DEVELOPMENT OF A FUEL ROD GUIDED WAVE INSPECTION SYSTEM

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ABSTRACT
Fuel failures are an expensive and undesirable event for nuclear utilities. The presence of leaking fuel is identified during plant operation; however, identifying the individual leaking fuel rod presents a challenge. Individual leaking fuel assemblies are identified during plant outages using nondestructive examination (NDE) techniques to prevent the re-insertion of failed fuel rods back into the reactor and to aid in root cause failure analyses. Due to false and missed calls experienced by traditional inspection techniques, alternative inspection methods are needed that can reliably identify individual leaking fuel rods in a leaking fuel assembly. A magnetostrictive transducer (MsT) probe was developed to perform guided wave inspections of sample fuel rods containing simulated fretting flaws and simulated circumferential, axial, and 45° cracks. In addition, a mechanical delivery unit was built to facilitate remote operation of the probe in conditions similar to field conditions. The complete system was tested in a dry laboratory environment as well as in a simulated spent fuel pool environment. The effect of nonlinear dependence of signal amplitude on the depth of the anomalies was investigated for data processing. The results showed that 100% through-wall defects can be identified and reliably distinguished from other non-through-wall defects. This paper presents the results of the examinations conducted to date in air and under water on simulated machined flaws located both in free spans and under supporting grids.

INTRODUCTION
Fuel rods in nuclear reactors consist of uranium fuel pellets that are encased in hollow metal tubes made from zirconium alloys. They are grouped together into fuel assemblies of up to 250 or more fuel rods. A reactor core typically contains several hundred fuel assemblies. 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 (BWRs), debris fretting is most common [1]. Other mechanisms include crud and corrosion failures, and pellet cladding interaction (PCI) cracks. The failure of a fuel rod can potentially lead to leaking of radioactive material into the primary coolant system. Because this release of radioactive materials is a safety concern, fuel rod failures can cause unscheduled plant shutdowns, which may cost as much as $40 to $80 million dollars [2].

Failed fuel assemblies may be identified through “sipping” techniques, in which the water surrounding the fuel assembly is sampled to determine the presence of radioactive materials. However, testing methods for identifying individual failed fuel rods are more costly and time-consuming. Visual, eddy current, and ultrasonic techniques have been in use for this purpose, but all are time-consuming and require scanning of the fuel rod. Long-range guided wave inspection is a method for rapidly surveying a long length of pipe or tube for flaws from a single test location without scanning [3]. Now widely used for examining pipelines in processing plants, this method could be used for identifying individual fuel rods with through-wall flaws.

Inspecting fuel rods with guided wave technology requires addressing the following issues:

- Development of a small diameter (less than 5 mm) guided wave probe
- Development of a reliable probe coupling mechanism
- Development of a testing procedure allowing discrimination of rods having through-wall flaws from all the other rods
- Development of a probe positioning system
- Development of a data acquisition system capable of conducting rapid screening of an entire fuel assembly at a rate of 15 min/assembly
- Development of a method for deploying guided wave inspection without the need to disassemble the fuel assembly, or ideally, in place in the reactor

Prior to the investigation presented in this paper, preliminary work on fuel rod samples showed good potential for using a torsional mode guided wave inspection for screening the entire length of the rod [4]. In this paper, the results of the second phase of the project will be described. A new probe was developed, together with a novel method for probe coupling. Also, a multi-frequency inspection approach was applied, along with the advanced signal processing.

PROBE DESIGN

MsT technology was chosen as the basis for the inspection probe [5]. In an MsT probe, an excitation coil is wound around an iron cobalt (FeCo) strip; this produces time-varying magnetic fields in the circumferential direction of the strip, as illustrated in Figure 1. The FeCo strip generates torsional waves that are mechanically coupled through a protective outer coating to the waveguide connected to the fuel rod.

![Figure 1. Configuration of MsT](image1)

There were a few reasons for the selection of the MsT-type probe. One was the ability of the MsT-type coil to introduce relatively high magnetization in the sensor strip, providing magnetostrictive strains up to 5 times that of conventional MsS sensors [6]. Another reason was the ability of the probe to generate high amplitude nonlinear harmonics utilized in signal processing [7]. The predominant effect allowing effective generation of the higher order harmonics is based on a relatively high strength magnetic field forcing the magnetic domains to rotate (in lower magnetic fields only the domain oscillation or movement of domain walls occurs). The domain rotation typically produces two cycles of magnetostrictive strains per cycle of input frequency. Compared to the testing when only one center frequency is utilized at a time (frequency sweep), simultaneous generation of several frequencies allows normalizing amplitude information more accurately since data over a range of frequencies are acquired simultaneously and no variations in coupling or rod temperature occur.

PROBE COUPLING

In order to minimize the size of the probe to meet the geometric constraints of the fuel rod assembly, a self-coupling waveguide was developed, as shown in Figure 2. A small axial force from a mechanical manipulator caused the waveguide to compress on the top surface of the fuel rod cap. This coupling provided for good signal strength and detection capabilities at a wide range of frequencies.

