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Monitoring Thicknesses along a Line using SH Guided Waves

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Abstract. Guided wave technology has been successfully implemented in the field of NDT as a defect screening technique for many years. The existing technique is able to detect large defects in pipes, albeit with limited sensitivity since the technique operates at low frequencies (10-70kHz). Ultrasonic wall thickness monitoring is also a well-established technique; using frequencies in the MHz range these spot measurements are able to measure precise wall thicknesses, but are very spatially selective. This project aims to explore the middle ground, using higher frequency guided waves to increase sensitivity whilst increasing the spatial area covered. SH guided waves (SH0 and SH1 modes) were sent between two transducers in a plate (simulating the propagation of a guided wave around the circumference of a pipe) and the time trace of the receiving transducer was analysed for changes in the group velocity as different defects were introduced into the plate. It is shown that the guided wave-defect interactions were too distorted for accurate thickness profiles to be extracted from line measurements. However, it is believed that this method can be a qualitative tool for defect screening.

INTRODUCTION

The corrosion of pipes and pipelines is a common problem for the petrochemical industry. In the United States alone it cost the industry an estimated \$8bn in 2014 [1]. Improving the ability to quantify the remaining remnant wall thickness of key infrastructure components will allow the industry to operate more safely and cost effectively.

Currently it is possible to build a 2D thickness map of a pipe by performing a series of pulse-echo measurements systematically scanned over the area under test (known as a c-scan). This technique requires a skilled operator to perform the measurements and takes a long time, therefore more effective methods are desirable. Conventional guided wave systems excite a wave packet in the pipe or plate at one location and rely on the reflection of the wave from a defect. This enables large areas of oil and gas infrastructure to be screened at any one time (e.g. up to 50m either side of an array of transducers [2]) from a single location/access point on a pipe). However, the defects in the pipe must be sufficiently deep and sharp for a detectable reflection to occur (5% cross sectional area is commonly quoted [2]). Therefore, this system is likely to miss smaller areas of wall thinning that might be of concern which have occurred due to corrosion. Ultrasonic systems are also available which accurately measure the thickness of a pipe or plate at a precise location (with a WT sensitivity of around 20µm [3]), using the pulse echo or pitch catch method. These spot measurements are able to constantly monitor the thickness of a pipe (approximately 1cm² directly under the sensor) and relay the information back to the plant operator. The individual sensors are low powered devices which can be permanently installed on pieces of oil and gas infrastructure. However, even though multiple sensors can be installed on the same pipe, this system is only able to relay a discretised thickness map of the pipe or plate, thereby potentially missing defects which are not directly under a sensor.

The sensitivity/measurement area trade-off is demonstrated in figure 1a, illustrating that the current in-service technology occupies either end of the sensitivity/area spectrum. The aim of this paper is to evaluate a technique which is sensitive to small thickness changes of a pipe over a larger area. More specifically this paper will evaluate a system which can monitor the average thickness around the circumference of a pipe from a single location by propagating an ultrasonic guided wave pulse around the circumference of the pipe (as shown in figure 1b). This paper begins with a brief description of the 'temperature compensated thickness extraction method' based on the SH guided wave modes,

followed by experimental confirmation of the method. Finite element analysis is then presented to further test the method and conclusions are drawn.

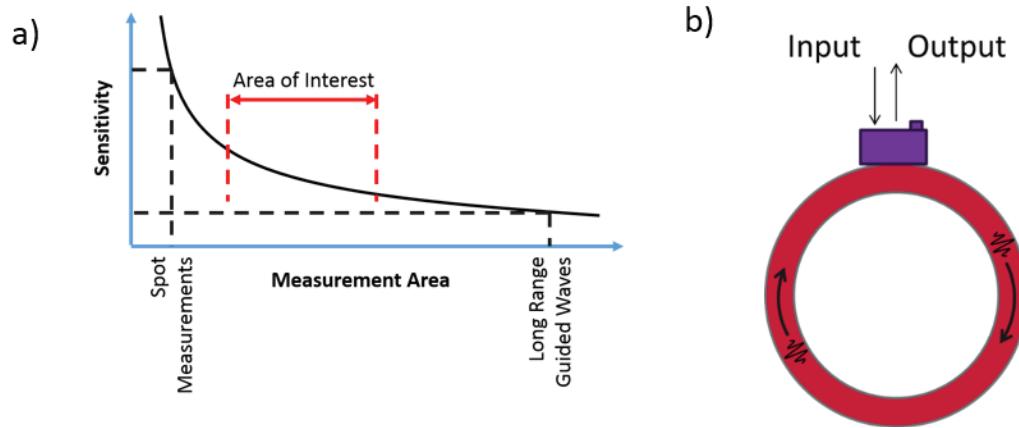


FIGURE 1. a) Shows the relationship between the sensitivity of a sensor and the measurement area, as well as the relative locations of existing ultrasound NDE technology, b) shows the proposed setup to be studied in this paper, inputting a guided wave pulse at a single location, sending it around the circumference of the pipe and detecting it at the same location.

