Detection of Service-Induced Damage in Steam Generator Tubes of PFBR using Ultrasonic Guided Waves

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Abstract
An ultrasonic guided wave-based inspection methodology is developed for the detection of sodium impingement damage in steam generator (SG) tubes of prototype fast breeder reactor (PFBR). Towards this, an axisymmetric guided wave mode namely, L(0,2) at 250 kHz is selected using dispersion curves and mode characteristics. To test the usefulness of the mode, an SG tube with multiple simulated impingement damage lying along the same line is first examined using finite element simulation. Then, the results are validated experimentally. The times of the flight and amplitudes from experiments and FE simulations correlate well. L(0,2) mode is seen to be very efficient in picking up the sodium impingement defects with the sensitivity of 10%WT (0.23 mm) depth. Further, FE studies performed with defects of various depths show monotonic increase in reflectivity with depth. It is also observed that the reflectivity is less influenced by the curvature of the defect.

Keywords: Ultrasonic guided wave, axi-symmetric mode L(0,2), sodium impingement damage, finite element simulation, reflectivity.

1. Introduction
Steam generator (SG) tubes of prototype fast breeder reactor (PFBR), being commissioned at Kalpakkam, carry water/steam inside the tube whose outer surface is in contact with hot liquid sodium. If any surface opening flaw is present, it may cause sodium and water to come in contact leading to damage of the neighbouring tubes and may affect the normal operation of the reactor. Hence, it is mandatory to ensure the healthiness of the sodium-water boundary. The flaws that may occur in SG tubes are circumferential and axial cracks, pin-holes, wearscars, sodium impingement damage, spatter, arc strikes and weld fusion at the ID of the SG shell etc. [1]. The present study aims at demonstrating the detection possibility of a service-induced flaw namely sodium impingement damage. These flaws occur when there is a leakage of water/steam through an SG tube wall into liquid sodium resulting in sodium-water reaction in the shell side. The reaction is exothermic with the liberation of 180 kJ/mole of heat, sodium hydroxide and hydrogen. When the leak rate is less than 50 g/s (small leak), the main effect observed is the impingement of sudden jet of corrosive products on the adjacent tubes leaving them punctured (impingement wastage or adjacent tube wastage). This puncture will initiate a secondary leak. Such occurrences will involve material wastage and will affect the smooth functioning of the reactor. The material selected for the steam generator tubes is modified 9Cr-1Mo ferritic steel for
its superior mechanical and thermal properties, better resistance towards caustic and chloride stress-corrosion cracking and wastage resistance [2]. However, its robustness should be tested time-to-time. Presently, service-induced flaws are checked by means of an NDT technique known as remote field eddy current testing (RFECT) [3]. The technique requires the insertion of an RFECT probe all along the length of the tube and hence, time consuming. Therefore, an alternate method of examination is being developed using ultrasonic guided waves. The technique requires the placement of an ultrasonic transducer at one location to get the thorough information about the entire tube. The technique proves to very successful in detecting multiple circumferential, axial, pinholes and tapered defects in SG tubes [4]. There is a vast literature available in the area of ultrasonic guided wave propagation in pipes. Basically, guided waves are formed by the superposition of mode converted L-wave and S-wave between the inner and outer walls of a tube. The propagation of guided waves is governed by Navier’s equation [5]. With the proper boundary conditions applied at the ID and OD of the tube and material properties, dispersion curves and the mode shapes can be obtained. There are three families of guided waves in a tube namely, longitudinal, torsional and flexural modes with their characteristic mode shapes and velocities. In general, guided waves are chosen for inspection of tubes because of their long-range propagation and wide variety of modes and sensitivity as opposed to bulk waves. In this study, an axisymmetric longitudinal mode has been chosen.

The present study considers a shallow flat defect (Flat mill) with curved edges simulating a sodium impingement damage. The flaws are considered to be non-axisymmetric w.r.t the axis of the tube. The shape of the defect simulating a partial puncture is reasonably chosen from the existing literature. All the defects considered in the study are of the same axial length. The objective of the study is to achieve the sensitivity of 50 %WT (1.15 mm of 2.3 mm WT) depth of a sodium impingement defect. The paper is organized as follows: (1) optimization of a guided wave mode using Disperse software, (2) FE study of multiple-defect scenario and experimental validation, (3) reflectivity of the guided wave mode for the defects with various depths and radii of curvature and mode conversion of L(0,2) and (4) conclusions.

