Hybrid simulation model of ultrasonic inspection of pressure tubes in nuclear industry

Huan Zhao, Jeff Dobson, Anthony Gachagan, Timothy Lardner and Gordon Dobie
Centre for Ultrasonic Engineering, University of Strathclyde
Glasgow, G1 1XW, United Kingdom
0141 444 7400
0141 548 2950
huan.zhao@strath.ac.uk

Abstract

Pressure tube inspection within CANDU nuclear reactors is a critical maintenance operation to identify and track the growth of defects within the tube. Current inspection approaches utilising ultrasonic techniques are technically challenging, which cause the whole inspection process to be resource intensive and expensive to implement. This paper will describe the initial stages in the development of a simulation approach for the ultrasonic inspection methodology to research advanced solutions with the objective of improving the inspection accuracy. Zirconium tubes with a thickness of 4.3mm and a required measurement accuracy of defect depth of 0.1mm require the use of high frequency ultrasonic transducers. The finite element modelling of high frequencies is challenging due to the increased mesh requirements to resolve the small wavelengths and the large propagation distance which can cause numerical dispersion. Hence, a 2D finite element hybrid model is developed in PZFlex software to overcome this difficulty with five subsequent components containing both finite element models and analytical solutions: ultrasound transmission; transmission extrapolation (wave propagation); target interaction; echo wave extrapolation and ultrasonic reception. To test the capability of defect inspection using the hybrid model, a slot with a depth of 1mm is introduced in the model. The depth information was calculated from the time-of-flight between the reflections of the tube surface and the slot. The predicted modelled depth estimates produces errors of less than 20micron for both 10MHz and 20MHz probe configurations validating the hybrid modelling approach. Moreover, experimental validation of the hybrid modelling approach is demonstrated.

1. Introduction

Pressure tubes are critical components of the fuel channel within CANDU (CANada Deuterium Uranium) nuclear reactors. Periodic inspections of the pressure tube are required to identify and track the growth of defects within the tube. Ultrasonic techniques are used for the inspection of the pressure tubes, which utilizes high frequency transducers (10MHz and 20MHz). The process of the replacement of the pressure tubes with unqualified material performance is time consuming, expensive and harmful to personnel due to radiation exposure [1]. Importantly, if accurate diagnosis regarding defect prognosis could be determined, then fewer unnecessary replacements would be performed. Therefore, the improvement of accuracy of the ultrasonic inspection is critical. Simulation methods offer a time and cost saving approach to determine solutions to improve inspection accuracy.

Finite element (FE) methods have played an important role for the analysis of ultrasonic Non-Destructive Testing (NDT) [2, 3]. Some FE analysis tools provide efficient solution of ultrasound relevant problems such as PZFlex (Thornton Tomasetti, Cupertino, CA) and Comsol (Comsol Inc., Burlington, MA). However, high frequency models become computationally demanding due to the increase in mesh density to resolve the small wavelengths. Especially when the models have a large number of elements, the numerical dispersion phenomenon [4] becomes apparent, which seriously degrades the reliability of the simulation. To overcome this difficulty, a hybrid model approach is a popular solution utilized in the analysis of ultrasonic NDT [5-10].

Hybrid models of ultrasonic wave analysis have been developed by many scholars.

Zhang et at. presented a hybrid model to predict array data for the Total Focusing Method (TFM) application [5]. They utilized the scattering coefficient matrices to model the interactions between the wave and the defect and combined it with a ray-based model of wave propagation, which allowed the simulation of longitudinal waves, shear waves and wave mode conversions. Rajagopal et al. investigated a generic hybrid model to analyse the ultrasonic wave propagation used in the bulk elastodynamics [6] by introducing an interface between two FE model-domains through the application of a generic wave propagator. The feasibility of this method was demonstrated in the application of the ultrasonic wave propagation and scattering problem. A hybrid 2-D FE and analytical approach has been used in the modelling of pipe inspection [7]. This proposed method provided an effective solution by using a 2-D FE simulation in the cross-sectional area and an analytical wave analysis in the axial direction, which is computationally-efficient for the inspection of fluid-filled pipes. Lee et al. employed a hybrid model combining both FE and Wave Based (WB) methods for the analysis of poroelastic materials [8]. The FE-WB modelling technique consisted of three parts comprising FE model, WB model and a direct coupling between them. This technique took advantage of the benefits of the WB approach and FE model respectively, which improved the convergence rates for the model of the analysis of poroelastic materials. A Combined Analytical Finite element model Approach (CAFA) has been proposed to simulate the Lamb wave damage detection by Shen and Giurguitui [9]. This approach utilized frequency and direction dependent complex-valued coefficients to model the Lamb wave damage interaction, which achieved good performance in accuracy and efficiency comparing to full-scale FE simulation and experiments. Dobie et al. applied a combined Linear Systems Model [11] and Local Interaction Simulation Approach (LISA) propagation model to simulate an air-coupled ultrasonic scanning platform [10]. This approach provided a solution for the high computational time associated with simulation work for complex geometries.

