Feasibility of Detection of Leaking Fuel Rods Using Side Coupled Guided Waves

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Abstract

Fuel rods in nuclear reactors consist of uranium fuel pellets that are encased in hollow metal tubes made from zirconium alloys. Due to the elevated temperature, pressure, and radiation inside of a reactor, fuel rods can fail during operation. The most common failure mechanism in Pressurized Water Reactors (PWRs) is grid-to-rod fretting wear while for Boiling Water Reactors, debris fretting is most common. Other mechanisms include crud and corrosion failures, and pellet cladding interaction cracks. The failure of a fuel rod can potentially lead to leaking of radioactive material into the primary coolant system. Identifying the individual leaking fuel rod presents a challenge. A magnetostrictive transducers and guided wave technology have been investigated recently with the focus on detection of through wall anomalies such as axial, skewed, circumferential notches and drilled holes. A probe coupled from the top of the rod was used. Due to the fact that the access to the fuel rods might be more practical from the side, a side coupling probe was developed in addition to the top coupling probe. The side coupling probe has gone through a number of evaluations and modifications with the major goal of improving its sensitivity to a pinhole type of defects. Fundamental T(0,1) guided wave mode at frequency range 100 - 350 kHz was used during tests. The probe design and results of mockup tests with known artificial anomalies will be discussed.

Keywords: Nuclear fuel rods, side coupled guided waves, pinhole, magnetostrictive transducer

1. Introduction

In an earlier project for the Electric Power Research Institute (EPRI), Southwest Research Institute\textsuperscript{®} (SwRI\textsuperscript{®}) developed a prototype inspection probe that, when positioned at the top of the fuel rod, could positively identify 100\% through-wall planar flaws (such as axial, circumferential, and 45\degree electrical discharge machining (EDM) notches and volumetric flaws (such as corrosion pits and fretting wear) in the entire length of the fuel rod. The inspection probe was remotely positioned and engaged with each fuel rod using a mechanical delivery system. The schematic of the probe coupling to the top of the rod is shown in Figure 1a. A high powered version of MsS probes called magnetostrictive transducer (MsT) was used in all probes designs. The inspection probe was remotely positioned and engaged with each fuel rod using a mechanical delivery system. The full integrated inspection tool was tested in simulated field conditions in a water tank at Waltz Mill tests facility, as shown in Figure 1b [1].
Upon the additional request from EPRI, a probe capable to couple to the rods from the side was developed. Figure 2a shows a field deployable version of side coupling probe developed to fit onto 0.404 inch (10.2 mm) diameter of fuel rods. The sensor elements in this probe are pressurized against the rod by blades positioned on the opposite sides from a pivot. Due to limited gaps between the rods, the blades were shortened in the way that only the rods located in rows from one to five could be tested using this method. The energy transfer was performed via two localized areas of the fuel rod circumference located on the opposite sides of the rod. Mechanical traction between the probe and the rod was supported by dry coupling method with applied pressure in the order of 40 PSI.

The sensitivity of the probes was evaluated at frequency range 50 – 250 kHz based on the following criteria: a - detection capability in free span area; b - detection capability under the grid; c - detection capability in the presence of fuel simulants.
A side coupling method was initially evaluated on the empty rods with pinholes of different diameters located at a distance of 0.97 m from the probe. Results of the test indicated the following: In the free span area, the smallest through-wall pinhole that could be identified based on signal to noise ratio (SNR) +6 dB criterion had a diameter of 0.059 inch (1.5 mm); When the pinhole was located under the grid, the 0.076 inch (1.9 mm) diameter pinhole could be detected based on SNR +6 dB criterion; High probability detection under the grid based on SNR +9 dB criterion could be accomplished for pinholes 0.116 (2.9 mm) in diameter and larger; The best results in terms of SNR were accomplished using higher frequency bands 200 – 250 kHz. A number of more challenging tests were conducted on fully assembled fuel bundle at GE facility in San Jose (shown on Figure 2 b) with simulated fuel condition (fuel was simulated by short metal rods filling the entire length of the fuel rod). The tests indicated that the presence fuel simulants caused increased coherent noise and higher signal attenuation. As an example, Figure 2 c shows A – trace acquired at 150 kHz. Accomplished SNR during the test was 28 dB. This SNR was calculated as a ratio between the reflection produced by the end of the rod (after distance amplitude correction was applied) and the highest amplitude of background noise (assuming that the end of the rod returned 70% of energy). It was found that indications produced by grids were buried in coherent noise produced by fuel simulants. With the 28 dB SNR, a 2.5 mm diameter hole could be detected based on formal criteria (this criteria will be discussed in the next section).

As a results of this test, it was decided to continue development of this probe concept to reduce the effect of interaction of guided wave with fuel simulants by moving the frequency range above 300 kHz. Another target was addressing the possibility of finding smaller (up to 0.005 inch (0.127 mm) diameter) pinholes.

