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DEVELOPMENT OF INSPECTION MODALITY FOR SHELL WELD OF CORE SUPPORT STRUCTURE OF A FAST BREEDER REACTOR USING CIVA

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ABSTRACT. The core support structure is welded with a 40 mm thick base plate of the main vessel, of 500 MWe Prototype Fast Breeder Reactor, Kalpakkam, India, along the circumference. This 'shell weld' situated at a distance of about 435 mm away from the weld overlay, is in-accessible to contact mode ultrasonic testing during in-service inspection. An unconventional ultrasonic methodology was developed for this purpose. This inspection modality is validated using the ultrasonic module of CIVA simulation software. There is reasonable agreement with experimental measurements.

Keywords: PFBR, Core Support Structure, Ultrasonic Testing, CIVA Simulation
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INTRODUCTION

A 500 MWe sodium cooled pool type fast breeder reactor (Prototype Fast Breeder Reactor, PFBR) is being constructed at Kalpakkam, India. The entire primary sodium circuit is contained in a large diameter vessel (diameter=12.9 m) called main vessel and consists of core, primary pumps, intermediate heat exchangers and primary pipings connecting the pumps and the grid plate. The vessel has no penetration and is welded at the top to the roof slab. The core subassemblies are supported on the grid plate, which in turn is supported on the core support structure (CSS). The CSS is welded to the main vessel in the knuckle region. The CSS consists of circumferential shell weld, which joins two plates using K type welds. The main vessel is surrounded by the safety vessel, closely following the shape of the main vessel, with a nominal gap of 300 mm to permit robot based and ultrasonic inspection of the vessels. Inspection of the welds in the vessels will be carried out remotely using the in-service inspection (ISI) module, which will move in the 300 mm space between the two vessels. The nondestructive methodologies have been developed for in-service inspection of the welds in the vessels. Some of these methodologies are similar to the conventional methodologies for defect detection as employed for critical components in other sectors also. However, some of the components warranted development of new methodologies due to the complications related to their accessibility or complex geometries. The inspection of the shell weld warranted a new methodology to be developed for in-service inspection because of the limited accessibility of the weld. The whole structure is submerged in the pool of sodium and the inspection of this weld can be carried out only from the outside surface of the knuckle

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region of the main vessel, where the CSS is connected to the main vessel on the inner surface. A new ultrasonic test methodology has been developed for ISI of shell weld of the CSS [1].

Experimental Ultrasonic Test Methodology Developed for ISI of Shell Weld in CSS

Figure 1 shows the cross-sectional view of the CSS in the main vessel showing the shell weld. The developed methodology involves inspection from the outside surface of the main vessel using normal beam ultrasonic transducer (Fig. 1). When the transducer is placed at a location away from the CSS, multiple backwall echoes corresponding to the main vessel thickness are obtained. As the transducer is moved towards the CSS, the backwall echo corresponding to the main vessel thickness is not obtained due to the presence of curvature in the weld overlay. This indicates that the absence of back wall echo corresponding to the main vessel thickness can be used to identify the region of the containment vessel just below the support shell plate. The inspection of the support shell plate can be carried out from this region. In this region, because of the presence of curvature in the containment vessel, ultrasonic beam enters the weld overlay at an angle α to the support shell structure (Fig. 1). Further, because of the presence of columnar grains in the austenitic stainless steel weld overlay in the K weld, ultrasonic waves get skewed and enter the support shell structure at an angle β (Fig. 1). Beyond this point, ultrasonic wave propagates in the support shell structure at an angle β and gets reflected every time it encounters the plate surface. When the wave encounters any defect/interface in the shell plate, ultrasonic wave is reflected from the defect/interface, retraces its path backwards and is picked up by the same transducer. By changing the location of the transducer, angles α and thus β can be changed and hence defect at any location including in the shell weld of the support structure can be detected.

The above methodology has been successfully demonstrated on the mock up sector of the main vessel specially fabricated. The ultrasonic testing, using this methodology, indicated that the defects of size up to ~20 % wall thickness on both sides of the plate could be detected reliably. The developed methodology has the advantage that inspection at multiple angles of ultrasonic wave propagation can be achieved just by moving a single normal beam ultrasonic transducer along the curved surface of the main vessel. Multiple angle beam inspection would ensure the detectability of defects of any orientation [1].