However, these methods are not specified for the efficiency of the simulation of the ultrasonic immersed inspection of pressure tubes with large diameter. The challenge of the work is to overcome the influence of the serious numerical dispersion phenomenon resulting from combination of the high frequency transducer and long distance propagation (relative to the short wavelength) in the FE model.

In this study, a 2-D hybrid model was developed by combining a FE package and a simplified but accurate analytical extrapolation approach to provide a solution to overcome the inherent restrictions in employing a full-scale FE model. The 2D hybrid model contains five subsequent components: ultrasound transmission; transmission extrapolation (wave propagation); target interaction; echo wave extrapolation and ultrasonic reception. The ultrasound transmission, target interaction and ultrasonic reception parts are simulated using FE method benefited by its accurate analysis of the wave interaction, while the analytical extrapolation analysis method is employed in the wave propagation for computational efficiency. The FE method is implemented by using the commercial software package, PZFlex. This paper is organized as follows. The definition of the hybrid model including the geometry and the method of the extrapolation is described in Section 2. The verification of the ability of the hybrid model to measure defect depth is introduced in Section 3. Section 4 demonstrates an experiment to validate the hybrid model.

2. Hybrid model for pressure tube inspection

2.1 Problem definition

The simulation of the ultrasonic inspection of the pressure tubes is essential for the analysis of the way to improve the accuracy of the inspection. The pressure tube is a zirconium alloy which has an inside diameter of 104mm and a thickness of 4.3mm [12]. Currently, a tool named CIGAR (Channel Inspection and Gauging Apparatus for Reactors) which contains five focussed ultrasonic transducers with frequencies of 10MHz and 20MHz are immersed in heavy water during the inspection and the water path is around 20mm. A wave propagation distance of 20mm in water contains 133 and 266 wavelengths for 10MHz and 20MHz transducers respectively. A simulation platform of the existing testing method forms the basis of the research to improve the accuracy of the inspection. PZFlex is used for the simulation. This software package has been applied in the NDT with its explicit time-domain approach which brings about rapid simulation time [13]. However, the serious numerical dispersion phenomenon in the large size model impacts on the accuracy of this approach. To decrease the influence of the numerical dispersion, the FE model will be combined with the extrapolation of wave propagation in the fluid.

In order to simplify the process of the development of the hybrid model and make the validation simpler to be realized at the initial development stage, water and titanium, which has the same crystal structure as zirconium, are used in the simulation as well as experiment.

2.2 Hybrid model simulation

The complete model is decomposed into five parts as shown in Figure 1: H1 (Ultrasound transmission), H2 (Transmission extrapolation), H3 (Target interaction), H4 (Reception extrapolation) and H5 (Ultrasonic reception). It simulates a focal transducer immersed in the water to test a titanium tube. Only the longitudinal section of the tube inspection is analysed in this paper.