![Figure 2. Schematic of the probe design and coupling concept](image2)
The MsT probe was positioned in the waveguide at a distance from the cut off end allowing constructive interference of waves traveling in the forward and the backward directions at discrete frequencies.

**FUEL ROD SAMPLES & LAB SETUP**

The MsT probe was tested on four empty fuel rods with simulated defects. Each rod contained a different type of defect – axial notch, circumferential notch, 45° notch, and volumetric flaw – in three different depths – 50% though-wall, 75% through-wall, and 100% through-wall. The defect layout is shown in Figures 3 and 4.

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**Figure 3. Sample defect sizes by type**

**Figure 4. Defect layout in the four sample fuel rods**

The system was first validated on a dry laboratory mockup. The sample fuel rods were mounted horizontally in spacer grids, and inspections were performed using a mechanical manipulator and remote camera system. The dry laboratory mockup is shown in Figure 5. The sample rods were moved to various positions in order to assess the effects of the spacer grids on defect detection signals.

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**Figure 5. Dry laboratory test setup the fuel rod assembly in a horizontal orientation**

After successfully completing the dry lab tests, the inspection system was taken to a water tank facility to be evaluated on the four sample fuel rods in conditions similar to field conditions. The rods with artificial defects were mounted vertically underwater in an assembly structure with defect-free empty fuel rods, grids, and control rods, as shown in Figure 6. As in the dry lab tests, the probe’s defect detection capabilities were evaluated with the sample fuel rods in various positions.
DATA COLLECTION & ANALYSIS

In the dry laboratory tests at 20 kHz, it was determined that an MsT probe allowed detection of all through-wall defects regardless of the type or placement of the defect. Grids and near through-wall (75% deep) flaws did not produce any significant indications. Dry laboratory data also showed that 200 kHz was the most effective frequency at which to locate the grids and other (75% and 50% through-wall) defects. Sample data obtained from the rod with axial flaws at 200 kHz (a) and 20 kHz (b) is shown in Figure 7.

![Figure 7. A-scan traces obtained from a sample rod with an axial notch at 200 kHz (a) and 20 kHz (b). The 100% through-wall defect is positively discriminated from grids and other defects.](image)

For the simulated spent fuel pool tests, MsT inspections at 20 kHz and 200 kHz were initially targeted, but the results of the tests were inconclusive. It was found that a 20 kHz inspection was not sufficient to positively identify 100% through-wall defects. This was possibly due to tighter mechanical contact between the fuel rods and the grids, causing the guided wave energy to leak into the grids. In actual fuel bundles after a few years of operation, it is expected that the grids will be not be as tight due to vibration caused by water flow. The option of using 20 kHz frequency as a discriminator for through-wall anomalies may still be viable.

To continue testing of the supplied fuel assemblies, a wider range of frequencies was examined to positively identify 100% through-wall defects. A multi-frequency scan on each rod was performed in the range of 20 – 200 kHz, with an increment of 1 kHz. New target frequencies were identified that allowed the discrimination of through-wall anomalies based on amplitude criteria. These new target frequencies varied depending on the type of defect, as shown in Table 1.
Table 1. The frequency at which different types of through-wall defects are positively discriminated from spacer grids and other defect signals, using a multi-frequency approach.

<table>
<thead>
<tr>
<th>Through-wall Flaw</th>
<th>Optimal Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volumetric</td>
<td>160 kHz</td>
</tr>
<tr>
<td>Axial</td>
<td>60 kHz</td>
</tr>
<tr>
<td>Circumferential</td>
<td>200 kHz</td>
</tr>
<tr>
<td>45° Flaw</td>
<td>200 kHz</td>
</tr>
</tbody>
</table>

This summary was made taking the multiple responses from the grids as a baseline noise floor level. The response from a through-wall anomaly was considered to be discriminated if its amplitude was at least 6 dB higher than the grid response or the response produced by near through-wall flaws. As shown in Table 1, each type of flaw was discriminated at a specific frequency. Also, a unique behavior was noticed with respect to the signal amplitudes as well as the signal's frequency content as a function of the flaw geometry during the frequency sweep. The behavior is believed to be related to a specific transfer function introduced by each type of flaws to a signal response. The understanding of the parameters of the transfer function should allow qualitative, and in some cases, quantitative explanations of the phenomena and how it can be utilized for enhanced flaw characterization.

NONLINEAR DEPENDENCE OF THE SIGNAL AMPLITUDE ON THE AXIAL EXTENT OF THE FLAW

As shown in Figure 3, four types of simulated flaws were examined in this research – a volumetric flaw, axial notch, circumferential notch, and 45° notch. The volumetric flaws and axial notches were of most interest due to their similarities to some of the most common defect mechanisms in fuel rods – grid-to-rod fretting and PCI cracks. Each different flaw type produced a specific backscattering signature.