MEASUREMENT PRINCIPLE

Figure 2a shows a setup which is equivalent to the setup in figure 1b. This propagates a guided wave between two transducers on a plate instead of around the circumference of a pipe. The plate can be thought of as an unrolled pipe. All the experiments and simulations presented in this paper have been conducted on a plate since this was more practical to implement and greatly simplified the FE model's geometry. For a large diameter/thickness ratio, the assumption that the dispersion curves are the same for waves around the circumference of a pipe and waves travelling in a plate of equivalent thickness is good [4]. Figure 2c shows the output/received time trace produced by this setup with the SH0 and SH1 pulses temporally separated (using a 5 cycle Hann windowed pulse with a 250kHz centre frequency over 0.5m in a 10mm thick plate – figure 2b). The windows that were placed around the two pulses for analysis purposes have also been indicated, this enables us to perform the thickness extraction algorithm described below.

Effective Group Velocity Extraction Method using SH Guided Waves

Ultrasonic guided waves are elastic waves which propagate in infinite plates of constant thickness. Guided waves are created from the super position of bulk waves continually being reflected between the upper and lower plate boundaries. This paper is concerned with the shear horizontal (SH) waves, specifically with the first (SH0) and second (SH1) modes.

All SH wave modes are dispersive, except for the SH0 mode, meaning that the group (and phase) velocity of the wave is dependent on the frequency-thickness of the plate in which they are propagating. If an SH1 wave packet is sent between two transducers and a change in thickness occurs then that change in the thickness of the plate will result in a measureable change of the effective group velocity of the wave packet that is travelling between the two transducers.

The setup described, in combination with the algorithm/method, has been designed to extract a value of the average thickness between two points on a plate or around the circumference of a pipe. The average thickness change directly relates to the change in the average slowness over the propagation path. Therefore, it is possible for different corrosion profiles (along the propagation path) to have the same value of average thickness. One corrosion profile could be

uniformly thinned by 1mm in a 10mm plate over 0.5m (as shown in figure 2a), compared to another corrosion profile which has 4mm of thinning in a 0.125m length. Both would have an average thickness of 9mm over 0.5m.