2. Optimization of Mode & Finite element simulation

2.1 Mode selection through Disperse software

SG tubes of PFBR are made of mod. 9Cr- 1Mo steel with inner and outer radii as 12.6 mm and 17.2 mm, respectively. With the radii, density of 7800 kg/m$^3$, Young’s modulus of 220 GPa, and the Poisson ratio of 0.2805, dispersion curves were obtained using Disperse software, developed at Imperial college, London [6,7]. Figures 1a & b show the phase velocity and the group velocity dispersion curves. The only modes that are nearly non-dispersive for the frequencies less than 1 MHz are F(1,2), L(0,2) and T(0,1). The cut-off of L(0,2) is around 150 kHz. For frequencies less than 200 kHz, L(0,2) mode is highly dispersive. For the present study L(0,2) mode at 250 kHz was chosen because of its highest group velocity, good separation from neighbouring modes, nearly uniform axial stresses indicating nearly equal sensitivity and easier excitability. The group velocity of L(0,2) mode is 5380 m/s. Figure 1c shows the mode shape of L(0,2) at 250 kHz. It can be seen that, L(0,2) has dominant axial displacement, small radial displacement and zero angular displacement. Since the axial displacement is dominant, there is a large amount of energy present in the axial direction indicating the potentiality of long-range propagation. Another advantage is minimal leakage of wave energy when the tube is surrounded by liquid.
sodium, as liquids, in general, do not support shearing forces. It can be seen in literature that either L(0,2) or T(0,1) mode is used for inspection of tubes [8]. Excitation of L(0,2) can be made by coupling an ultrasonic transducer to the one end of the tube, coupling of shear wave transducers to the circumference of the tube or by EMATS and magnetostriction [9-11].

![Fig. 1.](http://www.foxitsoftware.com) (a) Phase velocity and (b) group velocity dispersion curves for SG tubes made of mod. 9Cr-1Mo steel with the inner diameter of 12.6 mm and the wall thickness of 2.3 mm and (c) mode shape of L(0,2) at 250 kHz. L: longitudinal mode, F: flexural mode and T: torsional mode

### 2.2 Finite element simulation

To study the propagation and interaction of L(0,2) guided wave mode with defects, the finite element simulation software ABAQUS Explicit was used. For the present study, a 3D-finite element model of a 1.5 m long steam generator tube with four (multiple) sodium impingement damage along the same line was designed. The schematic of the shape of the flaws and their respective locations are shown in Fig. 2. The dimensions of the flaws are shown in Table 1. The elastic properties, as given in Section 2.1 were assigned to the model. The spatial step used was 0.55 mm and the time step of 1e-8 s was chosen based on CFL (Courant–Friedrichs–Lewy) condition [12]. The steps were optimized for convergence. The wavelength of the mode L(0,2) at 250 kHz is 21 mm and hence, there are nearly 40 elements across the wavelength. The number of through-thickness elements was chosen to be 4. The geometry was meshed with 8-node linear brick elements with reduced integration (C3D8R) and hourglass control. The linear and quadratic bulk viscosities used were 0.35 and 0.75. Figure 3 shows the mesh used in the model with the local seeds around the defect of 0.2 mm. The stress-free boundary conditions were applied at ID, OD and the end faces. The program was executed in two steps namely excitation step of duration 20 µs and the wave propagation step of 750 µs duration. A five-cycle Hanning windowed toneburst of 250 kHz center frequency was applied axi-symmetrically on the end face of the tube, as an axial displacement (Uz). The receiver points were set on the excitation end and the time signals corresponding to axial, circumferential and angular displacement components from the receiver points were averaged correspondingly.
Fig. 2. Schematic of a 1.5 m long SG tube with four simulated sodium impingement damage

