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Simulation of Ultrasonic Testing for Resolution of Corrosion Detection in Pipes

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Abstract—Ultrasonic testing is a conventional non-destructive test technique widely used in the industry. In this paper, we study ultrasonic testing for detection of internal corrosion of the thin-walled pipes. When the reflective surface is too close to the probe, ultrasonic excitation over a large area leads to interference in the reflection wave. This puts a limitation on the probe size, given the expected accuracy of the measurement. This paper investigates the relation between the accuracy and the probe size, using Finite Element Method (FEM) for simulation of ultrasound wave propagation.

Keywords—ultrasonic testing, Finite Element Method, corrosion detection, probe size, wave propagation simulation

I. INTRODUCTION

Supercritical water oxidation is an environmental friendly technology that uses water at supercritical condition (with temperature > 374 °C and pressure > 22.1 MPa) as the reaction medium, to process organic compounds and toxic wastes and decompose them into CO_2 , H_2O , N_2 and other harmless small molecules. However, concentration of dissolved oxygen at high temperature and high pressure makes corrosion a serious hazard for reliability and sustainability of the carrier pipes [1,2]. Therefore, early detection of internal corrosion of the pipes is crucial, yet challenging for engineers.

Several techniques have been utilized for fault detection and monitoring the condition of pipes, including magnetic particle, penetrant testing, eddy current, ultrasonic testing, X-ray and etc.. Ultrasonic testing is one of the conventional non-destructive testing techniques that use multiple propagation characteristics of ultrasound, such as reflection and refraction, diffraction and scattering, attenuation, resonance and change of sound velocity to detect the location and geometry of the surface and internal defects as well as microstructural changes. The ultrasonic Pulse-echo method [3] is widely used in ultrasonic testing. In this method, travel time of ultrasonic wave is measured and the changes in acoustic impedance are located. Defects such as corrosion cause discontinuity within the homogeneous material and thus lead to the inconsistencies of acoustic impedance. Reflection of ultrasonic wave at the interface of two mediums depends on the direction and size of the interface.

Finite element method (FEM) is a commonly used approach for numerical modeling of wave propagation in ultrasonic testing. Moser et al [4] modeled elastic wave propagation to determine structural integrity of engineering components with simple geometry such as plate and ring. Chen et al performed FEM modeling for fault detection in thick components, i.e. over 15 mm [5]. For pipeline inspection, Wang et al [6] investigated the effects of a defect's axial extent on the echo signal. Bikash et al [7] studied and optimized the FEM parameters for ultrasonic wave propagation in isotropic solid media using COMSOL Multiphysics®. The same research group also investigated the ultrasonic wave propagation in a multilayered composite structure [8]. Azar et al [9] modeled phased arrays technology, and Baskaran et al [10] and Honarvar et al [11] used FEM method to simulate the time-of-flight diffraction technique (TOFD). Despite the research in this area, one of the challenges in corrosion detection is detectability of incipient flaws with tiny dimensions, which is the case for the pipes with thin wall thickness. In this paper, we study the accuracy of ultrasonic testing using a range of probe sizes for detection of the defect at initial stages of corrosion.

II. METHODOLOGY

To simulate wave propagation and reflection across the pipe wall, a two-dimensional FEM model has been developed in COMSOL Multiphysics®, and the pressure acoustic analysis module was utilized for simulation.

A. Material

Nickel base alloys, e.g. Inconel 600 and Inconel 625 are commonly used materials in supercritical water oxidation that contain nickel, chromium and iron. The test object in this study is an Inconel 600 pipe with the following acoustic properties.

TABLE I. MECHANICAL PROPERTIES OF THE TEST MATERIAL

Density (ρ):	8440 (kg / m^3)
Young's Modulus (E):	185 (GPa)
Poisson's Ratio (ν):	0.312

B. Incident ultrasonic signal

For ultrasonic impulse generated by piezoelectric transducers, the transient excitation signal with cycles of cosine function as defined in Eq. 1 is commonly used for ultrasonic simulation [12].

$$Y(t) = \begin{cases} \cos(2\pi ft)[1 - \cos(\frac{2\pi f}{N}t)], & 0 \leq t \leq \frac{N}{f} \\ 0 & t \geq \frac{N}{f} \end{cases} \quad (1)$$

where f is the central frequency of the transducer and N is the number of cosine cycles. For the simulation in this research, an excitation impulse with 3 cycles and centre frequency of 10 MHz is applied on the outer surface of the pipe as illustrated in Fig. 1. The excitation impulse used in the simulation is shown in Fig. 2.

