Detectability of corrosion damage with circumferential guided waves in reflection and transmission

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ABSTRACT

There is an increasing interest in high frequency short range guided waves to screen or monitor for corrosion. This contrasts with long range guided waves (LRGWs) which screen pipes for large patches of corrosion and have been successfully used in corrosion management for the past twenty years. The fundamental setup described in this paper uses circumferential guided waves, which are excited at a single location on a pipe and travel around the pipe wall and are detected at the same location. The study uses a finite element model assisted method to evaluate the detection capability of two short range circumferential guided wave setups which use both the reflected and transmitted signals. The setups themselves consist of either an axial array of transducers, for monitoring, or a single transducer which axially scans a pipe. Both setups have an array or scan pitch between either adjacent transducers or measurements. The detection capability of the fundamental Lamb wave modes (A0 and S0) in both reflection and transmission have been compared, as well as a hybrid shear horizontal wave setup, which uses the SH0 mode in reflection and the SH1 mode in transmission. A sensitivity analysis was conducted using two separate methods to determine the probability of detection (POD) for either the reflection or transmission signals. Both methods determine a POD for a specific defect, noise level, and array or scan pitch. Probability images are produced which map the POD for a range of defect sizes. For the parameters investigated in this study, it was found that in transmission large diameter defects have a higher detectability, whereas deep, narrow diameter defects are more detectable in reflection. A generalised overview of the sensitivity of short range guided waves is presented by combining both the reflection and transmission PODs. The data fused sensitivity of the S0 and SH hybrid modes are given as 0.6% and 0.75% cross sectional area (CSA) respectively, allowing for the comparison with LRGWs. The A0 mode was excluded from the POD analysis because it was much less sensitive than the other two modes.

1. Introduction

Advances in finite element (FE) modelling allow for the rapid simulation of new NDE systems and techniques. Targeted FE simulations combined with probabilistic analysis methods enables the quick assessment of the viability of new systems or techniques, thus saving time and cost.

This paper is a continuation of the work by Howard et al. [1], which uses finite element (FE) simulations to evaluate the potential of dispersive circumferential guided waves as a technique for screening or monitoring for pipe wall thinning due to corrosion. In addition to the previously reported work this paper describes a model-assisted probability of detection (MAPOD) technique, which quantifies the ability of guided wave reflections to detect pipe wall thinning.

By conducting this analysis, and simultaneously evaluating these two detection methods (reflection and transmission), a more complete picture of circumferential guided wave sensitivity to wall thinning defects is obtained.

The two measurement methods under consideration are illustrated in Fig. 1a. A transducer propagates a guided wave pulse around the circumference of the pipe and detects it at the same location. The two measurement methods studied are through transmission and reflection. As explored in Ref. [1] the through transmission method uses the changes in travel time of dispersive guided waves to detect wall loss. This paper builds on previous research by additionally considering the potential for defect detection using reflections from the defects. Specifically, this paper will evaluate and compare the sensitivities of the A0, S0 and SH/0/1 guided wave modes each optimised for either measurement method.

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This paper will also simultaneously evaluate two modalities of the same measurement, which either monitor or scan for pipe corrosion defects. In monitoring mode (Fig. 1b) the measurement is performed by a permanently installed linear array of circumferential guided wave transducers; whereas in scanning mode (Fig. 1c) a single transducer is axially scanned along the pipe at a predetermined pitch. Both types of measurement have an associated array or scan pitch, which governs the coverage area and therefore the sensitivity to defects.

Circumferential guided waves are an appealing method for pipe corrosion detection since they sit between the two established ultrasonic pipe monitoring techniques: a) highly sensitive but localised ultrasonic spot thickness measurements (<5 mm in wavelength) [2], and b) low frequency guided waves that rapidly screen large areas for big defects (>100 mm in wavelength) [3]. Therefore, this paper explores the trade-off between sensitivity and transducer coverage using circumferential guided waves.

To fully evaluate the sensitivity of the guided waves (in either reflection or transmission) several assumptions have to be explicitly stated about the setup in Fig. 1a:

a) The guided wave transducer can preferentially excite a guided wave in one direction around the circumference of a pipe, this is a reasonable expectation since directional transducers have been successfully demonstrated in the laboratory [4] and in the field [3].

b) The transducer is able to separate the transmitted and the reflected signals from one another and treat them independently. This enables a fair comparison between the two measurement modalities.

c) The transducer can operate over a wide range of input toneburst parameters, allowing optimisation of input toneburst characteristics in either transmission or reflection.

There have been numerous papers presented on the mechanics of the reflections of guided waves, for the purposes of defect detection and characterisation, propagating either circumferentially around or axially along a pipe wall or in a plate. There is also commercial interest in circumferential guided wave systems [5]. The use of circumferential guided wave reflections for the detection of cracks in pipes has been studied by Valle et al. [6] and Fletcher [7], as have through holes [8], part thickness holes [9,10] and axial slots [11]. Many finite element and experimental studies have simplified pipe geometry to that of a flat plate to further study more complex defects such as irregular defects [12,13], part thickness ellipses [14] as well as to characterise the effect of sharp edges on defects [15]. Full, albeit very coarse, 3D FE simulation of guided waves have been commonplace since the early 2000s [16], however, current GPU FE software allows for both high fidelity and fast processing of many different defect sizes [17]. It is these recent developments that have allowed this study to model and subsequently probabilistically analyse a large range of defect sizes to ascertain the sensitivity of guided waves to wall thinning.

This paper first outlines the FE element setup as well as the selection of the input toneburst parameters. The method by which the reflection amplitudes are defined is then presented, followed by a sample of the finite element results. The probability of detection (POD) method used to quantify the reflection sensitivity of guided waves is then given. Results from the POD study are shown and their implications discussed, before conclusions are drawn.