Table 1. Dimensions and locations of sodium impingement defects,

<table>
<thead>
<tr>
<th>S.no.</th>
<th>Defect label</th>
<th>Dimensions of sodium impingement defects with the radius of curvature of 3.175 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Depth, mm</td>
</tr>
<tr>
<td>1</td>
<td>a</td>
<td>0.23</td>
</tr>
<tr>
<td>2</td>
<td>b</td>
<td>0.46</td>
</tr>
<tr>
<td>3</td>
<td>c</td>
<td>0.69</td>
</tr>
<tr>
<td>4</td>
<td>d</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Fig. 3 Mesh used in the model

Besides, to obtain the reflectivity of L(0,2) mode, different FE models were built with sodium impingement defects of different depths and the same axial extent of 8.6 mm in a 1.0 m long tube. Further, to study the influence of the radius of curvature (R), FE simulations with defects of 50%WT depth and different radii of curvature (R=3.175 mm, 5 mm and 7 mm) were also accomplished. Table 2 shows the locations and the dimensions of the defects with various depths and widths for the same radius of curvature R=3.175 mm.
Table 2. Sodium impingement defects with different depths and the same R

<table>
<thead>
<tr>
<th>S.no.</th>
<th>Defect label</th>
<th>Depth, mm</th>
<th>Dimensions of defects with R= 3.175 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Axial length, mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Width, mm</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Location, mm</td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>0.23</td>
<td>8.6</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>0.69</td>
<td>8.6</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>1.15</td>
<td>8.6</td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>1.61</td>
<td>8.6</td>
</tr>
<tr>
<td>5</td>
<td>E</td>
<td>2.07</td>
<td>8.6</td>
</tr>
</tbody>
</table>

3. Experimental

To conduct experiments, all four defects with the dimensions and locations, as provided in Table 1 were machined along the same line of sight in an SG tube segment of length 1.5 m. The schematic of the experimental set-up is shown in Fig. 4. An ultrasonic transducer (M/s. Panametrics) of frequency 250 kHz and the diameter of 40 mm was axi-symmetrically coupled to the one end of the 1.5 m long tube with four sodium impingement defects, as shown in Fig. 2 and excited by a high power Krautkramer Branson USD10 pulser-receiver. The signals received were transferred to the oscilloscope. The signals were sampled at 5 MHz and averaged 32 times and stored as ASCII data for post-processing.

4. Results and discussion

Figures 5 i and ii show FE simulated and experimental time signals obtained for multiple sodium impingement defects in a 1.5 m long tube. The FE signal corresponds to the averaged time signal of axial displacement component. For the sake of comparison, all the echoes are normalized w.r.t. to the end reflection in both FE and experimental signals. The experimental and FE amplitudes show good correlation for all four defects. The labels a-d correspond to the defects, as shown in Table 1. The relative amplitudes in the experimental signal are slightly higher than the corresponding ones in the FE signal. The group velocities, for the cases of FE and
experiment, obtained using the end reflected echo for 3.0 m propagation turns out to be 5362 m/s and 5359 m/s against the Disperse predicted velocity of 5380 m/s. The times of flight for FE simulation and experimental signals show a good correlation. In other words, the defects can be located within the maximum error of 10 mm. The end reflections in both cases show a slight dispersion due to interaction with the multiple defects. It appears that the reflections from the defects are mostly governed by the depths of the defects. The SNR for the case of the smallest defect turns out to be approximately 15dB. The sensitivity achieved was 10%WT deep defect, as required. To compare the response of L(0,2) to defects at higher frequencies, experiments were conducted at 500 kHz. Though the defects were picked up, the signals show additional modes. Even though the defects are picked up, it will be confusing to interpret the signals in actual testing. Figure 6 shows the experimental signal obtained using 500 kHz transducer.

Fig. 5. Comparison of sodium impingement defect signals obtained using (i) FE and (ii) experiment, for frequency of 250 kHz. a-d are defect labels, as in Table 1. f, the tube end reflection.

Fig. 6. Sodium impingement defect signals obtained using 500 kHz transducer. a-d are defect labels, as in Table 1. f, the tube end reflection.

