Structural Integrity Assessment of Nuclear Spent Fuel Canisters Using Guided Waves

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ABSTRACT

Dry storage canisters (DSC) are primarily used for storing nuclear spent fuel rods for an extended period. Due to the critical role of these assemblies, periodic inspections are necessary for mitigating potential accidents and subsequent release of radioactive material to the environment. Aside from visual inspections, the most effective approach to evaluate their structural integrity is by non-destructive techniques. In this work, we utilize helical guided ultrasonic waves (HGUW) to develop a non-destructive scheme for the structural health monitoring of DSC. These waves share identical characteristics with traditional Lamb waves but travel circumferentially in cylindrical waveguides. The proposed methodology is comprised of instrumenting the canister with a permanently attached network of piezoelectric patches (PZT) capable of transmitting and receiving high frequency HGUW. Using the data collected from the HGUW inspection, a probabilistic imaging technique is employed to localize defects within the span of the PZT arrays. Furthermore, an investigation of the scattering of the fundamental Lamb modes from different cracks and notches is investigated and the patterns are exploited for improving the fidelity and accuracy of the imaging method. Experiments have been conducted on various specimens including a 6-in-diameter cylinder in the lab and an actual DSC with a diameter of approximately 6 feet.

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INTRODUCTION

A common practice for disposing nuclear spent fuel (NSF) is by utilizing the dry-storage canister (DSC) systems. After the cooling process of the NSF, the rods containing the fuel are placed in a large metallic canister with two end caps being welded to minimize leakage. The canisters are usually custom-made out of four stainless-steel plates, bended and welded to desired dimensions. The large canister is then placed in a concrete overpack in either horizontal or vertical configuration at appropriate sites for long-term storage. During the service life of the canister, different factors contribute to accelerating stress-corrosion cracking (SCC) namely the exposure to saline environments as well as non-relieved stresses during construction. The initiation and growth of SCC is extremely important to be identified considering the dire consequences of an accident.

Various non-destructive techniques have been utilized to assess the condition of the surface of DSC, like ultrasonic testing (UT) and Eddy current (EC) [1]. Although the reported findings are reliable and accurate, a point-by-point measurement is required which significantly increases the inspection time. Alternatively, efforts have been made to identify and quantify different forms of cracking in DSCs using guided wave-based techniques. Guided waves propagating though the canister's thickness is an excellent candidate for interrogating the DSC due to their low attenuation when propagating in metals and ability to travel longer distances with minimum loses. Applications of different types of guided waves have been reported including the use of shear-horizontal (SH) type waves for screening DSC for circumferential and longitudinal cracks [2]. Other studies have investigated the use of Lamb-type guided waves to identify and monitor the growth of SCC [3].

A newer class of guided ultrasonic waves has immerged in the past years that is well suited for the interrogation of structural integrity of cylindrical structures[4]. The so-called helical guided waves (HGW) can be used in cylinders and their propagation path follows a helix around the waveguide. This allows for multiple Lamb modes, like the A0 and S0 to propagate and thus effectively reducing the requirement for sensing units[5]. In this work we leveraged the HGW in order to inspect the surface condition of a stainless-steel DSC. This was achieved by instrumenting the canister with a total of 24 piezoelectric patches, each acting as an actuator and a receiver. Surface damage was simulated using rear-earth magnets and the localization was attempted utilizing two well-established techniques, the algebraic and the probabilistic reconstruction methods.

This paper has the following outline: Section 2 presents the experiment while section 3 briefly introduces the imaging techniques used in the study. Section 4 presents the results while concluding remarks are presented in section 5.