2. Pinholes detection criteria

A formal detection criterion for guided wave testing is similar to conventional UT and is based on amplitude ratio between indication produced by anomaly and background noise. This ratio is supposed to be at least ‘two to one’ or +6 dB. The size of anomaly is estimated based on its cross-section area of anomaly (CSA) in the reference to the cross section of the metal portion of the tube. Figure 3 shows traces representing a highest background noise (black dotted trace) and a required SNR for detection of pinholes based on +6dB detection criterion. A vertical scale for the black traces is shown on the left side of the plot. The black trace was calculated based on formula:

\[
\text{SNR} = 6 + 20 \times \log \left( \frac{A_o}{A_{def}} \right)
\]

Where \(A_o\) – amplitude produced by an anomaly with 100% cross-section (the end of the rod), \(A_{def}\) – amplitude produced by a defect (pinhole)

An orange trace on the Figure 3 shows calculated cross section of pinhole in the reference to the cross-section of the metal portion of the fuel rod in percent. A vertical scale for the black traces is shown on the right side of the plot. This plot allows to get a theoretical estimate of the size of the pinhole that could be detected at a given SNR. It should be noted that estimated SNR is based on the assumption that guided wave uniformly fills the entire cross-section of the fuel rod.
This plot could be used to evaluate the results of the test shown in Figure 2c. For example, 28 dB SNR accomplished on rods with fuel simulants is shown with a red dotted line. With this SNR, a pinhole with diameter close to 2.4 mm could be detected based on +6 dB detection criteria. Based on the yellow trace, 2.4 mm diameter pinhole will represent a 7.5% change in cross-section of the fuel rod with the diameter 0.404 inch (10.2 mm). Based on this plot, detection of small pinholes will require accomplishing quite high SNR. For example, detection a pinhole with 1% cross-section in would require SNR 46 dB or higher. It is typical for conventional magnetostrictive sensors to provide SNR in the range of 50 - 62 dB [2,3]. However, the actual SNR might be reduced by coherent noise that is specific to conditions of each particular component. In application to nuclear fuel rod, strong contributors to the coherent noise would be grids acting as a mechanical attachments and fuel inside of the rod.

Coherent noise produced by grids could be pretty well evaluated at laboratory conditions. Condition of fuel inside the fuel rod is dependent on many variables and could vary from pellets just slightly touching the wall to pellets pressurized against the wall. To get a more realistic estimate of coherent noise, rods filled with tungsten powder were used for testing and the results will be discussed below.

![Figure 3. A plot showing required SNR for detection of pinholes (black trace) and cross section of pinholes in the reference to the cross-section of the metal portion of fuel rod (yellow trace).](image)

3. Higher frequency guided waves in fuel rods

To investigate the possibility of finding smaller (up to 0.005 inch (0.127 mm) diameter) pinholes a fuel rod with the dimensions 0.374 x 0.03 inch (9.5 x 0.7 mm) was provided by EPRI. Dispersion curves for zirconium tubes are shown in 4 (calculated using CIVA, CIVA is a software program developed by Commissariat à l’Énergie Atomique (CEA), and its Guided Wave computation module was used for this study). All previous tests on fuel rods were conducted in frequency range 30 – 250 kHz using a fundamental torsional T(0,1) mode (marked as frequency range A in Figure 4). The frequency range proposed for this test was 250 – 450 kHz (marked as frequency range B). Velocity of SH0 mode guided waves calculated by CIVA was 2220 m/sec (87.4 inches/msec).
Utilizing higher frequencies has the advantage of a more compact sensor design, with higher axial resolution and higher sensitivity to smaller anomalies. Additional advantage of higher frequencies was expected to be reduced interference with mechanical attachments such as grids and fuel inside the rods.

4. Comparison of SNR accomplished on empty rod and a rod with tungsten

Next set of experiments was conducted using a mix of tungsten powder with the grain in the range 0.2 – 1 mm. When the guided wave testing method is applied to rods filled with high density powder, test ranges and SNR could be significantly compromised and unpredictable due to energy leakage into the embedding substance and back to the wall of the fuel rod. Interaction with tungsten powder can significantly vary depending from its conditions, including loose, compacted or mechanically compacted. Relevant research was conducted earlier on pipes surrounded by sand [4]. It was reported that depending from the sand conditions, attenuation values were found to be in the range of 1.65–5.5 dB/m for the torsional mode guided wave over the frequency of 11–34 kHz.