SIMULATION OF ULTRASONIC WAVE PROPAGATION FOR INSPECTION OF SHELL WELD IN CSS

As the ultrasonic methodology proposed for the inspection of shell weld in CSS is of unconventional type and CSS being complex and critical structure, it is required to validate/ improve the same by simulation of ultrasonic wave propagation and develop the inspection modality through the simulation studies. In this direction, an attempt is made in the present study to simulate the ultrasonic wave propagation as per the above methodology and develop the inspection modality by using the CIVA ultrasonic simulation software.

In this study, software developed by the French Atomic Energy Commission (CEA) was used to predict ultrasonic beam propagation in the complex geometry of main vessel sector of PFBR. The software allows bulk wave beam field predictions using the electrodynamics pencil technique and discontinuity response predications using Kirchhoff's, geometric theory of diffraction or Born models for beam/discontinuity interaction. [2-3].

A computation zone was selected that encompassed the region of interest. To reduce the computation time, model accounted only mode conversion, but did not account for material noise, attenuation or shadowing from discontinuity over geometry.

Multiple Reflections and Concept of Unfolding

In the above mode of inspection, the beam encounters multiple reflections within the support structure up to the weld. The simulation of these multiple reflections leads to exorbitant computational burden. In order to circumvent this, a method is adopted in which the component is unfolded on the reflecting surfaces. This is based on the principle that the angles of incidence and reflection are the same and the reflecting surface can be considered as a mirror. By unfolding, the space replicates itself as in a mirror around the surface of unfolding/reflection, thus leading to extended virtual space with the same material. Correspondingly, the defects considered are reproduced symmetrically. Such defects are herein referred as virtual defects. Figure 2 shows schematic of a defect (edge crack) in the support structure and corresponding virtual defects in the unfolded configuration. It may be noted that, on the left side, the first virtual defect is placed in juxtaposition with the true defect, since the unfolding is over a common surface. Whereas the first virtual defect on the right side is on the farther end and is juxtapositioned with the second virtual defect on the right side. The virtual defects repeat themselves many a time. Thus one defect in the true structure will manifest itself as an ensemble of virtual defects, following reflection laws in the unfolded structure. This is an important characteristic of this simulation.

Model-Characteristics Considered

The following are the characteristics taken into consideration in the model.

Computation is done only for L-wave. The echoes due to T-wave will be feeble and will arrive after considerable delay due to its lower velocity hence not considered here. Computation is done in 2D-domain. Noise is not simulated in the model. While the profile of the shell, weldment and the support structure are true, the microstructure introduced in weldment is representative (in the absence of actual microstructure). While unfolding the support structure, in principle, we have to introduce effective attenuation experienced by the beam due to reflection at the surface. This has not been incorporated in this study. Introduction of this will decrease the intensity of the images of virtual defects as a function of its order. Larger order will introduce higher attenuation. This factor will be introduced in the next phase of the modeling.

TABLE 1. Parameters used in CIVA modeling.

Main Vessel Plate and Support Structure:	
Material	Stainless Steel
Symmetry	isotropic
Density	7.8 g/cm^3
L-wave velocity	5650 m/s
Attenuation	Exponential
Attenuation Coefficient	0.005 db/mm
Structural Noise	Nil
Weldment Symmetry	Orthorhombic
Defects: The defects considered are rectangular slots placed on the surface of the shell weld of the core support structure	
Probe: Single element, 25 mm diameter, flat focusing circular transducer without wedge	
Signal: Central frequency 1 MHz, Sampling frequency 25 MHz	

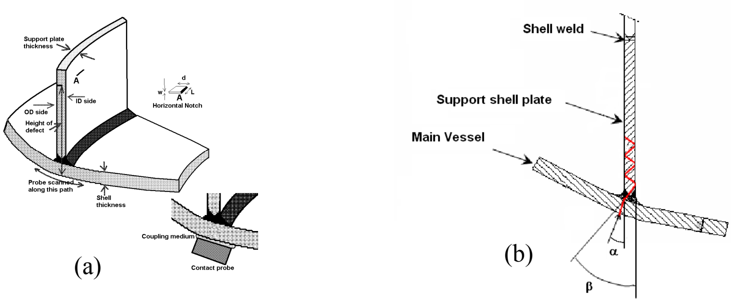


FIGURE 1. (a) Schematic of the main vessel and support shell plate showing the defect introduced in the support shell weld and (b) cross-sectional view of the core support structure showing the shell weld.

