ABSTRACT

Regular, in-service inspection is important to verify the integrity of welded nozzle sections in the nuclear industry. Nozzle sections are susceptible to crack growth due to thermal fatigue and stress corrosion. Early detection of cracks is therefore essential to ensure the continued safe operation of the facility. The aim of this project is to design an inspection system that is capable of reducing the inspection times, improving defect detectability and sizing and reducing human intervention. This will reduce the risk of exposure of the workforce to harmful radiation, reduce the requirement for robotic manipulation and consequently reduce the size and cost of robotic deployment systems. In order to reduce the time and cost of such inspections, there is a need to develop a system capable of performing a full inspection of nozzles without the need to change probes. This paper will present the initial studies of the inspection technique, concentrating on the ultrasonic simulation using CIVA, carried out to determine the most appropriate phased array probe and its detection capabilities. The work includes the assessment of design parameters including the beam propagation through the material, the beam coverage and the defect response at critical areas of the nozzle.

INTRODUCTION

NozzleInspect\(^{(1)}\) is a collaboration between EU companies and research organisations supporting the effort of the nuclear industry in achieving better safety standards through improved inspection of plant. The project aims to develop a novel scanner and probe manipulator combined with a phased array technique for the inspection of Boiling Water Reactor (BWR) nozzles. The project focuses on the development of a new semi automatic NDT phased array ultrasonic system that can be deployed for the inspection of nozzles in nuclear reactors.

Cracking in BWR feedwater reactors discovered during the 1970s led to a change in both the design and the materials of the nozzle. Guidelines were established for periodic ultrasonic testing with work undertaken since the early 1970s aimed at specialising NDT testing methods for the application of in-service inspection of nozzles in boiled water reactors\(^{(2)}\). Early investigations serve to illustrate that complicated probe configurations were required to provide the necessary beam angle within a tangent plane of the target area\(^{(3)}\). The requirement to manage defects in nozzles was addressed through the investigation of the choice of optimal inspection parameters based on three areas of inspection of the geometry of the nozzle\(^{(4)}\).

Applications where the external geometry of the test specimen varies across the test area require the control of the degradation of contact between the transducer and specimen\(^{(5)}\). Experimental techniques were developed to overcome variation through adaptability of different control configurations\(^{(6)-(7)}\). Physically flexible phased arrays overcome irregularities in the test surface and improve the coupling between surface\(^{(8)}\). These arrays have been implemented in the interpretation of irregular shaped components of BWRs including the nozzles\(^{(9)}\) and for more challenging inspection configurations in nuclear and conventional power plant applications\(^{(10)}\). Phased array techniques overcome issues associated with complex geometries through adaptability based on a combination of electronic commutation, beam-steering and focusing in complex geometries\(^{(11)-(12)}\).
In such an approach, each element of the probe is controlled independently and can therefore be delayed in responding to a signal. If all of the elements are activated simultaneously, the probe behaves like a conventional device but, when a delay is introduced, the resulting beam can be controlled and focussed as required.

The aim of the NozzleInspect project is to develop a phased array inspection technique and system supporting the ease of inspection of reactor feedwater nozzles. This development will replace the current ultrasonic testing that requires multiple probes and will therefore reduce the inspection time required. As a result, radiation exposure to the inspection personnel will be reduced. The main objectives of the work are to determine the factors affecting the ultrasonic detectability of in-service defects in the nozzle to vessel weld as well as the nozzle inner radius. These two areas are known to be critical to the integrity of the feedwater nozzle.

**MODELLING APPROACH**

This paper presents a series of modelling studies undertaken using CIVA 9.2^{(13)} ultrasonic modelling software. These models enable the simulation of the wave propagation and interaction of ultrasound with simulated flaws in models of nozzle to vessel weld and the nozzle inner radius. The analysis of the beam propagation and interaction with the defects was simulated in order to optimize and predict the performance of the phased array technique in terms of critical area coverage and defect response. These simulations included several different configurations of probes, defect parameters and locations. The simulations show the ultrasonic defect response from various defects, where changes in the length, height, skew and tilt angle determine the effect on the ultrasonic detectability. The results are presented in terms of dB drop compared to a 100% reflector, in this case a rectangular shaped simulated defect, and the incidence ultrasonic beam perpendicular to the defect.