Figure 1. Testing set up for ultrasonic simulation

Figure 2. Equivalent impulse force, simulated for ultrasonic probe with 10MHz and 3 cycles

With regard to the wall thickness of the pipe in the study, the frequency is selected 10 MHz to have a suitable wavelength such that there is a distinguishable gap between the impulse and the echo signal. Propagation velocity of longitudinal wave in the assumed material is [13]:

$$v_L = \sqrt{\frac{E}{\rho}} = \sqrt{\frac{185 \times 10^9}{8440}} = 4682 \text{ m/s} \quad (2)$$

As a result, longitudinal wavelength λ_L is 0.4682 mm.

C. Model geometry and setup

The specimen in the study has 305 mm length, and the outer and inner diameters of 25.4 mm and 22.1 mm respectively. The wall thickness of the pipe is therefore 1.65 mm. Corrosion defect is modeled as a circular dent and its radius is taken as the variable of the defect magnitude. Depth of corrosion is assumed 0.5 mm for all defective cases.

The discrete wave motion equation for an element in FEM analysis is [13]:

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = P \quad (3)$$

where M is the structural mass matrix, C is the structural damping matrix, K is the structural stiffness matrix and P is the vector of applied force. $u(t)$, $\dot{u}(t)$, $\ddot{u}(t)$ are the displacement vector and its first and second time derivatives respectively. Damping effect of the material is considered negligible in this study.

In the COMSOL Multiphysics® model, the entire geometry is meshed into free triangular elements and then solved by the time dependent solver within the specific time period. In order to ensure the accuracy of the FEM solution and to get high temporal and spatial resolution, it is crucial to choose an adequate integration time step Δt for calculation. Components with high frequency vibration cannot be modeled accurately if the integration time step Δt is not sufficiently short. Generally, the accuracy of the FEM model increases as the integration time steps becomes smaller, whereas too small integration time step leads to a waste of calculation resources. Thus, it is essential to find a balance between the accuracy and calculation time when choosing an integration time step for the model. Reference [14] has provided the following equation as a rule of thumb for an adequate integration time step:

$$\Delta t = \frac{1}{20 f_{\max}} \quad (4)$$

where $f_{\max}$ is the highest frequency of the ultrasonic probe. In this simulation with $f_{\max} = 10 \text{ MHz}$, we will have $\Delta t = 0.005 \mu\text{s}$.

The model is constructed in two-dimensional solid structure. The free triangular elements available in COMSOL Multiphysics® are used for meshing. Beside the integration time step, size of the elements is another important factor for the FEM model. The minimum requirement to simulate a wave type is 8 nodes for the shortest wavelength [5]. More nodes are required for higher accuracy and 20 nodes are recommended when taking the calculation time into consideration [4]. The size of the elements is determined base on equation (5) to retain the original shape of the wave for analysis in the next steps.

$$l_e = \frac{\lambda_{\min}}{20} \quad (5)$$

where l_e is the length of element and $\lambda_{\min}$ is the shortest wavelength of the ultrasonic impulse.

III. NUMERICAL RESULTS AND DISCUSSION

FEM simulation was performed for different probe sizes, including 2mm, 6 mm and 10mm. A simulation with hypothetical 0 mm probe size was also performed as the ideal baseline for comparison. Based on the results to be explained later, a simulation with 8 mm probe size was also performed and included in the analysis. The defect magnitudes were considered no defect, 0.5 mm, 1 mm and 1.5 mm. The simulation was run for wave propagation in 2 microseconds.

Figure 3 shows the simulation results for the echo signal in the pipe wall in a non-defective part (a), and a defective part (b). The model with defect shows an obvious earlier reflection of the incident wave, which is due to the loss of material of the inner surface of the pipe and the thinner remaining thickness of the wall. In this condition, the echo signal travels a shorter distance and retains more energy in form of the amplitude. The amplitude of the echo signal fades after each time of reflection due to energy loss during wave transmission.

Figure 3. Simulation results for: (a) non-defective part and (b) defective part

The simulation was performed for 20 scenarios by modeling 5 mentioned sizes of the probe at 4 different magnitudes of the defect. In the real condition, the measurement signals are contaminated with noise, which may mask the early moments of the echo signals and reduce detection accuracy when the amplitude of the original signal is comparatively small. There are two main sources for such noise: scattered echoes from non-homogeneous structure of the material, and electronic circuitry noise [15]. Given $s(t)$ the original echo signal, a noise component of $e(t)$ appears in the measurement signal $\hat{s}(t)$.

$$\hat{s}(t) = s(t) + e(t) \quad (6)$$

For simulation purpose, the noise can be acceptably modeled by a Gaussian white noise [15]. In this simulation, a benchmark value of 15 dB is adopted for the signal to noise ratio (SNR) [16,17].