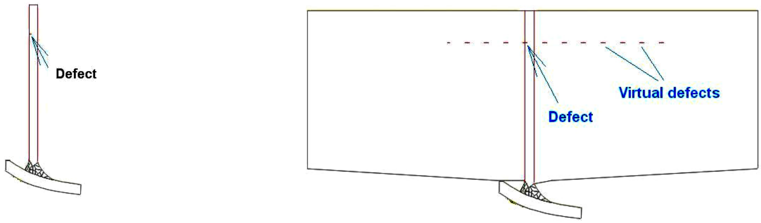


FIGURE 2. Schematic of a defect in the support structure and corresponding virtual defects in unfolded consideration.

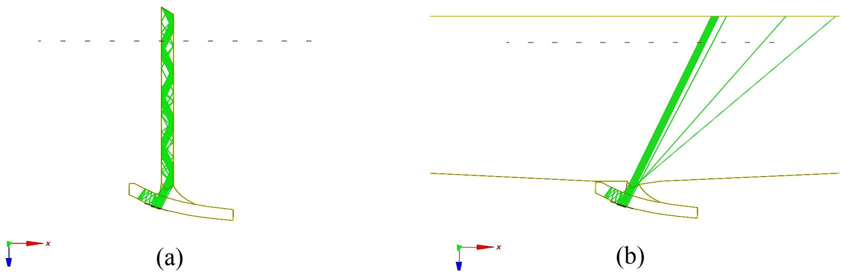


FIGURE 3. The ray tracing for ultrasonic beam propagation in (a) the actual structure, (b) the unfolded structure.

PROPAGATION OF ULTRASONIC WAVE

In this simulation, the propagation of ultrasonic wave in a structure is studied using the ray tracing model and the acoustic field (true beam profile) model. In the ray tracing model, the rays are considered to emerge normal to the surface of the probe and hence the computation burden is considerably lower as compared to the acoustic field model, in which the true beam profile is considered. Because of the lesser computational burden, multiple reflections within the support structure can be simulated in ray tracing mode. However, the beam divergence and in-turn the signals generated due to the reflection of diverged beams can not be simulated in the ray tracing model. The ray tracing is presented to demonstrate the validity of the unfolded structure. After demonstrating the validity of the simulation modality, the acoustic field is computed to understand the ultrasonic wave propagation in the unfolded support structure. The ray tracing and beam characteristics in the support structure are considered first without incorporating the weldment.

Ray Tracing

Figures 3 (a) and (b) show the ray tracing for ultrasonic beam propagation in the actual and the unfolded structure respectively. Here ten rays are considered to emerge normal to the surface of the transducer. It can be seen that a major part of the beam is encountering the defect from the same perspective in both the true structure and in the unfolded structure. In the true structure, the 10^{th} reflection of the beam encounters the defect. In the unfolded structure, the beam is encountering the 10^{th} virtual defect on the right side.

Beam Characteristics

Beam characteristics computed at two slightly different positions of the probe are presented in Fig. 4. It can be observed that a (major) part the acoustic field from the probe is lost in the shell region due to multiple reflections. Further, a part of the acoustic field tunnels through the neck region of the structure. Depending upon the position of the probe, a part of the beam is scattered around. Thus, scanning the probe along the curvature of the shell manifests as though the unfolded structure is scanned radially from the neck region of the structure.

Defect Response – Study of Virtual Defect in Isolation

Though conceptualised to save computational burden, the unfolded model has the advantage of studying each of the phenomenon involved in isolation. For example, we can study the defect response of say isolated r^{th} virtual image due to r^{th} reflection. Thus, giving better insight into the defect response. In the following examples (Fig. 5), the three virtual defects (r, r+1 and r+2) are studied in isolation and their corresponding B-scans projected on to the component plane are presented in Figs. 5 (a), (b) and (c). It may be noted that there is slight discrepancy in the spatial location of the virtual defect and its corresponding image, possibly due to cumulative errors of computation in the modeling. When the defect response is studies with the virtual defects together, we get a superposition of their corresponding images (Fig. 5(d)). Figure 6a shows the B-scan projected on to the component plane when an ensemble of virtual defects is considered. The B-scan projected along the scanning axis is shown in Fig. 6(b). This is the signature of a defect in this ultrasonic inspection modality.