Original model Decomposed model

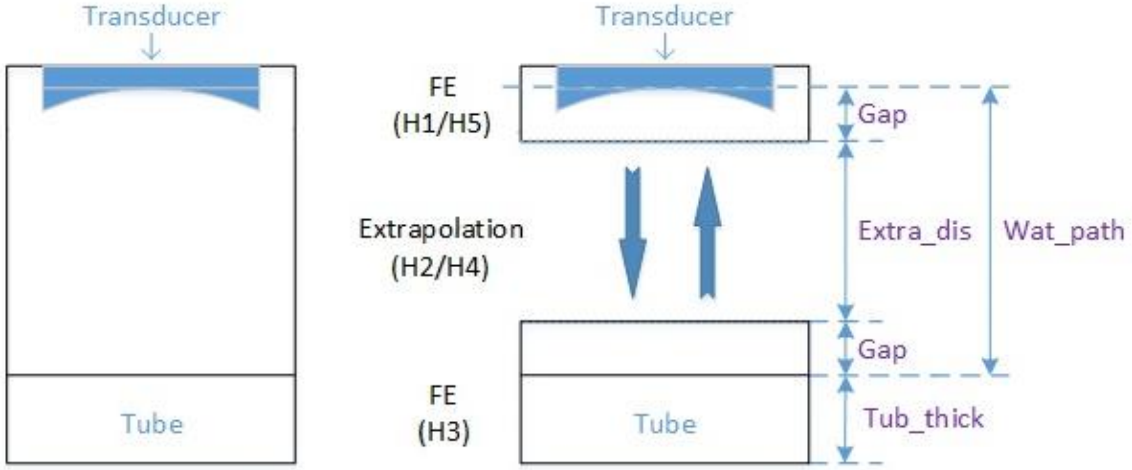


Figure 1 Hybrid model decomposition

2.2.1 Finite element modelling

The simulation of ultrasound transmission, target interaction and ultrasonic reception are executed in PZFlex.

Ultrasonic transmission is shown in Figure 1 as H1 and is defined as a FE process. The diameter of the transducer is 9.5mm, with the transducer represented using two solid blocks of transducer material plus the geometry of a lens with a focal length of 33mm attached to the front face. The model excitation will be a mechanical pressure wave applied at the interface between these two solid blocks, with reflection at the outer surface (top) block minimised by application of an absorbing boundary condition. After excitation, the FE model records the received signals across the full aperture width at a specified distance from the transducer, this distance is defined as *Gap* in Figure 1, and these signals are then stored for use by the extrapolation phase, H2, of the model.

Ultrasonic reception is effectively reciprocity with respect to the transmission process, with H4 the extrapolation phase and H5 defined as the FE receiver model.

The final FE model represents the target interaction, H3, for the inspection of the pressure tube. The transmitted waves after the process of extrapolation (H2) are loaded as the input to this FE model, with a small water channel included prior to the tube wall itself – this is defined in Figure 1 with a thickness of *Gap*. The FE model will simulate the ultrasonic interaction with the component, including defects if included, and the returning echoes will be recorded at the same interface for use by the receive extrapolation model, H4. The tube thickness has been defined as *Tub_thick*.

To avoid corner and boundary effects caused by loading of waves on the boundary, an additional water layer is augmented onto each of the sub-models H1 (bottom), H3 (top) and H5 (bottom).

2.2.2 Extrapolation method

The parts of transmission (H2) and reception (H4) wave propagation employ the extrapolation method which combines the Green's functions and Huygen's principle to deal with the high frequency wave propagation in the homogeneous material.

2.3 Simulation Example

The use of the analytical extrapolation of the wave propagation in the water reduces the FE model available for the simulation. This is a computationally efficient approach and can improve the accuracy of the simulation by decreasing the influence of the numerical dispersion phenomenon of the FE method. These analytical modules are combined with the previously described FE models to make the simulation work available. Importantly, there is an extrapolation function in PZFlex which can realize the transmission extrapolation and reception extrapolation. Figure 2 displays the excitation signal and the result of the transmission extrapolation. The excitation signal is transmitted from a 10MHz focal transducer with a diameter of 9.5mm and a focal length of 33mm. The high amplitude pressure in transmission extrapolation shows the received signal at 30mm in front of the transducer. The -6dB longitudinal size of the signal is 0.66mm, which provides a reference for the setting of the defect size in the model to test the capability of the defect depth measurement.