**Defect parameters**

The position, size and orientation of the defects were defined from the end user’s requirements and the ASME Code XI. The impact of parameters such as size, position and orientation of simulated defects on the overall detectability of the ultrasonic inspection was studied. The modelling task also addressed the probe skew angle required to maintain the ultrasonic beam normal the weld. This is an important parameter as it improves detectability and inspection sensitivity and assists in the design and manufacture of the resulting 2D matrix probe.

The defects to be detected in the main weld are planar (cracks) and parallel to the axis of the nozzle to the vessel weld. The defects in the nozzle to vessel weld are likely have an allowable tilt angle in the range 5-15° with respect to the normal of the vessel wall, as defined in ASME code section XI. Defects may also be skewed with respect to the weld axis within the range ±10°. Figures 1a and 1b show a schematic representation of the defect orientation within the nozzle to vessel weld. These parameters of the defect skew and tilt angle were used for the modelling of the defect response.
Table 1 - Defect parameters for the nozzle to vessel weld and nozzle inner radius

<table>
<thead>
<tr>
<th>Inspection area</th>
<th>Length (mm)</th>
<th>Height (mm)</th>
<th>Skew angle (º)</th>
<th>Tilt angle (º)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld</td>
<td>5.8-23.6</td>
<td>2.9-11.8</td>
<td>±10</td>
<td>5-15</td>
</tr>
<tr>
<td>Inner radius</td>
<td>-</td>
<td>6.4</td>
<td>±10</td>
<td>5-15</td>
</tr>
</tbody>
</table>

Ultrasonic modelling

Feedwater nozzle parameters

The nozzle under investigation is at the junction of the 300mm diameter feedwater pipe with the cylindrical wall of the reactor vessel. The diameter of the nozzle is 605mm with the diameter of the nozzle to vessel weld at 840mm. The wall thickness of the reactor vessel is 139mm. The materials are low alloy ferritic steel. 3D modelling and simulation of the inspection of the nozzle was performed using the CIVA 9.2 software. The 3D model of the nozzle under investigation created in the CIVA software is presented in Figure 2a. The possible positions from which the weld can be inspected are shown in Figure 2b. It can be observed that the weld volume can only be inspected from the side of the vessel. Inspection from the side of the pipe is problematic due to the curved surface of the nozzle and insufficient distance. The inner surface of the vessel wall outside the weld is normally covered by cladding and in such a case the use of the techniques based on the reflected from inner surface of the wall signals (full skip) is not recommended.

Figure 2 - (a) CIVA 3D CAD model (b) areas to be inspected and probe positions

Phased array probe parameters

The geometry and the parameters of the investigated phased array probes are presented in Table 2. The 32-element probe was applied to the beam coverage studies, while the 64-element probe was applied to defect response studies.

<table>
<thead>
<tr>
<th>32 elements probe</th>
<th>64 elements probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type: 1D linear</td>
<td>Type: 1D linear</td>
</tr>
<tr>
<td>Frequency: 2MHz</td>
<td>Frequency: 2MHz</td>
</tr>
<tr>
<td>Element width: 0.53mm</td>
<td>Element width: 0.55</td>
</tr>
<tr>
<td>Element pitch: 0.78mm</td>
<td>Element pitch: 0.6mm</td>
</tr>
<tr>
<td>Active aperture: 24.71mm</td>
<td>Active aperture: 38.44mm</td>
</tr>
<tr>
<td>Passive aperture: 25mm</td>
<td>Passive aperture: 15mm</td>
</tr>
</tbody>
</table>
MODELLING RESULTS AND DISCUSSION

Beam computation

Inspection of nozzle to vessel weld

An investigation of ultrasonic field coverage of the nozzle to vessel weld was undertaken with a 32-element, 2MHz ultrasonic phased array probe. Figure 3 illustrates the position of the probe with respect to the sample and the associated ultrasonic field computation zone. Phased array inspection, using the shear wave mode was used to inspect the component. The region of interest was insonified using a sectorial scan with beam angles ranging from 35° - 80° in 5° increments.