EXPERIMENT

The experiment took place at the training facilities of Orano Tn in Aiken, South Carolina on a horizontal storage module mockup canister. An overview of the canister and the experimental configuration is depicted in Figure *1*. The specimen was made from 10mm (1/2") thick stainless steel with a dimeter of 1.7m (67.25"), and a total length of 5m (196"). The canister was uncovered and empty on the inside. The construction of these canisters is achieved by bending and welding four individual steel

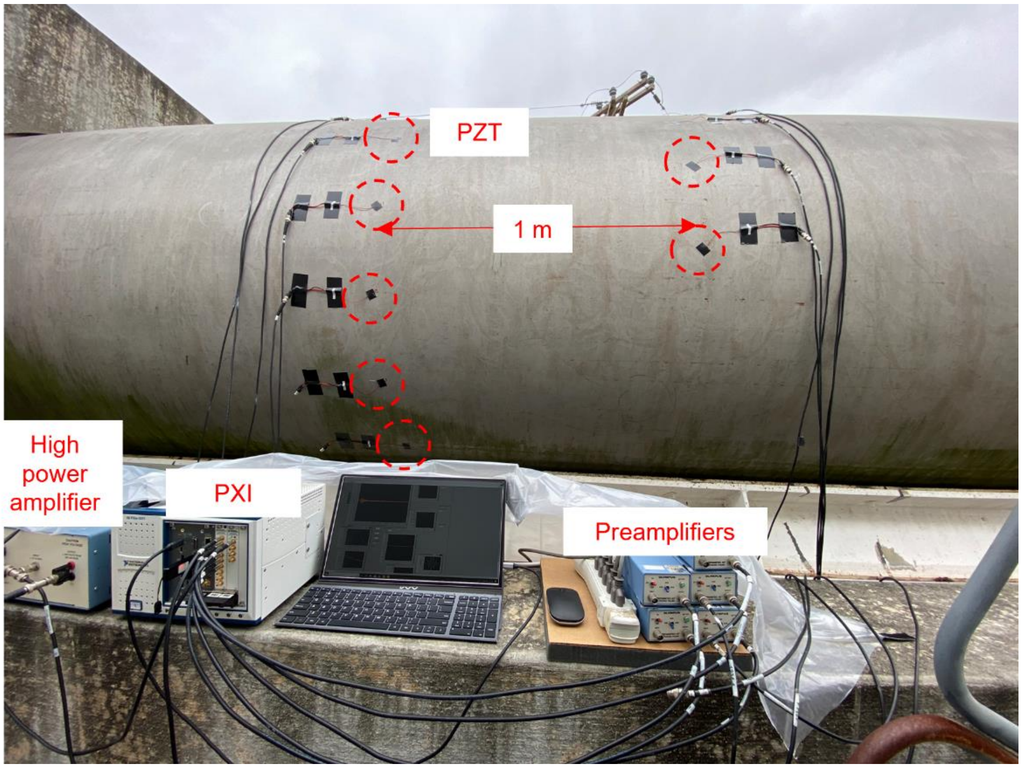

Figure 1. Experimental setup

plates thus two seems could be identified, a longitudinal at the top and a circumferential at mid-length. The canister was instrumented with a total of 24 piezoelectric (PZT) patches (diameter = 12mm, thickness = 0.6mm) in a two-array configuration one meter apart. The spacing between the sensors was approximately 20 degrees while the relative angle between the two arrays was 50 degrees. The specific layout was chosen for maximizing the effective aperture of the helical wave inspection (add more). The PZT's were attached to the surface of the canister using Loctite instant glue. Waveforms were generated using a 20 MHz Bandwidth, 1-Channel, 14-Bit PXI waveform generator and amplified using a high-power amplifier. The signal recorded by each PZT was first amplified using an OLYMPUS 5560B preamplifier with a gain of 40 dB and digitized using a 60 MHz, 12-Bit PXI oscilloscope. Each signal was 80000 points long sampled at 20MHz and averaged 250 times to increase the signal-to-noise ratio. Three rear-earth magnets were attached in the middle of the two arrays of sensors to simulate the defect. Even though stainless-steel is non-magnetic, it was possible to attach the magnets along the circumferential welding.

METHODOLOGY

Two established imaging algorithms have been utilized for inverting experimentally recorded data. The first, is an algebraic reconstruction technique (ART), that is described by the following expression:

$$A_{(m\times n)}x_{(x\times 1)} = d_{(m\times 1)} \tag{1}$$

This method requires the evaluation of the weight matrix A at each pixel x of the assumed 2D surface of the canister and the damage coefficient vector d for all helical paths m considered in the problem. The damage coefficient is estimated using the baseline subtraction of the signals collected from defected and pristine states of the canister. Solution to (1) is achieved using Kaczmarz's method. Detailed implementation of the ART for cylinder can be found in [6].