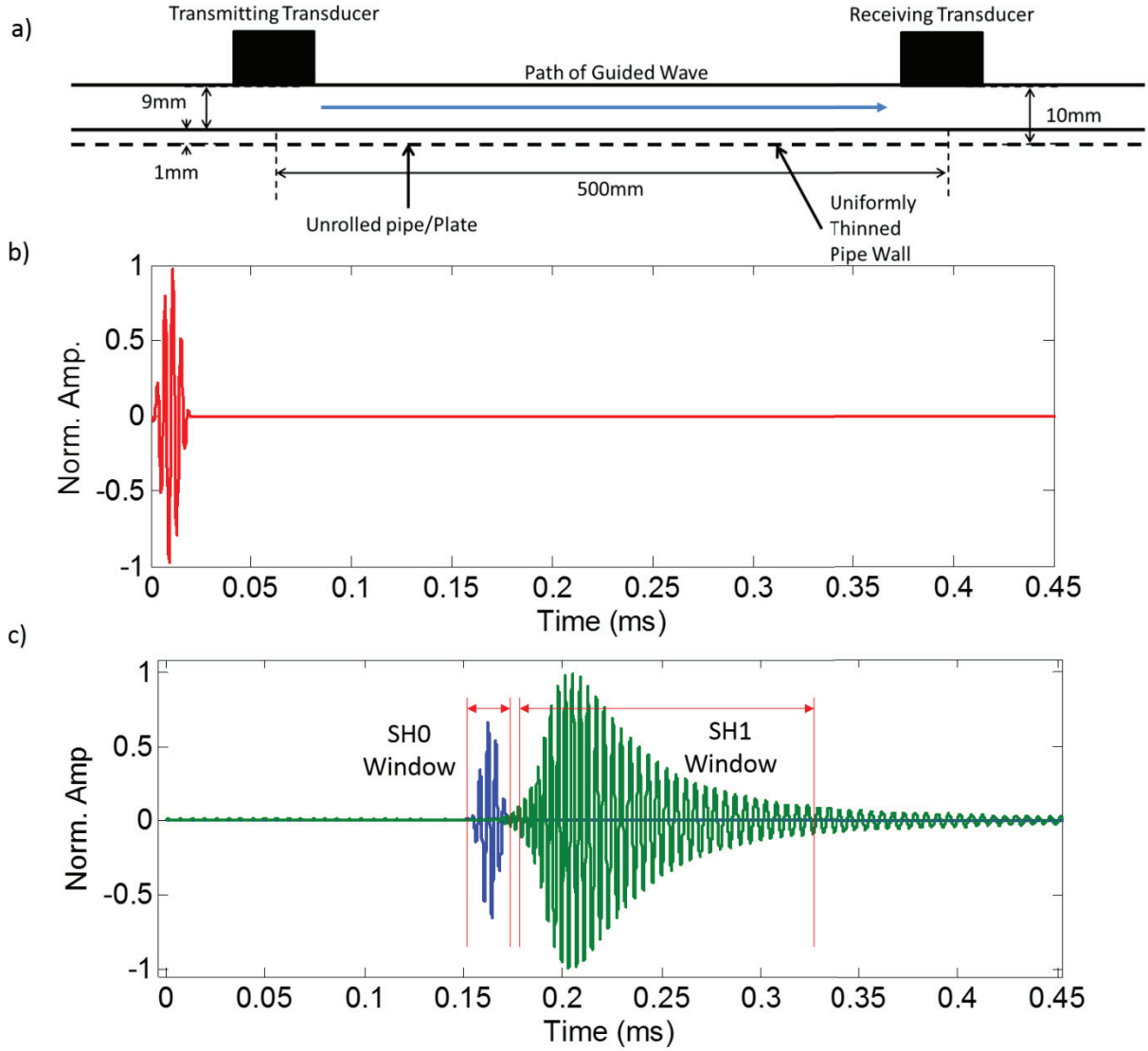


FIGURE 2. a) Shows a schematic of a cross-section of an unrolled pipe (i.e. a plate), with two transducers 500mm apart with a uniform wall thickness thinned from 10mm to 9mm., b) shows the input signal to the transmitting transducer, which is a 250kHz 5 cycle Hann windowed pulse, c) shows the resultant time trace received by the receiving transducer (0.5m separation in a 10mm thick plate).

The group velocity of the SH1 (c_g) is shown in Fig. 3 and can be expressed as an analytical equation, which is dependent only on the frequency (f), thickness (b) and shear velocity (c_s):

$$c_g(fb) = c_s \sqrt{1 - \frac{(c_s/2)^2}{(f/b)^2}} \quad (1)$$

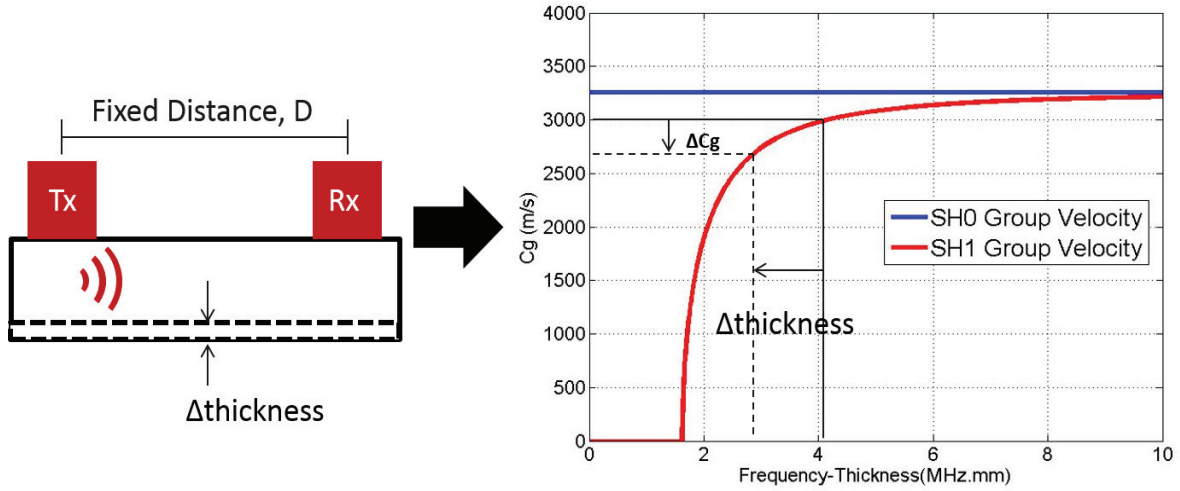


FIGURE 3. Shows the group velocity curves for the non-dispersive SH0 (blue) and dispersive SH1 (red) modes in steel ($c_s = 3235\text{m/s}$) produces in DISPERSE [5]. The effect of a change in the thickness of a plate using a pitch catch SH guided wave setup is shown, as well as the resulting change in the group velocity (at a single frequency-thickness value)