Figure 3 - (a) Positioning of the probe on the primary cylinder (b) ultrasonic field computation zone (from 35 to 80°) with the zone to be inspected

The cumulated image of the ultrasonic field coverage is presented in Figure 4a. The model indicates that good inspection coverage of the Heat Affected Zone (HAZ) and the weld can be achieved from one scanning position using a 32-element linear array probe. This result serves to illustrate that good coverage can be achieved using the half skip technique and that the inspection zone is covered by angular scanning of the beam. The most complicated inspection is the area close to the outer surface of the reactor wall due to the limited angular scanning ranges. Due to this limitation, the ability to detect defects close to this surface needs to be tested by both modelling and experimentation. The possibility of analysing a second position, closer to the weld is recommended as part of the future work in the project.

Figures 4 b,c and d illustrate the ultrasonic field of beam at 40°, 60° and 80°, respectively and indicate that the focal point moves as the angle of incidence increases. The intensity of the focal point decreases as the incidence angle increases, especially at higher angles (ie 80°). This effect results from the combination of material attenuation and the presence of side lobes that reduces the intensity of the main ultrasonic beam.

Figure 4 - (a) cumulated image of the ultrasonic field of 2MHz phased array scanned from 35° to 80° (b) beam at 40°; (c) beam at 60°; (d) beam at 80°
Inspection of the nozzle inner radius

Computations of ultrasonic field coverage of the nozzle zone to be inspected (inner radius) were performed. Positioning of the probe on the sample and the calculated angles of the phase array are shown in Figure 5. During modelling it was assumed, that the nozzle material is steel with a velocity of longitudinal waves in the test object of 5900 m/s and a velocity of shear wave is 3192 m/s and density \( \rho = 7.8 \text{ g/cm}^3 \). Phased array inspection, using the shear wave mode was used to inspect the component. The region of interest was isonified using a sectorial scan with beam angles ranging from 35° - 70° in 5° increments. Modelling of the wave propagation in CIVA is based on an integral formulation of the radiated field. The software has the ability to overlay resulting ultrasonic beam profiles onto the model of the part. The cumulated image of the ultrasonic field overlaid on the nozzle is presented in Figure 5. This illustrates that angular scanning from a phased array from a single position covers the region of interest. However, from this position only volumetric defects and planar cracks with radial orientation are detected. Whereas, the defects at bigger radius positions (close to inner surface of the vessel) are inspected at a relatively small angle.

![Figure 5 - (a) Positioning of the probe on the secondary cylinder and ultrasonic field computation zone (b) cumulated image of the ultrasonic field of 2MHz phased array scanned from 35° to 70°](image)

Defect response

An extensive ultrasonic modelling programme of work was carried out to determine the best inspection parameters appropriate for the inspection of the critical areas within a BWR nozzle. This work programme included the development of simulated defects in a CAD model of the nozzle critical areas within ultrasonic modelling software. The position, size and orientation of the defects were defined from the end user’s requirements and the ASME Code XI (Table 1). The aim was to assess the impact of various parameters of the simulated defects such as size, through thickness and circumferential position and orientation on the overall detectability of the ultrasonic inspection. The modelling task also addresses the probe skew angle required to maintain the ultrasonic beam normal to the weld. This is a necessary requirement as it improves detectability, inspection sensitivity and assists in the design of the 2D matrix probe.

Figure 6a shows the nozzle model incorporated into the ultrasonic modelling software along with the defect position within the nozzle weld circumference. A total of seven defects were introduced into the nozzle weld at 15° intervals along the weld circumference. The defects have the same size and orientation within each of the simulated models. The purpose of these simulations was to gain a better understanding of the effect of the beam position relative to the defect. The model also supports the determining of the skew angle required to ensure that the ultrasonic beam will be normal to the defect regardless their angular position at the weld circumference. These simulations were essential to determine the most suitable inspection parameters for the nozzle to vessel weld inspection.