Effect of the Weldment

So far the beam propagation was studied without considering the weld structure of the main vessel and CSS joint. The weld structure is also introduced in the simulation. Due to

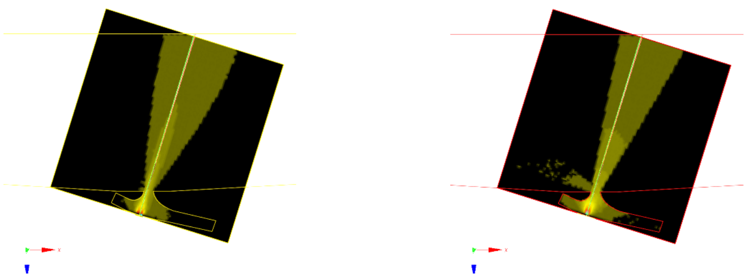


FIGURE 4. Beam characteristics at two slightly different positions of the probe.

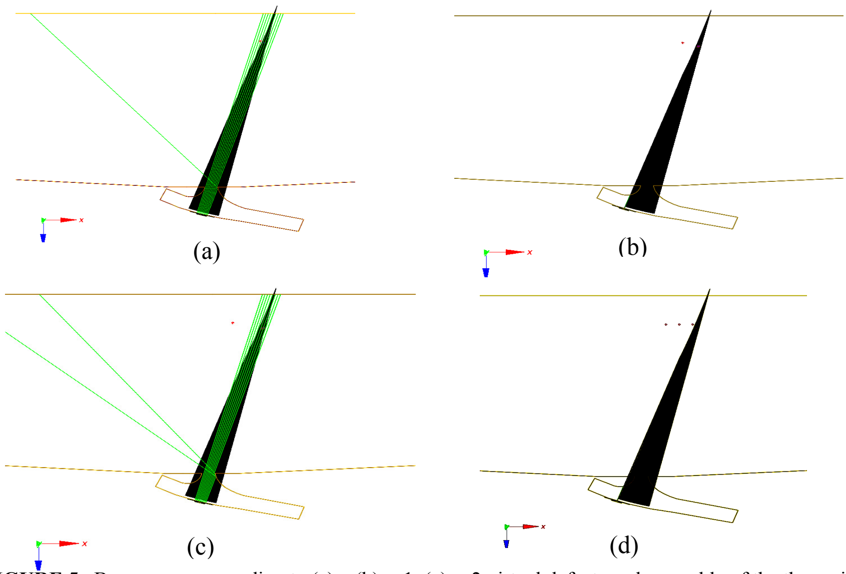


FIGURE 5. B-scans corresponding to (a) r, (b) r+1, (c) r+2 virtual defects and ensemble of the three virtual defects projected on to the component plane.

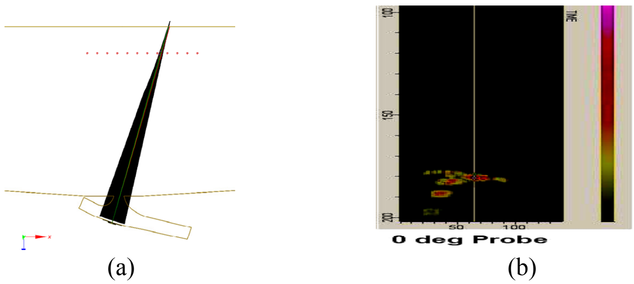


FIGURE 6. B-scans corresponding to ensemble of virtual defects (a) projected on to the component plane and the (b) corresponding B-scan along the scanning axis.

anisotropic nature of the weld region, the beam will undergo skewing resulting in uneven distribution of acoustic field. But for this, the characteristic radial scan remains the same (Fig.7).