Average Thickness Extraction Algorithm

Group velocity can be extracted from two spatially and temporally separate wave packets [6]. In the case of the pipe setup described in this paper, an input pulse will be propagated around the circumference of the pipe and detected at the same location, giving us the output pulse. In the case of the plate, the input signal is the excited signal in the transmitting transducer (figure 2b) and the output signal is the signal received at the receiving transducer (figure 2c). The zero phase slope of input and output can be calculated over the spectra of the pulse and the effective group velocity can be determined using the following equation:

$$c_g(\omega) = \frac{D}{\frac{d\varphi(\omega)_{in}}{d\omega_{in}} - \frac{d\varphi(\omega)_{out}}{d\omega_{out}}} \quad (2)$$

where D is the separation distance between the two transducers, ω is the angular frequency of the spectral component, and $\frac{d\varphi_{in}(\omega)}{d\omega_{in}}$ and $\frac{d\varphi_{out}(\omega)}{d\omega_{out}}$ are the phase slopes of the input (figure 2b) and output signals respectively. SH1 pulse in the output signal must be windowed in order to extract the effective group velocity of the SH1 mode (this can be seen in figure 2c).

The analytical equation for SH1 group velocity depends on frequency, thickness and shear velocity. As the frequency and shear velocity of the metal are constant, the analytical group velocity can be fitted to the extracted effective group velocity by varying the thickness, b . This is implemented by minimizing the residuals between the extracted group velocity and the analytical group velocity over the spectra of the wave packet.

$$\min\left(\sum_{\omega_{low}}^{\omega_{high}} |c_{g,extracted}(\omega) - c_{g,analytical}(\omega, b)|_{c_s}\right) \quad (3)$$

The thickness extraction method above depends on the shear velocity of the plate being constant (see equation 1); however, the shear velocity of the metal plate is proportional to the temperature of the plate [3]. If not accounted for, this would induce a large error in the extracted thickness. A mechanism was therefore devised to compensate for changes in temperature, exploiting the fact that the group velocity of the non-dispersive SH0 mode is equal to the shear velocity of the metal. By propagating both the SH0 mode and the SH1 mode, the SH0 mode can be windowed (shown in figure 2c) and the shear velocity can be extracted using the group velocity extraction described above (in equation 2).

EXPERIMENTAL VALIDATION OF TEMPERATURE COMPENSATED THICKNESS EXTRACTION

In order to validate the temperature compensated thickness extraction method, a pitch-catch measurement was performed. Two shear horizontal electromagnetic acoustic transducers (EMATs) were placed at a fixed separation distance (0.367m) on a 10mm thick aluminium plate. A 5cycle Hann-windowed toneburst at a centre frequency of 200kHz was propagated between the transducers, this excited both the SH0 (non-dispersive) and SH1 (dispersive) modes. The SH0 and SH1 modes had a wavelength of approximately 13mm and 17mm respectively.