Figure 6b illustrates the simulation of a defect introduced into the midwall of the nozzle to vessel weld. The simulated defects within different models have different sizes with various tilt and skew orientations.
Figure 6 - (a) Defect positioning around the nozzle circumference and defect numbering used (b) Defect position in the nozzle to vessel weld

Figure 7 illustrates a C-scan (plan) view of simulated data representing a response from seven defects. The defect sizes in this case are all 5.8mm x 2.9mm, 5° tilt and 0° skew. Two sets of defect reflections, present in the C-scan image, are attributed to the propagation of the ultrasonic beam through the material and the reflection on the defect. In one case, the sweeping ultrasonic beam interrogates the weld volume using the half skip (direct) and in the other case using full skip in which the ultrasonic beam first reflects at the backwall of the vessel and then reflects towards the weld.

Figure 7 indicates strong reflections from the defects when the beam is scanning the weld volume by direct angular scanning. However, when the beam first reflects on the backwall and then to the weld (full skip) there is a very weak response from the defects introduced in the midwall of the weld. This is due to the longer material path that the ultrasonic beam is required to propagate through in order to reach the weld area. This naturally leads to beam energy losses due to the material attenuation. As the inner surface of the vessel wall outside the weld is covered by stainless steel cladding, it is not recommended to base the inspection techniques on the backwall reflected signals (full skip). The ultrasonic signal is heavily distorted and attenuated at the backwall/cladding interface resulting in weak responses from any defects in the region of interest.

Figure 7 - C-scan (plan) view of the defects introduced into the nozzle to vessel weld
Figure 8 shows an example of the simulated sectorial data superimposed on the nozzle CAD model. The sweep sectorial incidence angles used for the simulation are shown along with a reflection that occurred due to the presence of the defect.

![Sectorial scan simulated data from defect 1 superimposed on the nozzle CAD model](image)

**Figure 8 - Sectorial scan simulated data from defect 1 superimposed on the nozzle CAD model**

The maximum reflected amplitude from the defects for each model was measured to assess the response and to determine the parameters that affect inspection sensitivity. Figure 9 shows an example of the amplitude variation (in the form of A-scan) from defects positioned along the weld circumference (at every 15°) in model 1. This serves to illustrate that, as the position of the defects change relative to the weld circumference, so the reflected amplitude reduces. This reduction is attributed to the incident beam angle relative to the defect. In the case where the incidence beam is normal to the defect (ie at 0°), more energy is reflected back to the probe, thus ensuring maximum sensitivity. Therefore, it can be stated that the reduction in amplitude reflection is relative to the defect circumferential position and is dependent upon the skew of the phased array probe relative to the defect orientation. Correct probe skewing ensures that the incident ultrasonic beam is normal to the defect independent of the circumferential position and thus ensures maximum detectability and sensitivity.

Figure 9 indicates that the effect on reflected amplitude is greatest at the defect positions of 30°, 45° and 60° when compared to the normal position. This indicates that probe skewing needs to be introduced into the inspection system to compensate for the disorientation of the incident ultrasonic beam with respect to the defect.

![A-scan representation of the reflected response from the defects positioned at different circumferential positions](image)

**Figure 9 - A-scan representation of the reflected response from the defects positioned at different circumferential positions**
Figures 10 represents all amplitude measurements taken from the simulations and indicates the maximum reflected amplitude from the defects. From the defect amplitude measurements taken from defects positioned at 30º, 45º and 60º, a considerable amplitude drop was observed compared to the defect response at 0º. The dB drop at those circumferential positions ranges from -4.8dB to -13dB. In all cases, the defects introduced into the model were detected regardless of their size by using the phased array probe proposed in this work (64 elements). However, some amplitude drop differences were observed in the simulation results from different circumferential positions.