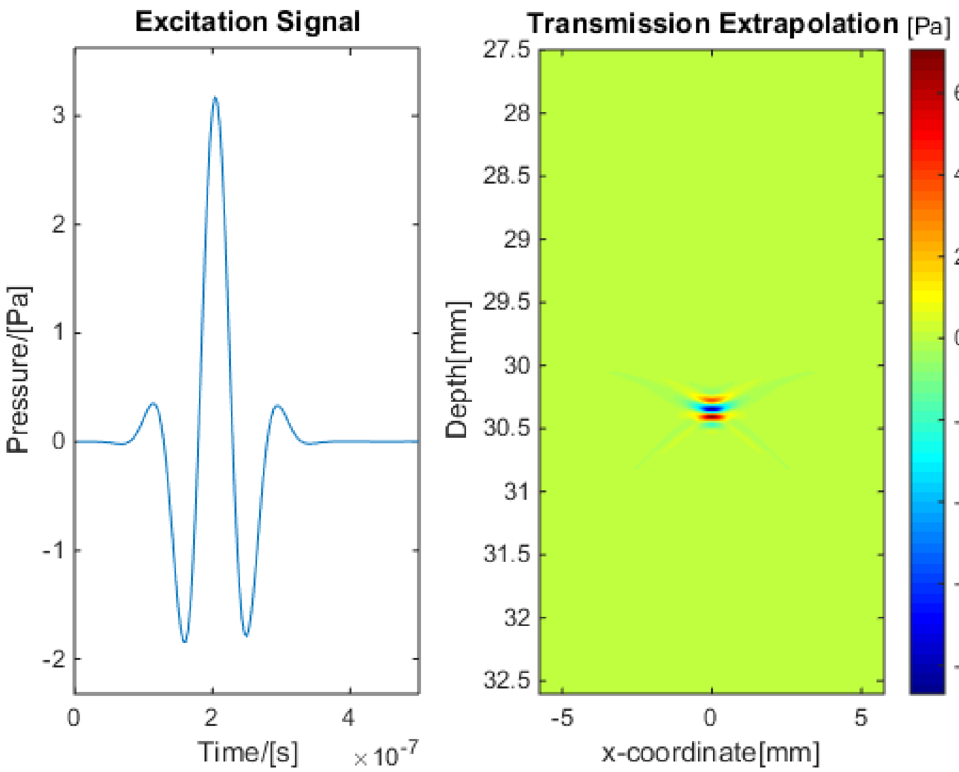


Figure 2 Demonstration of the excitation signal and the result of transmission extrapolation. The high amplitude pressure shows the received signal at 30mm in front of the transducer (frequency: 10MHz, diameter: 9.5mm, focal length: 33mm)

3. Capability to measure defect depth

In order to test the capability of defect inspection of the hybrid model, a slot is set in the target part of the hybrid model. The slot is situated at the centre of the tube surface with both depth and width of 1mm (Figure 3 (a)). The received signals of the hybrid model without slot and with slot are shown in Figure 3 (b). The blue solid line in the Figure indicates the received signal from a model without defect on the tube surface. The red dashed line in the Figure indicates the received signal from a model with a defect.

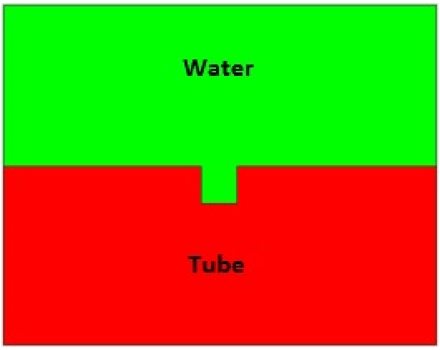
Two signal peaks with data cursors in Figure 3 (b) demonstrate the reflected signals from the tube surface and the slot respectively in a 10MHz probe model. The depth information is calculated from the time difference between the reflections of the tube surface and of the slot. Table 1 presents the depth information obtained from 10MHz and 20MHz probes as well as the measurement errors. The wave speed for heavy water used in the model is 1417m/s. According to the calculated results, the defect depths are 1.0132mm and 1.0061mm in the hybrid model for 10MHz and 20MHz probes which have measurement errors of +13.2µm and +6.1µm respectively.

In terms of the results, it can be found that the error of the inspection simulated in the hybrid model is less than 1.5% for 10MHz and 20MHz probe configurations. Therefore, this hybrid model is reliable for simulating defect inspection of a pressure tube.