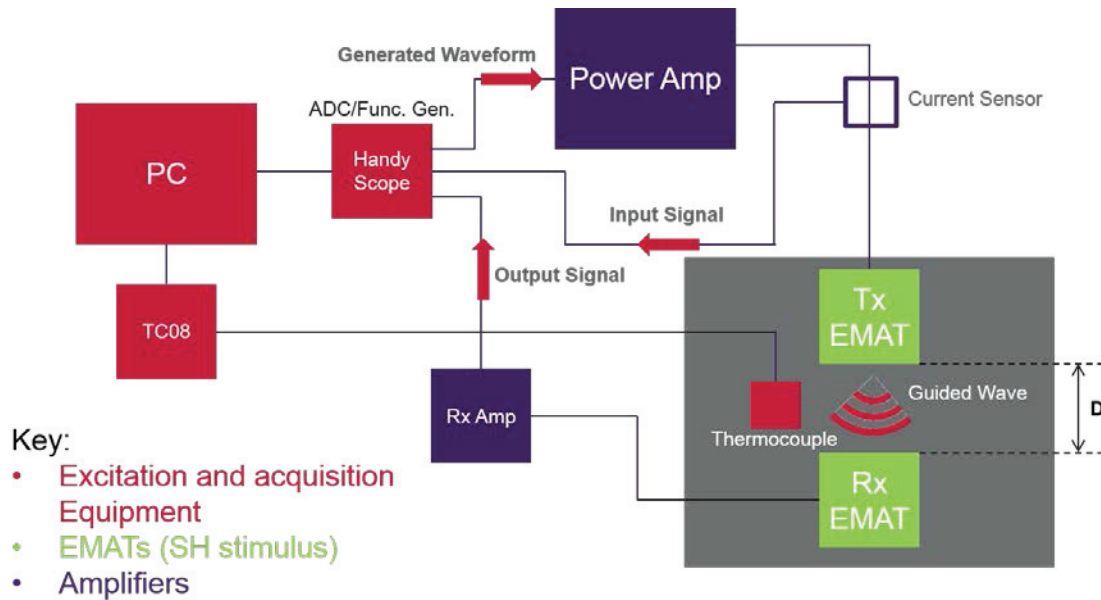


FIGURE 4. Shows a schematic of the experimental setup

The toneburst was generated using a HandyScope HS3 Function generator/ADC (TiePie Engineering, Sneek, NL) connected to a laptop running MATLAB. The toneburst was input into a Yamaha AS500 Power Amplifier (Yamaha, Iwata, JP), which in turn drove the transmitting (Tx) EMAT. The guided wave packet excited by the Tx EMAT propagated to the receiving (Rx) EMAT. EMATs were custom built by the Imperial NDE group for the excitation of SH0 and SH1 at 200-300kHz. The signal detected by the Rx EMAT was amplified and fed into the HandyScope, which passed the resulting time trace on to the MATLAB code for post processing. The input signal was also collected, by the HandyScope, using a current sensor which consisted of a coil of wire through which the power amplified Tx EMAT signal passed. Multiple time traces of both the input (Tx) and output signals (Rx) were collected per measurement and averaged. The experimental setup described above was placed in an environmental testing chamber (Vötsch VT³/VC³ - Temperature and Climate Test Chamber. Vötsch, Lindenstruth, DE). The chamber was heated to the required temperature and kept at that temperature for at least 30 minutes to ensure that the plate was in thermal equilibrium with the chamber. The environmental chamber was then switched off to improve the sensitivity of the measuring equipment whilst the thickness measurement was performed. Ten measurements were taken in quick

succession (within 2 minutes). Measurements were taken at approximately 10°C intervals between 30°C-90°C, plus a measurement at room temperature (26°C).

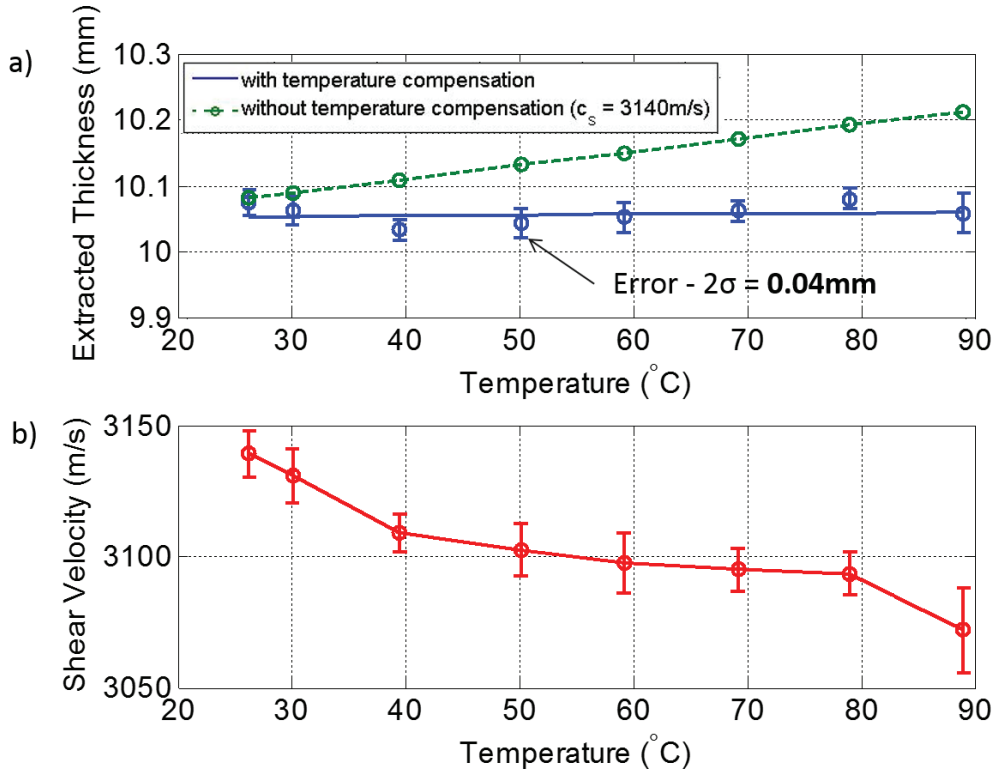


FIGURE 5. Shows the effect of temperature on a) the extracted thickness (blue) and the extracted thickness without temperature compensation is shown in green ($c_s = 3140\text{m/s}$), b) the measured shear velocity (red) using the group velocity thickness extraction methods with SH waves in an aluminum plate. Error bars are 95% range in the extracted thickness values.