B-scans corresponding to ensemble of virtual defects projected on to the component plane and corresponding B-scan along the scanning axis are shown in Figs. 8 (a) and (b) respectively, after incorporation of the weld structure. It is found that, while the B-scans projected on to the component plane have marked differences with the introduction of the weldment, the B-scan image projected along the scanning axis has retained its characteristic signature. The presence of weldment introduces additional attenuation. The maximum amplitude of the signal has reduced to nearly 53% (2.57E-7) to 70% (3.34E-7) compared to the maximum signal without weldment (4.79E-7)

COMPARISON WITH EXPERIMENTAL RESULTS

Figure 9 (a) shows experimental setup used for the developed methodology. A 2 MHz normal beam ultrasonic transducer is used along with a microprocessor based ultrasonic flaw detector. Figures 9 (b) shows the photograph of the cross section of the CSS and the main vessel plate. The same profile is transferred for the simulation studies. Figure 9 (c) shows the photograph of defect of maximum depth of 9 mm introduced in the support shell weld for establishing the sensitivity of the developed methodology. Figure 9 (d) shows the A-scan signal of the maximum amplitude obtained corresponding to the defect of 9 mm depth on the outer surface of the shell weld (as shown in Fig. 9 c). A sharp reflection at about 630 mm beam path is obtained, which corresponds to the probe location of α~25^0 and β~41^0 (Fig. 1b).

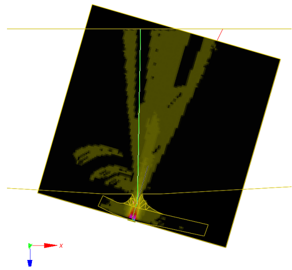
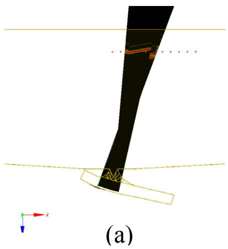
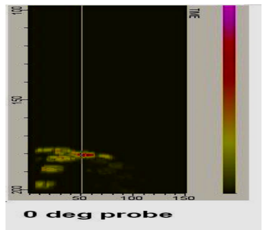


FIGURE 7. Uneven distribution of acoustic field by considering the weld structure.



(a)

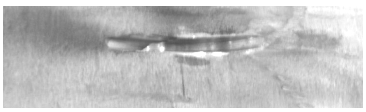


(b)

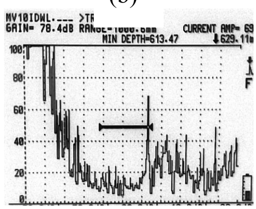
FIGURE 8. B-scans corresponding to ensemble of virtual defects (a) projected on to the component plane and (b) corresponding B-scan along the scanning axis after incorporation of the weld structure.

(a)

(b)



(c)



(d)

FIGURE 9. (a) Experimental setup for ultrasonic inspection, (b) the support structure profile (which is transferred for simulation), (c) a defect of 9 mm maximum depth on the outer surface of the shell weld and (d) corresponding A-scan signal with maximum amplitude obtained at α~25^0.

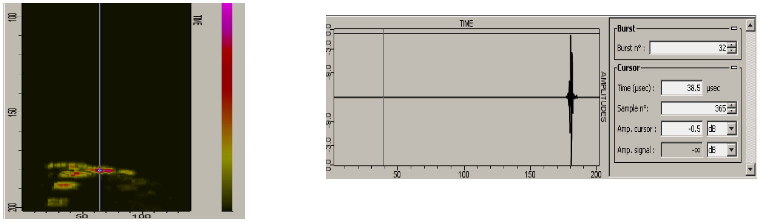


FIGURE 10. The simulated B-scan image and an A-scan image corresponding to the virtual defect of maximum response.

Figures 10 (a) and (b) show the simulated B-scan image and an A-scan image corresponding to the virtual defect of maximum response. The position of the virtual defect is 182 microseconds [(514 mm), L-wave velocity 5650cm/s]. The location of the virtual defect is at about 535 mm. Computation is done only for L-wave. The echoes due to T-wave are expected to be feeble and will arrive after considerable delay and hence not considered here. Computation is done in 2D-domain.

SUMMARY

CIVA ultrasonic simulation software has been used to simulate the wave propagation in the case of a new ultrasonic testing methodology developed for in-service inspection of shell weld of core support structures of a PFBR main vessel. The concept of unfolding is introduced in the modeling to simulate multiple reflections. Correspondingly, each real defect is transformed, in the unfolded model, into an ensemble of virtual defects following reflection laws. B-scan image of this ensemble of defects along the scanning axis is a signature of the defect in this inspection modality. One has to look for this pattern in the B-scan for positive identification of defect. The simulated results are compared with experimental measurements. There is reasonable agreement considering the limitations in the model. Simulation results suggest that use of angle beam transducer may give better signal to noise ratio.

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