4.1. Reflectivity of L(0,2) at 250 kHz

To obtain the reflectivity of L(0,2) mode for sodium impingement defects of different depths and widths and the same axial length and the radius of curvature, FE simulations were performed. The dimensions and locations of the defects used were shown in Table 2. Figure 7 shows the reflectivity of L(0,2) from the defects. The amplitudes are normalized w.r.t. that of the biggest defect E. It can be seen in the figure that the reflectivity increases monotonically with the depth. The only varying parameters from one defect to another are depth and width. The variation in reflectivity could be due to width as well. However, it can be guessed that the depth should play a dominant role, as guided waves are more sensitive to reduction in thickness. Then, to study the influence of the curvature of the defects, FE simulations were performed with 50%WT deep
defects with the different radii of curvature $R=3.175$ mm, 5 mm and 7 mm. Figure 8 shows the reflectivity of $L(0,2)$ from the defects with 50%WT deep defect with the different radii of curvature. It can be observed that the amplitudes of defect signals, indicated by $G$ in the figure, are almost the same. Hence, it can be expected that for a defect of a given depth, the reflectivity will remain the same even if the defect were to be of hemispherical shape. At the same time, what remains to be investigated is the influence of curvature on reflectivity for bigger defects with large curvatures. Though the lengths of the defects in all the cases were considered to be the same (8.6 mm), reflectivity should vary with the length also.

![Fig. 7. Reflectivity of $L(0,2)$ for defects of different depths and widths and the same radius of curvature $R=3.175$ mm. A-E stand for different defects.](image)

![Fig. 8. FE signals obtained for 50%WT deep defects with the radii of curvature (a) $R=3.175$ mm, (b) $R=5$ mm and (c) $R=7$ mm, respectively. $G$ stands for the defect signal and $H$, the end reflection.](image)
4.2. Mode conversion of L(0,2) at 250 kHz

To obtain the nature of interaction of L(0,2) mode with the sodium impingement defect, FE simulation was performed with a 50%WT deep defect with the radius of curvature, R= 3.175 mm located at 600 mm in a 1.0 m SG tube. The axial (Uz), radial (Ur) and angular displacement (Uθ) components were recorded at the receiver points and averaged. Figure 9 shows the time signals of the axial, radial and the angular displacement components. It can be seen in the figure that Uz component shows a defect signal and the end reflection and both of which correspond to L(0,2), based on the group velocity obtained from them. However, Ur and Uθ components show mode converted signals of F(1,3) and F(1,2) and the end reflections do not show up due to their slower propagation than L(0,2). They can be observed on a larger time scale than that shown in the figure. This points out to a fact available in literature that when a symmetric mode like L(0,2) is incident on a non-symmetric defect, L(0,2) mode converts to non-symmetric flexural modes [13]. The percentages of amplitude of F(1,3) and F(1,2) for the angular displacement (Uθ) w.r.t. the amplitude of the defect signal of Uz are 20% and 40% , respectively. While, the percentages of amplitude of F(1,3) and F(1,2) for the radial displacement (Ur) w.r.t. the amplitude of defect signal of Uz are 0.097% and 0.03% , respectively

Fig. 8. Axial (Uz), radial (Ur) and angular displacement (Uθ) components obtained for 50%WT deep defects with the radius of curvature, R=3.175 mm.

5. Conclusions

In this paper, optimization of a guided wave mode for detection of sodium impingement defects and reflectivity of L(0,2) mode from sodium impingement defects in SG tubes of PFBR have been presented systematically. L(0,2) at 250 kHz has been optimized because of its non-dispersive nature and the highest group velocity. L(0,2) mode at 250 kHz picks up defects of
different dimensions with the sensitivity of 10%WT deep defect of 8.6 mm length and 3.9 mm width, as required. It can also be said that L(0,2) mode very effectively detects multiple defects present along the same line. FE study for multiple defect case was carried out and validated by experiment. The results correlated exceedingly well. FE studies were also performed to study the reflectivity of L(0,2) from the defects of various dimensions. The reflectivity is seen to increase monotonically with depth and is almost independent of the curvature for a given depth. Finally, it was also observed that the interaction of L(0,2) with a sodium impingement damage generates mode converted non-axisymmetric flexural modes. Further, the mode L(0,2) at 250 kHz also proves to be a suitable candidate for the early detection of sodium impingement damage in SG tubes, as the requirement stands at the detection of 50%WT deep defects.

References