A rod used for this test had a tungsten powder poured when the rod was in vertical position. The powder was slightly compacted by hitting the rod in vertical position over the floor at different stages of filling. Figure 5a shows A-scan traces acquired from empty rod (blue trace) in comparison with A-trace acquired from a rod filled with tungsten (red trace). These two rods had different tested length and the area where both traced are overlapped is marked as ‘Area X’ and its zoomed view is shown in Figure 5b.
Test results obtained at 350 kHz indicated that SNR accomplished on empty rod was in the order of 42 dB. With this SNR, 1.6% CSA (0.45 mm diameter pinhole) could theoretically be detected. SNR accomplished on the rod with tungsten varied from 34 to 26 dB depending from the area along the length of the rod. The areas are marked as areas ‘A’ (20 – 45 cm area), ‘B’ (45 – 55 cm area) and ‘C’ (80 – 85 cm area). As it follows from the data, the net effect of tungsten powder is increased coherent noise in the range from 8 dB – 16 dB. Pinhole diameters that could be theoretically detected in the rod with tungsten are shown on Figure 5b. They were found to be in the range from 1 mm (3.4% CSA) for the area ‘A’ to 3 mm (11% CSA) in the area ‘C’.

5. Experiments with detection of 0.005 inch (0.127 mm) diameter pinhole

Pinhole with diameter of 0.005 inch (0.127 mm) represents a 0.4% CSA anomaly for 0.374 x 0.03 inch (9.5 x 0.7 mm) fuel rod. It is common for practical guided wave testing to claim detection threshold 2% CSA as a viable sensitivity [5]. For detection of anomalies representing 0.4% CSA, estimated SNR should be in the order of 54 dB. Figure 6 shows a calculated SNR plot and position of 0.005 inch (0.127 mm) diameter pinhole on it.

Figure 5. Experiments with tungsten powder fill: a - A-traces acquired from empty rod (blue trace) in comparison with A-trace acquired from a rod filled with tungsten (red trace), b - zoomed view of ‘Area X’.

Figure 6. A plot showing required SNR for detection of pinholes with diameter 0.1 – 1 mm (black trace) and cross section of pinholes in the reference to the cross-section of the metal portion of fuel rod (orange trace)
Another practical way to detect smaller anomalies is shortening inspection range and using sensor with partial coverage of the circumference of the components. In this case, for a certain distance, the guided wave energy stays predominantly on the side of the rod providing better detection. Figure 7 shows experimental arrangement used for experiment with detection of 0.127 mm diameter pinhole. A side coupling probe was coupled to empty fuel rod at a distance 10.4 inch (265 mm) from a pinhole. A probe had two flat surfaces and connection to the rod was conducted via two localized coupling interfaces shown on the right side of Figure 7. A spacer grid was placed between the probe and the anomaly. A pinhole introduced in the rod is shown on the bottom side of Figure 7 and the probe was coupled in the same circumferential position as the location of pinhole.

![Figure 7](image)

Figure 7. Experimental arrangement used for experiment with detection of 0.127 mm diameter pinhole.

Figure 8 shows A-scan trace acquired using this setup at 350 kHz (black trace). The trace is overlapped with a trace acquired from another rod with tungsten powder (red trace). The area of interest is marked as ‘area Y’ and is shown at larger scale in Figure 8b.

![Figure 8](image)

Figure 8. Results of experiment with detection of 0.127 mm diameter pinhole: a - A-scan trace acquired using this setup at 350 kHz (black trace). The trace is overlapped with a trace acquired from another rod with tungsten powder (red trace); b – zoomed view of the area ‘Y’ in a.

As it follows from the results, a pinhole produced indication about 6 dB higher amplitude compared to the background noise (estimated at -34 dB). Grid also produced indication about 4
dB higher amplitude compared to the background noise. Even though this grid indication has lower amplitude compared to the pinhole indication, in case if these two indications overlap, the pinhole indication could be compromised. It should also be noticed that the background noise at -34 dB was the lowest produced by the rod with tungsten fil and the highest estimated noise could be up to 8 dB higher making detection of 0.127 mm diameter pinhole impossible.

The weakness of this method is that detection of anomalies located in on the side of beam propagation direction will be undermined and will require re-clamping the probe at different circumferential position. With current design constrains of fuel bundle, accomplishing this goal would be a challenge.

6. Conclusions

Experiments with detection of 0.005 inch (0.127 mm) diameter pinhole indicated that this sort of anomaly could be detected at some sort of ideal conditions (shorter range, the probe is located at the same circumferential position as the pinhole, assuming the presence of the lowest amplitude of coherent noise produced by the tungsten). All these conditions might never be met in case of real field test environment. However, the outcome of this work could be projected in direction of determining the smallest pinhole size that could be detected using current method. For example, assuming the coherent noise to be -34dB (the most favorable scenario with tungsten powder), detection of 0.04 inch (1 mm) diameter pinhole could be feasible (detection area is marked in Figure 6). In the worst case scenario (with the coherent noise at a level -26dB), detection of 0.12 inch (3 mm) diameter pinhole is feasible. Indications produced by grids at 350 kHz were found to produce indications with rather low amplitude (about 4 dB higher compared to coherent noise in rods with tungsten). This makes the side coupling probes and tested (350 kHz) frequency to be potentially effective method for detection of 0.04 inch (1 mm) diameter and larger pinholes in the areas covered by grids. It should be noted that actual coherent noise produced by fuel pellets is an unknown variable at this point.

References