In general, the amplitude dB drop difference at the same defect circumferential position was in the order of 2dB, which is acceptable for inspection purposes. However, some simulated results indicated a bigger amplitude dB drop when compared to the three different sizes defects. For example, a defect with 15º tilt and at the 60º position resulted in a -12dB drop compared to the same defect at 0º position. There are a number of possible explanations for this amplitude variation in the simulation results: (1) the position of the incident ultrasonic beam relative to the defect topography; (2) the spatial scanning step is not small enough and the beam might not be incident to the middle of the defect. Nevertheless, these results are still useful for the development of the inspection technique because they provide information about the worst-case scenario and can be used to improve the simulation results. In the future, the calculation parameters will be further refined to provide more accurate evaluation of the influence of the defect parameters such as size, tilt and skew angle.

In all simulation cases it was found out that there is a considerable amplitude drop (-5dB to -13dB) from the defects positioned at angular positions of 30-60º compared to the defect amplitude response at 0º. This information will be used to develop and refine the phased array inspection technique. To demonstrate the effect of the beam orientation relative to the defect and the effect of the defect tilt angle two simulated defects (14.6mm x 7.3mm) were introduced into the model. The first was oriented perpendicular to the incident beam; the second was presented with a tilt angle such that it was not perpendicular to the incident beam. Figure 11 shows the simulated results, where a strong reflection from the perpendicular to the incident ultrasonic wave defect can be observed along with two weak edge reflections from the tilted defect. Similar defect response was observed from the defects that have been skewed in relation to the weld axis. When the ultrasonic incident wave was perpendicular to the defect a strong planar reflection was observed (Figure 11b), while when the defect was skewed by 10º in relation to the weld axis it resulted to two tip diffracted signals. In general, the defects in the weld are “visible” from one position of the phased array possessing the parameters discussed above. However, it was observed that this results in a weaker reflected response from defects that are not perpendicular to the incident beam.
Figure 11 - The B-scan image of two elliptical defects in the weld (a) effect of defect tilt angle (b) defect parallel to the weld (c) defect skewed by 10º

To overcome the issue of amplitude drop from the defects positioned along the weld circumference, and to increase the sensitivity and detectability of the technique, a skew will be applied to the probe. The skew angle will be dependant upon the specific probe position relative to the weld with the aim of keeping the incident ultrasonic beam normal to the defects. Table 3 shows the skew angle required to maintain the ultrasonic beam perpendicular to the weld axis. These values were obtained by changing the probe skew angle to achieve 100% reflection from the defects positioned along the weld circumference. The introduction of variable beam skewing with respect to circumferential position will increase the inspection detectability capabilities and inspection sensitivity by ensuring the beam remains focused in the optimum orientation.

<table>
<thead>
<tr>
<th>Circumferential position</th>
<th>0º</th>
<th>15º</th>
<th>30º</th>
<th>45º</th>
<th>60º</th>
<th>75º</th>
<th>90º</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe skew angle</td>
<td>0º</td>
<td>1º</td>
<td>1.5º</td>
<td>2º</td>
<td>1.5º</td>
<td>1º</td>
<td>0º</td>
</tr>
</tbody>
</table>

CONCLUSIONS

This paper presents an extensive modelling programme of work carried out to determine the effect that defect parameters such as size, orientation and position have on defect detectability in the critical areas of welds in BWR nozzles. A number of simulations have been carried out to simulate the beam coverage from commercially available probes and the responses from the simulated defects have been reported. It has been demonstrated that the defects introduced in the vessel to nozzle weld can be detected by sweeping the ultrasonic beam in a range of angles. This was achieved without the need to change the position of the probe. The results illustrate that, if the probe’s distance from the centre line of the weld is changed during the inspection, better results and detectability will be obtained. Future work will simulate this scenario and the results from existing simulated data will be compared.

In all simulation cases it was found that there is a considerable amplitude drop (-5dB to -10dB) from the defects at angular positions of 30-60º compared to the defect amplitude response at 0º. This information will be used to develop and refine the phased array inspection technique. Applying a skew angle to the probe will overcome the issue of amplitude drop from the defects positioned along the weld circumference and will increase the sensitivity and detectability of the technique. The skew angle will be dependant upon the probe position relative to the weld with the aim of keeping the incident ultrasonic beam normal to the defects.
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