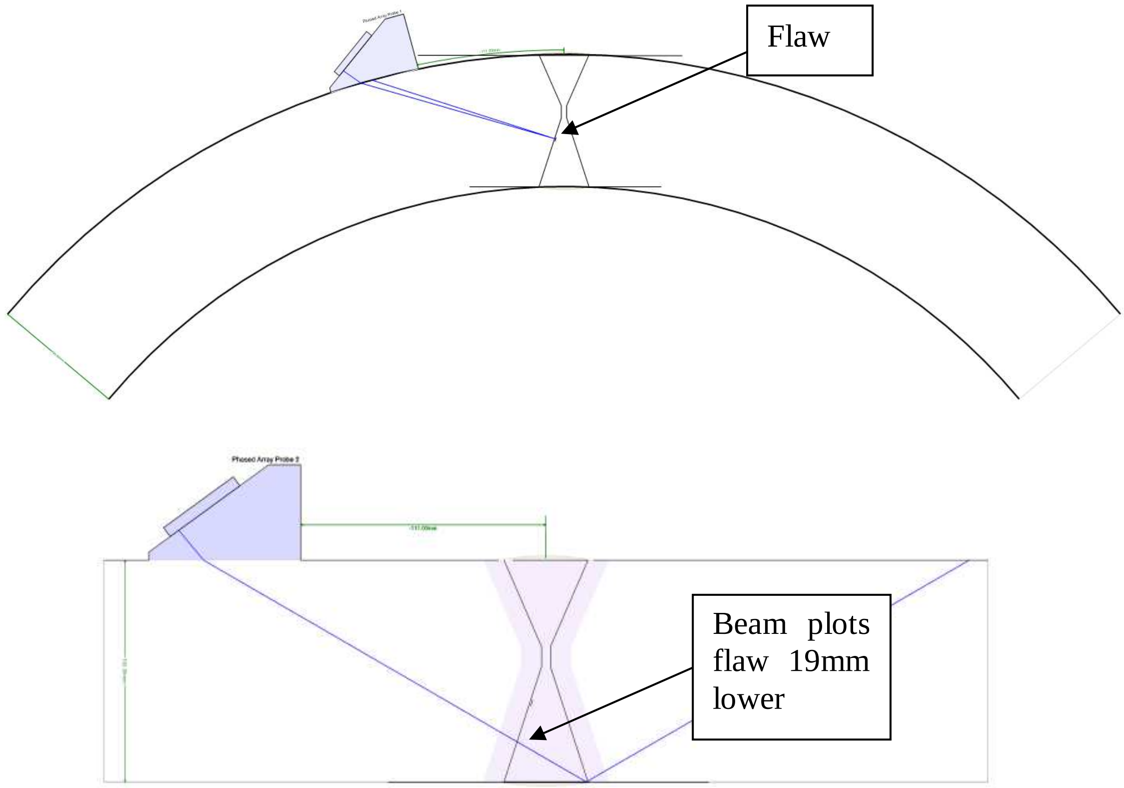
Phased array software typically uses CAD generated cross-section overlays to image where flaws are located relative to the weld bevel geometry. A problem with most software displays using these overlays is the inability to correct for curvature. Making repeated (flipped) cross-section images in a stacked fashion is a useful method for plotting the 2D position of a flaw in E-scans or S-scan displays. However this is limited to the flat plate condition (see Figure 12).

Figure 12 Flat plate symmetry using overlay “flipping”



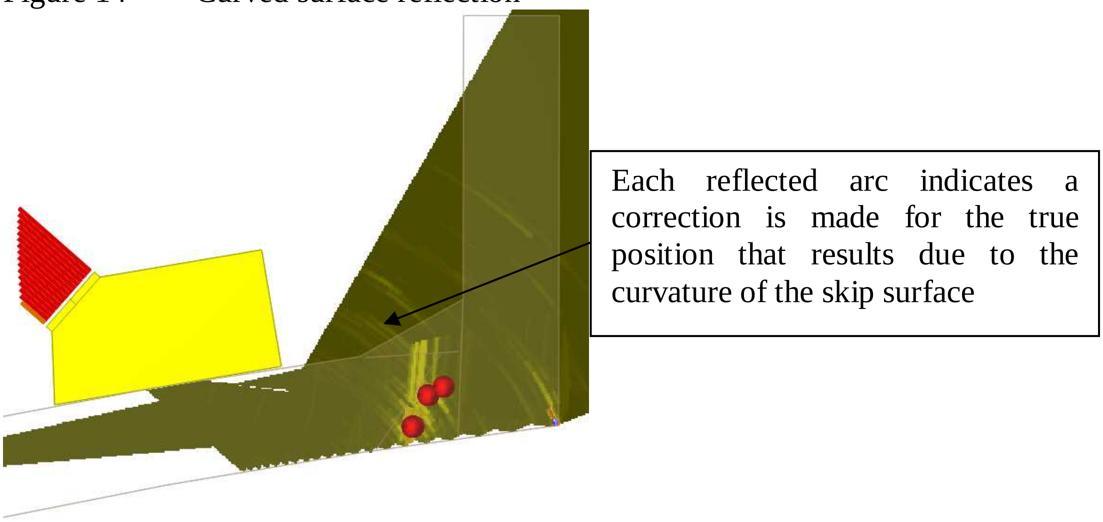
For curved surfaces this concept fails if the software does not compensate for the variation in travel time to the skip surfaces on the backwall. Simply making symmetrical “flipped” images of the curved surface does not address the fact that the probe exit point is not at the same level as the weld surface. Figure 13 illustrates how a simple butt weld in a cylinder cannot have its flaw location correctly plotted when a flat parallel surface is assumed. The upper image in Figure 13 is of a cylinder 1000mm OD and 100mm thick. Indicated is a flaw near the fusion line that is detected by a 60° beam in the upper view. When the probe is positioned incorrectly, as would be the case for software assuming flat test surfaces, we see that the beam is plotted far below the actual position of the flaw, approximately 19mm lower in this case in lower portion of Figure 13.

Figure 13 Depth error due to assumed flat entry surface



Some software is capable of geometric correction for skip on curved surfaces and can correctly place the indications with respect to the local weld geometry. Figure 14 is an image from the CIVA simulation software that uses the CAD geometry to plot the ray paths of each focal law and makes provision for the curvature.

Figure 14 Curved surface reflection



7. Conclusions

Nozzle weld inspections using encoded and mechanised phased array scanning was carried out and the results compared to modelled results.

- With suitable weld geometry tracking capabilities, good detection of planar defects can be expected.
- Using suitable focal laws and suitable geometry tracking hardware for probe position control, full volume coverage and detection of the most commonly expected flaws is achieved. Multiple standoff focal laws are generally required for good volume coverage (i.e. voxel redundancy).
- Software with the provision for correction of flaw position due to skips off curved surfaces is required to correctly plot flaws in 3D space so as to ensure any repairs are correctly made. This is also critical when fracture mechanics acceptance criteria are used and flaw proximity to the nearest surface is to be considered.

Parts 1 and 2 of this presentation have considered aspects of weld inspection of set-through nozzles. Future work will be considered for a similar treatment of set-on nozzles.

8. Acknowledgements

We would like to thank Darrel Johnson for his work in preparing the scans and images used in the analysis of the phased array data collected from the mock-up. Eclipse and MRI extend best wishes to Darrel for his future work in Australia.