For automatic detection of the echo signal, an amplitude threshold equal to 2.5 times the standard deviation of the noise is devised. The choice of threshold is a design decision and an optimal value can be achieved through the trade-off between missed-positive and false-positive numbers and values. To quantify the uncertainty associated with random nature of the noisy echo signal, noise simulation was performed 100 times for each simulated ultrasonic wave reflection scenario. The resulting signals were compared with the assigned threshold with two considerations: 1) detection of echo signal starts when the excitation impulse tapers off, i.e. after $\sim 0.35 \mu s$; 2) time of reflection detection is assigned the earliest moment the measured echo signal exceeds the threshold. The average and the standard deviation of the remaining wall thickness were calculated based on the results for the detection time of the echo signal. Figure 4 shows the detection process and the results in selected scenarios. The original signal, the simulated noise and the noisy signal with the detection threshold are shown in each scenario. In addition, based on 100 trials for noise simulation, the probability distribution function for the measured thickness is provided in the figures.

In Fig. 5, the achieved results for different sizes of the probes at different magnitudes of the defect are provided. In part (a), the measurement over 100 trials are averaged and normalized with the actual thickness value. The probe size of 0 mm corresponds to the simulation scenario where only a single node was utilized for ultrasonic excitation. In this condition, when the defect is small (0.5 mm), measurement error is about 12%. With growth of the defect up to 1.5 mm, the error decreases to 8%. This is a reasonable result, because a larger defect provides a bigger area to reflect the signal more effectively. Similarly, for probe sizes of 2 mm and 6 mm, we observe that measuring error decreases with increment of the defect magnitude. For the incipient defect, i.e. 0.5 mm however, the accuracy of the 2 mm probe is almost two times better than the 6 mm probe. This can be explained by the fact that the submitted ultrasonic signal from a large cross sectional area of the probe scatters with its own components and the shape of the resulting echo signal gets eroded.

As the plot shows, for the probe size of 10 mm, the results are not promising. To check the intermediate size between 6mm and 10 mm, we performed a simulation with 8 mm probe diameter. Similar to the 10 mm probe, the corresponding results for the 8 mm probe are not accurate. In other words, with this simulation, the largest probe to provide acceptable results is the 6 mm probe.

In Fig. 5(b) the normalized standard deviation for 100 trials of noise simulation are provided. The results show that repeatability of the measurement increases with larger magnitudes of the defect for the 2 mm and 6 mm probes. The probe of 6 mm shows a better repeatability in the measurement compared to the 2 mm probe. This might be due to a more powerful reflection signal the 6 mm probe transmits; however, further investigation is required for an accurate conclusion. In the same plot, measurement with 8 mm and 10 mm probes show very high repeatability. It should be noted that it is due to the repetitive false-positive phenomena and the results carry no reliable information.

Figure 4. Post-processing FEM results for thickness measurement at selected scenarios, (a) probe size 0 mm and defect magnitude of 0 mm, (b) probe size 2 mm and defect magnitude of 0.5 mm, (c) probe size 6 mm and defect magnitude of 1 mm, and (d) probe size 8 mm and defect magnitude of 1.5 mm

IV. CONCLUSION

In this paper, FEM models were established in COMSOL Multiphysics® to simulate ultrasonic wave propagation for corrosion detection in inner walls of the pipes. Several sizes of ultrasonic probe were tested at different magnitudes of the defects and the measurement accuracy and repeatability were investigated through simulation by adding Gaussian white noise to the original signal. For the incipient defects with small dimensions, i.e. 0.5mm, the 2mm probe outperformed all the other probe sizes. For larger defect magnitudes, both the 2 mm and the 6mm probes showed similar accuracies. However, for the defects over 1 mm, repeatability of measurement with the 6 mm probe is better than other sizes in the study. Probes larger than 6 mm of diameter did not show an acceptable performance in any scenario.

This study was the first stage of a comprehensive research on ultrasonic fault detection. Experimental verification of the results will be performed in the next steps.

Figure 5. Measurement accuracy: (a) normalized mean error, and (b) repeatability error (normalized standard deviation of measurements)

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