Figure 5b shows that as the temperature of the plate increased, the shear velocity of the metal decreased, as expected [3]. When the thickness extraction algorithm was applied, the expected thickness was approximately constant over the entire temperature range. In fact the extracted thickness (with temperature compensation) has significantly deviated away from the extracted thickness without temperature compensation (calculated by fixing the shear velocity value at 3140m/s). The error in the individual temperature compensated thickness measurements was found to be 0.04mm (95% range).

FINITE ELEMENT MODELLING

A finite element model was created to simulate the effect of different defect sizes and shapes on SH guided waves. This is to test the ability of the thickness extraction algorithm to extract a value of the average thickness between two points with different defects. The base model, to which defects were added, was solved in the time domain using explicit time steps, performed by either the open source POGO software package [7] or ABAQUS. The model of the plate is $500 \times 200 \times 10\text{mm}^3$ and consisted of either 10 or 20 elements through the plate thickness. This corresponds to either a $1 \times 1 \times 1\text{mm}^3$ or $0.5 \times 0.5 \times 0.5\text{mm}^3$ element size respectively. The wavelength of the SH0 mode at 250kHz is 13mm and the SH1 mode is 17mm. Therefore, using 20 elements through the plate thickness satisfies the 20-30 elements per wavelength considered sufficient to accurately model the behaviour of elastic waves [8]. Absorbing boundaries were placed along the longest side of the model. These used the Absorbing Boundaries using Increasing Damping technique (ALID), in which adjacent vertical layers of elements have an increased damping factor trapping and dissipating any elastic energy within the ALID region [9].

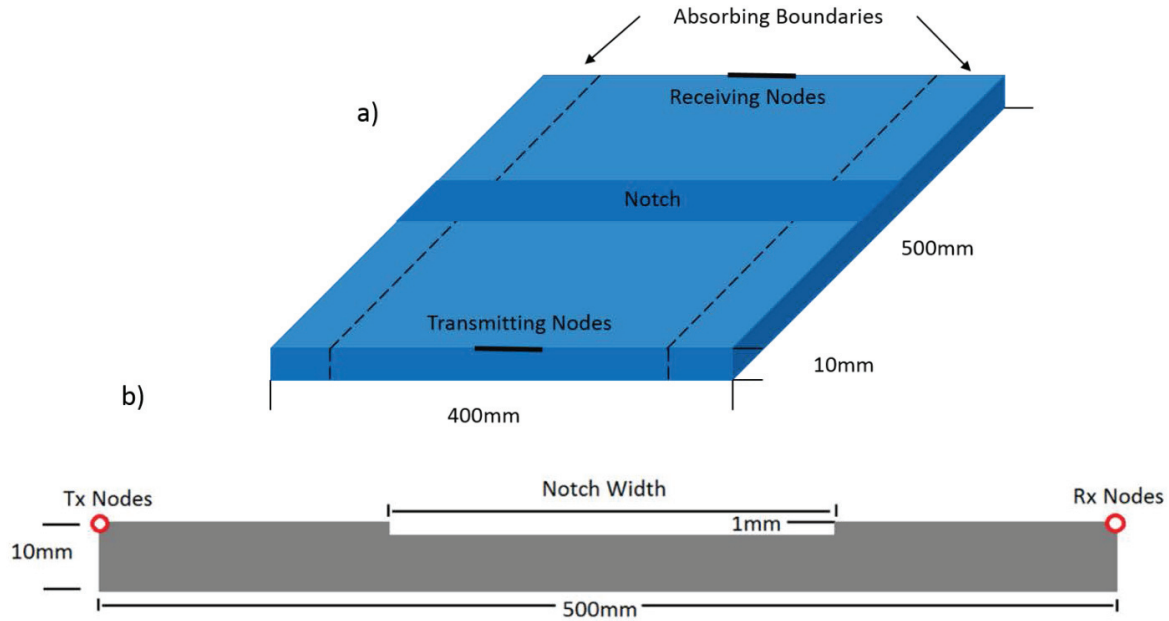


FIGURE 6. a) Shows the finite element model containing a notch, b) is a cross-section of the notch, which has a variable width and fixed depth of 1mm

The meshing was performed by a custom C++ code which generated the node positions and identified the nodes within each linear brick element. Two defect types were placed in the finite element model: a) a notch across the entire length (400mm) of the plate (figure 6) and b) a circular Hann profile defect (figure 7). In order to create the notch defect the appropriate number of elements were removed to create the notch with the desired width. The notch defects had a constant depth of 1mm and only the width was variable. For the Hann profile defect the height (z component) of all the nodes through the thickness were scaled to form the desired profile. The Hann profile defect was 60mm in diameter (equivalent to 3.5λ of the SH1 mode) and 1mm deep at its deepest point.