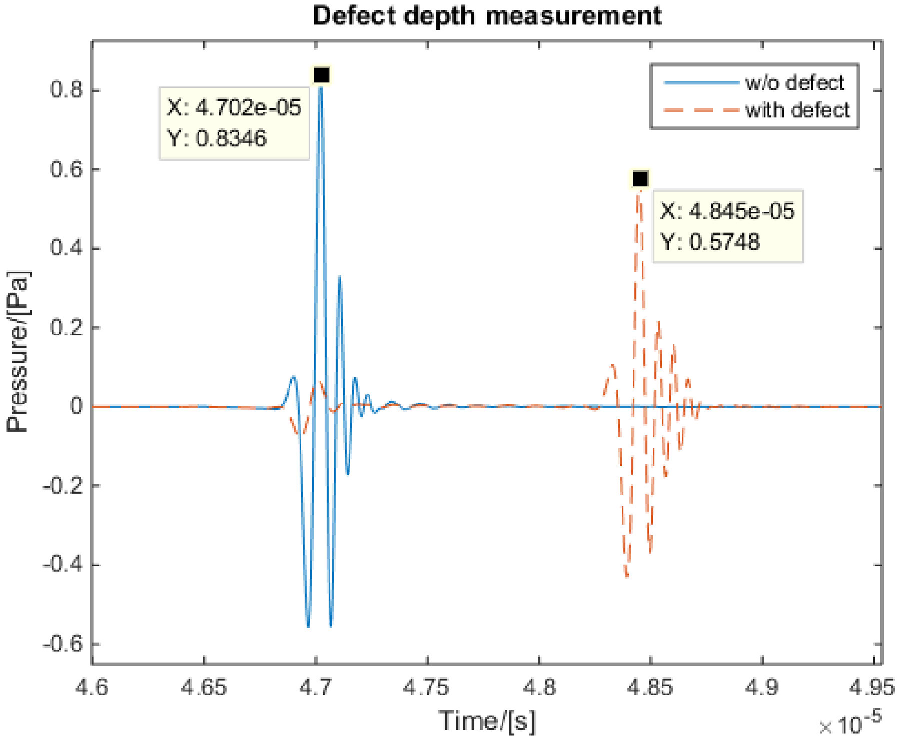
4. Experimental result

The transducer illustrated in Figure 1 is not fully represented in the model as this is a commercial device and full details of the construction and materials are unknown. In order to maintain suitable accuracy in the model, the transducer response is experimentally measured and used as the input excitation function. Hence, a membrane hydrophone was positioned at the focal length, 33mm, of the 10MHz transducer and the measured waveform in a water load is presented in Figure 4, in both the time (note: DC offset has been removed) and frequency domain representations.

To validate the hybrid modelling approach, a simple pulse-echo experiment has been setup. Here, the 10MHz transducer is immersed in the water and the first echo recorded from a flat titanium plate with a thickness of 5mm. The reflected signal from the surface of the titanium plate in the experiment is recorded and compared to that of the hybrid model, where the input excitation to the model is the measured transducer response presented in Figure 4. Comparisons of the signals are demonstrated in Figure 5 with normalized amplitudes, which show the time-domain signals and their frequency spectra, respectively. Good correlation is demonstrated in the time-domain result, albeit the initial half cycle is not aligned and the simulation demonstrates a slightly longer ringdown. These issues are clearly evident from the frequency spectra comparison, in which both spectra have similar profiles but the predicted result seems to have undergone additional attenuation/damping. Nevertheless, the accuracy of the temporal characteristic is considered sufficient for the intended purpose of evaluation of the CANDU transduction system.



(a)



(b)

Figure 3 (a) Target part of the hybrid model with a slot; (b) Comparison of 10MHz model w/o and with defects

Table 1 Depth information obtained from hybrid model

Probe Frequency	Peak Time		Depth	Error
	W/o defect	With defect		
10MHz	47.02μs	48.45μs	1.0132mm	+13.2μm
20MHz	46.90μs	48.32μs	1.0061mm	+6.1μm