The second algorithm is the probabilistic reconstruction technique formulated according to:

$$\mathrm{P}(x,y) = \eta \sum_{k=1}^{N} \sum_{h=1}^{N_h} A_{kh}^{m} \frac{\gamma_h - R_{kh}(x,y)}{\gamma_h - 1} \tag{2}$$

This technique assumes an elliptical distribution R_{kh} of the probability that a defect lies between a transmitter and a receiver, with the maximum being the direct path connecting the two. This distribution is weighted with a damage index A_{kh}^{m}, that is estimated using the baseline subtraction of the signals collected from defected and pristine states of the canister. Variables η and γ_h are constants. The superposition of all combinations of transmitter-receiver and helical paths produces the final probability distribution. Details on the implementation of this algorithm can be found [7].

RESULTS

Figure 2 demonstrates the scenario when sensor 16 acts as an actuator and sensors 1-12 as the receivers. Given the chosen time duration of the signal, four orders of helical paths can propagate as highlighted in Figure 2(b). These time-domain plots demonstrate also that the anti-symmetric mode A0 is dominant over the symmetric mode S0 and thus was chosen for the damage index calculations using the baseline subtraction.

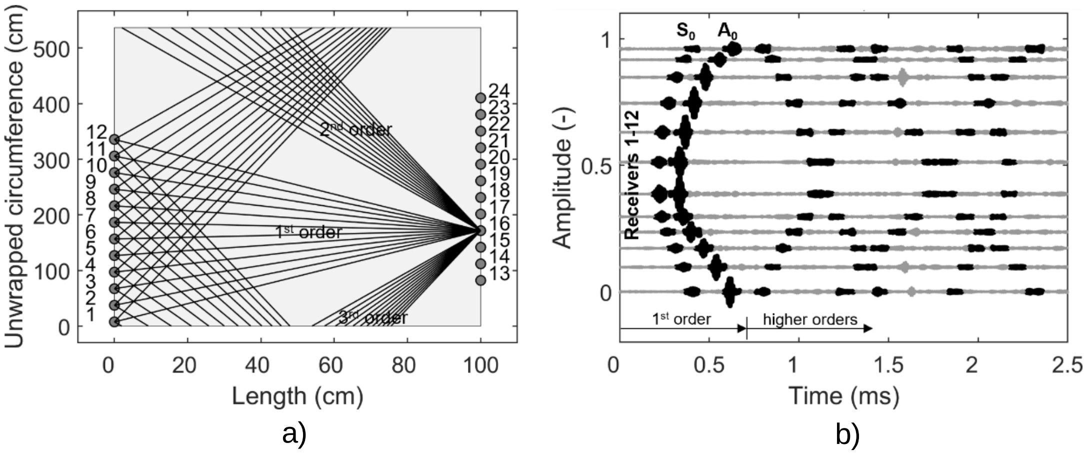

Figure 2. Three orders of helical paths propagating from sensor 16 to receivers 1-12 and the corresponding time domain signals depicting the multiple arrivals of S0 and A0 modes.

The localizations from the ART and PRA algorithms are presented in Figure 3. For both the reconstructions the anti-symmetric A0 mode was utilized and a total of 4 helical orders between the 2 arrays of sensors. Both methods depict damage in the close vicinity of the magnet location which is great for assessing their accuracy. In terms of noise, the PRA seems to produce slightly higher artifacts in comparison to ART due to the elliptical distribution of the probability between transmitter and receiver.

CONCLUSIONS

In this work, we presented one of the first applications of the helical-guided ultrasonic wave method for evaluating the structural integrity of a spent-fuel dry-storage canister. Experiments on an actual DSC have revealed that it is feasible to use a small number of piezoelectric patches and different imaging algorithms to localize defects on the canister's surface. Ongoing work is investigating the potential for the HGW to measure the surface temperature of the canister as well as pressure variations in the canister's inside.