B-scan of the Hann profile defect was performed to more accurately model the effect of the position of the defect, since in reality the corrosion is unlikely to manifest itself directly along the path of the guided wave beam. B-scan data was simulated at regular intervals (every 5mm) over a 100mm range. When the B-scans were modelled in the finite element model the defects were repositioned at each point, and only half of the simulations were performed since the scan is symmetric either side of the defect. An element size of 1mm (i.e. 10 through the plate thickness) was chosen to increase computational speed.

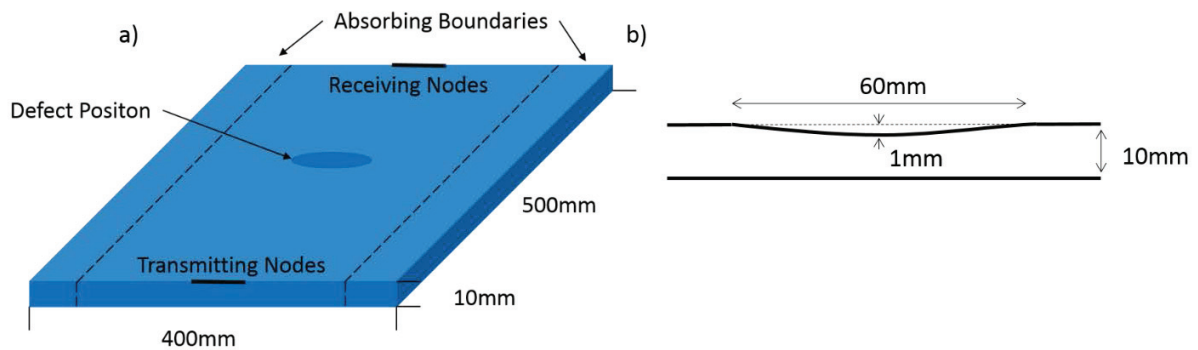


FIGURE 7. a) Shows the finite element model containing a circular shaped defect, b) is a cross-section of the Hann profile defect with a 60mm with and 1mm deep

A collimated guided wave beam was generated (in the SH wave case) by applying a 5 cycle Hann toneburst (with 250kHz centre frequency) on a 50mm wide linear array of nodes at one edge (on the 400mm edge). A similar array of nodes on the opposite edge was used for receiving the elastic wave. Both the time traces of the input (transmitting – figure 2b) and output (receiving – figure 2c) nodal arrays were recorded in order to be used in the group velocity thickness extraction algorithm. The nodes were placed on the surface of the plate ($z=0.01\text{m}$) since the SH1 mode has zero displacement at half thickness.

Notch Defects

In order to test the ability of the thickness extraction algorithm to quantify the average thickness between two transducers, a 10mm plate with 1mm notch of variable width was created. The notch width was varied between 0.125m (25% of the propagation distance) to 0.5m (100% of the propagation distance). The length of the notch is effectively infinite since it extends across the entirety of the plate and into the absorbing boundaries. A cross section of the plate is shown in figure 6b.

Figure 8 shows a good relationship between the expected and extracted change in thickness. There is a slight deviation from the expected thicknesses. This is probably due to numerical error caused by the finite element model, even after performing relative difference measurements.

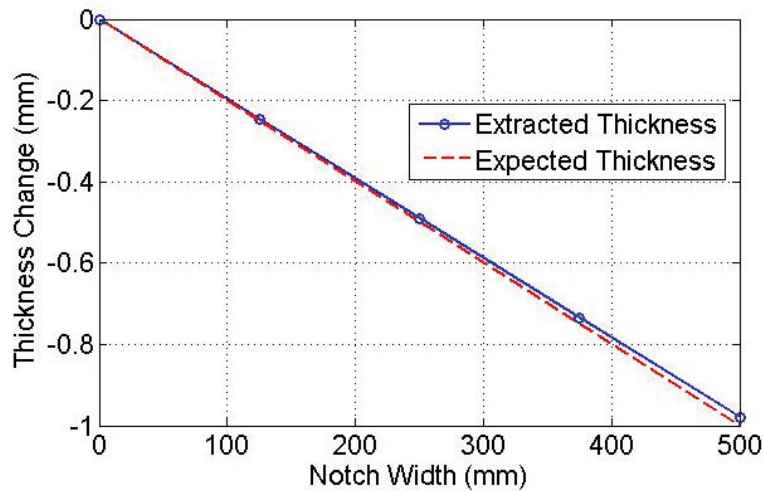


FIGURE 8. Shows the extracted thickness using the group velocity method from a 10mm thick FE plate model containing a notch of variable width using SH waves at 250kHz with 20 elements through the plate thickness, performed in ABAQUS