Volumetric flaws in fuel rods typically have a specific shape resembling the shape of the supporting springs, with pronounced edges. The front and rear edges of the flaw both produce guided wave responses that become superimposed. Figure 8 shows that the flaw response amplitude is strongly dependent on the ratio of the signal wavelength to the flaw length. This effect has been shown on tubing mockups in the past [7]. As long as the axial extent and the depth of the flaw allow the front and rear edge signals to interfere, either destructive or constructive interference may be observed in the response amplitude at discrete frequencies. Significant gain in the amplitude is expected when a near through-wall flaw becomes a 100% through-wall flaw. This effect occurs due to the interruption in propagating the reflection from the rear side of the opening. Total gain in the signal amplitude can be expected on the order of 12 dB (transition from point D to point E in Figure 8). This effect could be diminished if the guided wave reaches the rear edge of the flaw from the sides. This might be the case if the circumferential extent of the flaw is a small fraction of the wavelength.

However, the volumetric flaw simulated in the sample rod for this research had a circumferential extent of approximately 25% of the wavelength.
Axial notches represent a flaw with a near zero cross-section to the incident guided wave. Torsional mode guided waves produce a response from this type of flaw, which includes conversion of the fundamental T (0,1) mode to the SH (0,1) mode traveling around the rod circumference, followed by conversion of the SH (0,1) mode back to the T (0,1) mode [9]. Since the response is formed by a chain of mode conversion events, some discrete frequencies may affect the efficiency of this process. For the given rod dimensions, the highest signal amplitude for the axial through-wall notch was obtained in the range of 55 – 65 kHz, while responses for a near through-wall notch (75% deep) and a grid were more than 16 dB and 9 dB lower, respectively.

Circumferential notches have a very short axial extent, representing a small fraction of the wavelength, and causing the front and the rear side flaw responses to interfere destructively (point A in Figure 8). This is believed to be the reason why even a rather deep notch might produce a rather small response. On the other hand, when the notch is 100% through-wall, approximately 12 dB amplitude gain can be expected (transition from point A to B in Figure 8).

Backscattering from 45° notches was similar to the backscattering from the circumferential notch. In addition, this type of flaw produced pronounced, flexural vibrations that can be used for flaw characterization.

UNDERWATER TEST RESULTS

The goal of this testing was to create a more realistic situation with the probe operation and the probe coupling under water. Since fundamental torsional mode guided waves T (0,1) do not couple with water, no changes in performance were expected as compared to the dry test. As stated above, however, the grid springs used for this testing were much tighter than those used in the dry lab test. Figure 9 shows an A-scan trace obtained from the rod without defects at 200 kHz after distance amplitude correction at a rate of 1.2 dB/m was applied. The amplitude of the grid responses, marked with the red dotted line, was taken as the baseline noise floor level for further tests.

![Figure 9. A-scan trace obtained from the rod without defects at 200 kHz after distance attenuation correction at a rate 1.2 dB/m was applied](image)

Figure 10 shows four A-scan traces obtained from the rods with a volumetric flaw: (a) axial notch, (b) circumferential notch, (c) and 45° notch, using 160, 60, 200, and 200 kHz, accordingly. Each rod was inspected twice: first with grids placed near the through-wall defect (Test 1) and then with grids placed on top of the through-wall defects (Test 2). The data acquired during Test 1 are rectified positive and the data acquired during Test 2 are rectified negative on all four pictures. This was done to evaluate the effect of interference between the indications produced by grids and the indications produced by flaws.

Indications produced by through-wall flaws as well as indications produced by near through-wall flaws are shown with arrows. As shown in the data, all four through-wall anomalies produced indications 6 – 9 dB higher in amplitude compared to the noise floor level determined by the amplitude of the grid indications. It should also be noticed that near through-wall (75% deep) flaws produced responses either lower or only slightly higher (75% circumferential notch on C) in amplitude compared to the noise floor level.
Considering the applied amplitude-frequency criteria, the multi-frequency inspection approach correctly distinguished the 100% through-wall flaws in both locations – in the free span and underneath the grids.

SUMMARY
A prototype MsT guided wave fuel rod inspection system was developed to inspect individual fuel rods in an assembly for 100% through-wall defects. In a dry laboratory environment, a two-frequency inspection was adequate to positively discriminate all 100% through-wall defects, regardless of their type and location. However, conditions in the simulated spent fuel pool tests were different, prompting a multi-frequency approach to identifying the same defects.

This project is ongoing, and further evaluation of the system on more realistic full assembly mockups is planned. Also, further research and development is recommended to understand the detailed interaction mechanisms of guided waves with flaws of different types and sizes in order to improve flaw characterization.

REFERENCES
2. Frequently asked questions; Fuel Reliability Guidelines, Electric Power Research Institute, 2008.
4. H. Kwun, E.V. Mader, K.J. Krzywosz, Guided wave inspection of nuclear fuel rods. NDT.net, 2010