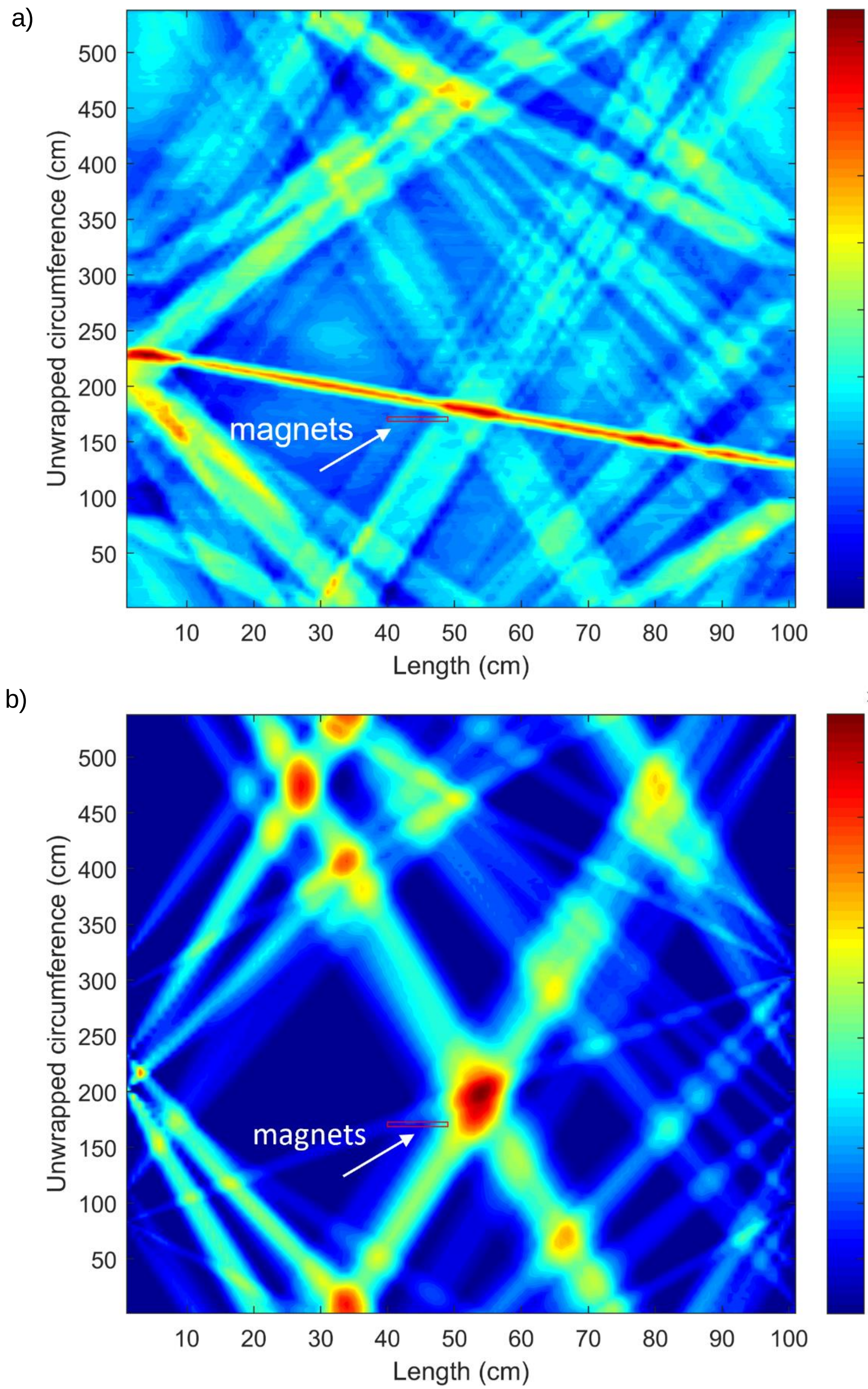

Figure 3. The outputs of the a) algebraic reconstruction technique (ART) and b) probabilistic reconstruction algorithm (PRA).

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