B-Scan of a Hann Profile Defect

The B-scan of a more complex defect profile tests the robustness of the thickness extraction algorithm to cope with defects that more closely resemble reality. The Hilbert windowed time traces from the B-scan of a 60x1mm Hann profile defect is shown in figure 9a. The SH0 mode is minimally affected by the presence of the defect, whereas the SH1 mode is substantially attenuated over the width of the defect. Figure 9b shows the result of the thickness extraction algorithm having been applied to the time traces of figure 9a. Clearly the extracted thickness (blue) does not correlate with the expected thickness (red). As the transducers approach the edge of the defect, the extracted thickness decreases; however, over the width of the defect the extracted thickness increases reaching a maximum at the centre of the defect. This is a result of the scattering that has been caused by the defect.

Two further remarks can be made about this result. Firstly, this technique cannot be used as a reliable single measurement, because the location of the defect heavily influences the extracted thickness. In fact, if a single

measurement was taken at approximately 20mm then no thickness change would be detected. Secondly, the thickness profile in figure 9b could be used as a qualitative method of defect detection/screening, especially since the peak-to-peak value of the extracted thickness profile (0.11mm) is greater than the expected thickness profile (0.06mm).

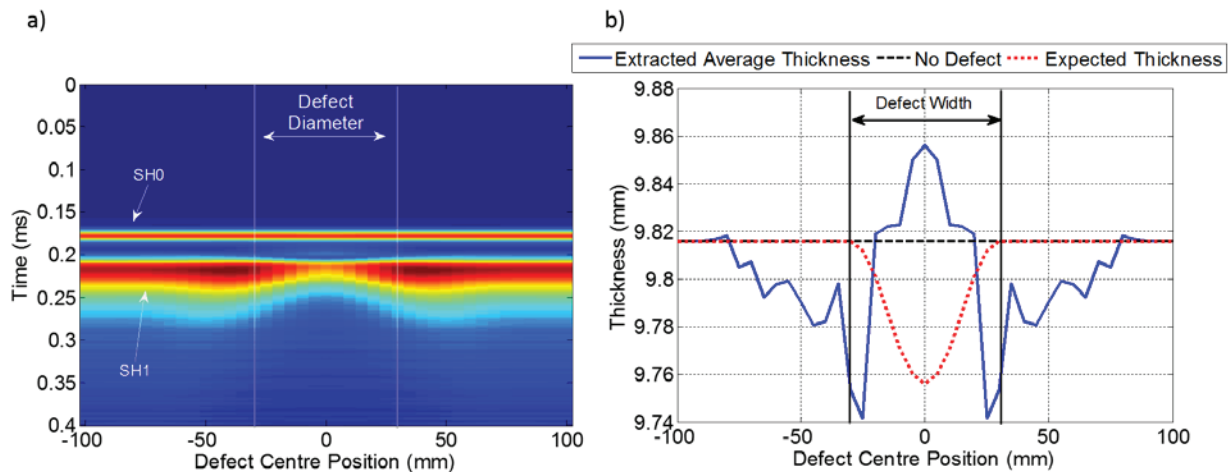


FIGURE 9. a) Shows the Hilbert enveloped signals of the B-scan performed in POGO, using a 250kHz 5 cycle Hann windowed input pulse, b) shows the thickness extracted (blue) from the B-scan. The expected thickness (red) is also shown.

CONCLUSION

This paper has evaluated the performance of dispersive guided wave thickness measurements along a line of a plate. The temperature compensated group velocity thickness extraction algorithm has been shown to be able to precisely determine the average thickness between two transducers, using SH0 and SH1 guided waves. The experimental data showed that the temperature compensated thickness value had an associated error of 0.04mm and the average thickness along the line could be determined to that precision. When the same thickness extraction algorithm was applied to simulated signals from plates which contained flat bottomed notches spanning the whole width of the plate, an accurate value of the average thickness could be extracted.

When testing the thickness extraction algorithm on signals that had passed through simulated Hann profile defects, it was clear that the presence of the defect distorted the received signal significantly and that the thickness extraction algorithm was unable to extract the correct value of the average thickness. The interaction of the wave with the defect led to an increase in the measured thickness at the centre of the defect. If the corrosion patch is much wider than the beam width, then the proposed corrosion monitoring method appears to work as intended. However, in order for the proposed method to be useful in the field, defects of different sizes and profiles must be detectable and ultimately measurable. The B-scan simulation over a 60mm diameter, 1mm deep Hann profile defect has shown that the presence of a defect elicits a detectable/qualitative response but the magnitude of the detected change varies greatly with the relative position between probe and defect. Although, this method provides a means of screening a pipe for defects, it would be difficult to implement as a monitoring system that returns quantitative defect size information.

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