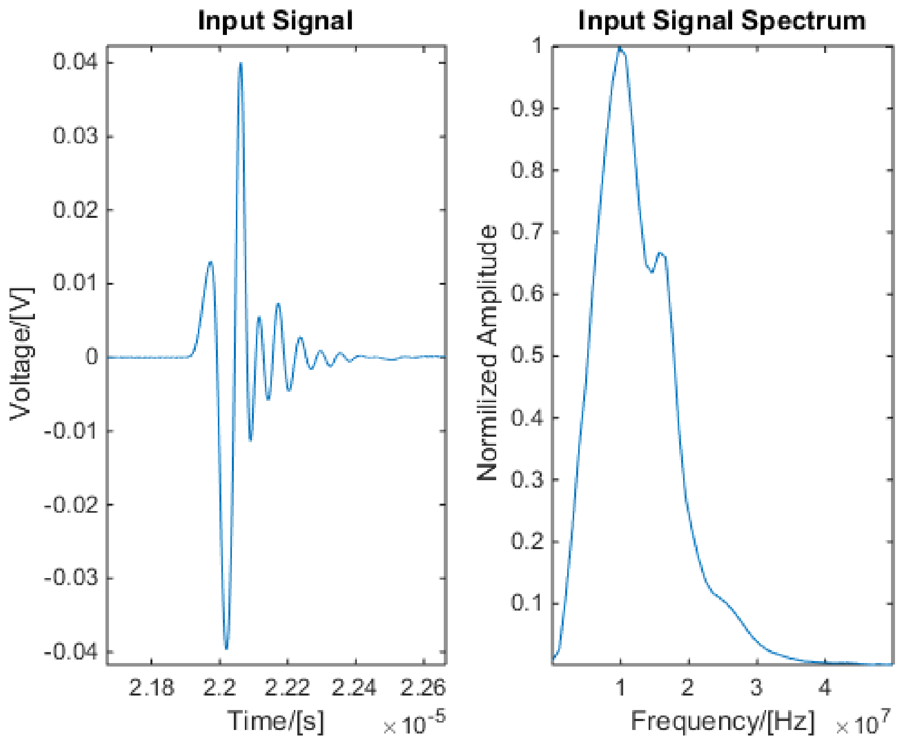


Figure 4 The input signal of the hybrid model recorded by a hydrophone situated at the focal point of the transducer

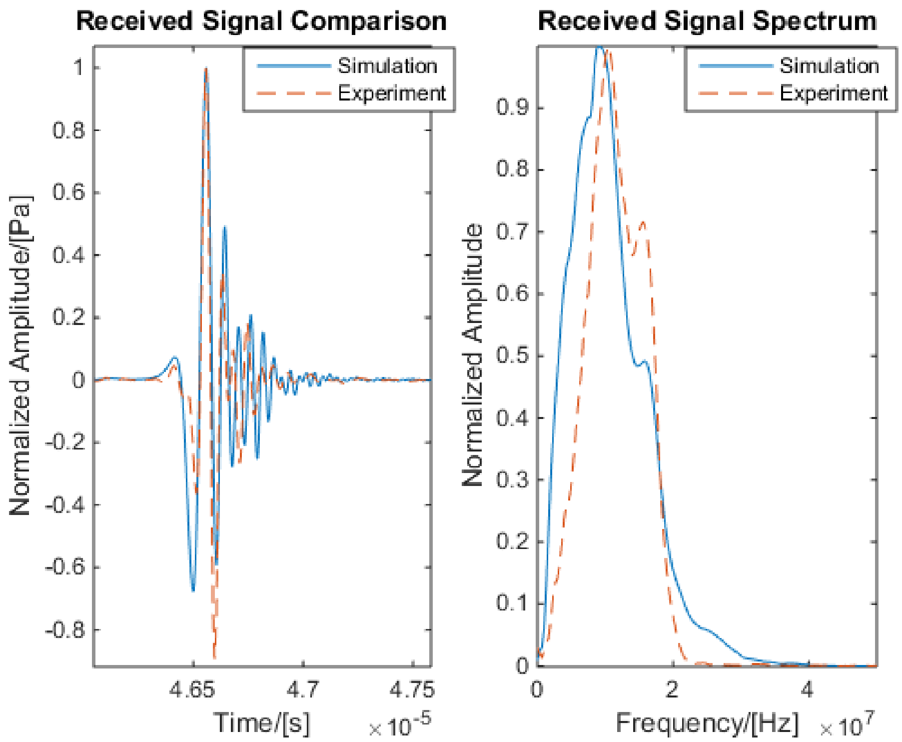


Figure 5 Comparison of the signals from the simulation and the experiment in time-domain and the spectrums

5. Conclusion

In this paper, a hybrid model incorporating a PZFlex finite element model has been presented. The FE approach has utilised an extrapolation method of wave propagation in water. The capability of the defect depth measurement of the hybrid model has been demonstrated and the errors are shown to be minimal for the 10MHz and 20MHz transducer samples used in this work. Importantly, the simulation result correlates well with experiment. This hybrid model approach is now able to be used as the platform to investigate advances in transducer technology and/or signal processing techniques utilised in the inspection of CANDU fuel channels.

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