2. Setup of finite element model

The same finite element model dimensions were used as in the previous study [1] (as illustrated in Fig. 2a), whereby the pipe's geometry was simplified to that of a plate. The guided wave propagated over a 500 mm distance and the plate thickness was 10 mm, these dimensions roughly correspond to pipes of 6–8” diameter.

The base FE model was a structured mesh, to which defects were added. The base model has similar characteristics to the experimentally validated FE model presented in Ref. [18]. It was solved in the time domain using explicit time steps, performed by the open source POGO software package [19], which uses a GPU solver taking advantage of the higher processing speeds associated with parallel processing. The model of the plate is $400 \times 700 \times 10 \text{ mm}^2$ (XxYxZmm), Fig. 2a) and consists of 10 elements through the plate thickness. An element size of $1 \times 1 \times 1 \text{ mm}^3$ was used. Two 50 mm wide absorbing boundaries were placed along the longest side of the model. These used the “Absorbing Layers with Increasing Damping” technique (ALID), in which adjacent vertical layers of elements have an increased damping factor attenuating any elastic energy within the ALID region [18]. The excitation and receiving node sets were 50 mm in length simulating a realistic transducer width of 50 mm. The 50 mm excitation node set was placed at half thickness enabling the generation of pure guided wave modes (see Table 1 for the different displacement directions), whereas the node sets representing the transmitting (Tx) and receiving (Rx) transducers were located on the model’s surface, thereby being able to detect an accurate representation of the reflected signal. The meshing was performed by a custom C++ code, which generated the node positions and identified the nodes corresponding to each linear brick element.

2.1. Modelling of Hann profile defects and dimensions

A circular Hann profile defect was placed into the FE model by scaling the z-height of all the nodes through the thickness of the model. Therefore, at the deepest point of a 5 mm deep defect all the nodes were 0.5 mm in height as opposed to 1 mm. The diameter and depth of the defects are variable and are defined in Fig. 2b.
A wide range of defect diameters and depths were modelled. The defect diameters ranged from 10 mm to 90 mm (in 10 mm steps) and the defect depths ranged from 1 mm to 5 mm (in 1 mm steps), which is 10%–50% wall loss in a 10 mm plate. The upper diameter bound was inferred from previous dispersive guided wave studies (whereby the defect diameters ranged from 1$\lambda$ to 3$\lambda$ + [18,20]). The lower diameter bound was inferred from previous guided wave reflection studies which studied defects with diameters around or just below one wavelength [13,14]. The wavelengths of the toneburst centre frequency of the guided waves in reflection evaluated are displayed in Table 1, and for comparison the

| Mode | Centre freq (kHz) | Maximum allowable BW (kHz) | Wavelength (mm) at centre freq | Excitation Direction (from Fig. 2) | Range of centre freq from literature (MHz.mm) |
|------|-------------------|---------------------------|--------------------------------|-----------------------------------|---------------------------------------------|
| A0   | 140               | 80–220                    | 60                             | Z                                 | 0.8–1.75                                    |
| S0   | 90                | 0–180                     | 18                             | Y                                 | 0.1–1.7                                     |
| SH0  | 90                | 0–170                     | 36                             | X                                 | 0.1–1                                      |

Fig. 3. Method used to select the operating frequency range of the input signals for the A0 and S0 modes by applying limits to the a) phase velocity curves b) group velocity curve and c) attenuation due to fluid loading. Time traces of the input and output waveforms of the d) S0, e) A0 modes (in a plate), and f) SH0 mode (in a pipe) over a 500 mm propagation distance with a 10 mm wall thickness, using input toneburst parameters from Table 1. All graphs produced using the DISPERSE software package [16].
input toneburst parameters used in Ref. [1] are shown in the Appendix.

Further simulations using the transmission method described in Ref. [1] were carried with these defect dimensions, therefore allowing direct comparison of the two measurement methods over the same defect space.

2.2. B-scan simulations using the finite element model

B-scans, conceptually illustrated in Fig. 2c, of all defect sizes were performed to examine the effect of defect location in the x direction on detectability. Simulations were performed at regular intervals (every 5 mm along the x-axis) over a 300 mm range, 150 mm either side of the defect, to assess the effect of position on the reflection measurements. The B-scans were modelled by repositioning the defect in the finite element model and only half of the simulations were performed since the scan is symmetric either side of the defect.

2.3. Guided wave modes evaluated and selection of input toneburst parameters

As was conducted in Ref. [1] three guided wave modes have been evaluated in this study whose input toneburst parameters have been selected to have a high sensitivity in reflection to defects. The findings from the existing literature on the reflections of guided waves [6–8,11–14,21–34] guided the choice of input parameters. There is, however, no consensus in the literature on the optimal input toneburst parameters, therefore the present study needed to perform its own independent analysis, specifically focussing on maximising the sensitivity and detectability. Table 1 includes the range of centre frequency values found in the existing literature.

Most guided wave modes are dispersive, meaning that the group (and phase) velocity of the wave is dependent on the frequency-thickness of the plate in which they are propagating. The group and phase velocity curves for the A0 and S0 modes are shown in Fig. 3a and b. In contrast to the previous transmission study [1], when optimising for reflection the less dispersive the guided wave mode the better, since the higher the dispersion the greater the distortion of the wave packet as it propagates, which reduces the amplitude of the pulse. Therefore, the non-dispersive shear horizontal (SH0) mode was used (in place of the SH1 mode) and the centre frequencies of the fundamental Lamb wave modes (A0 and S0) were chosen as to limit their dispersiveness. In further contrast to [1], the bandwidths of the modes need to be as wide as possible. This is because guided wave reflections from defects have been shown to be heavily dependent on wavelength [15], thereby increasing the bandwidth enhances sensitivity. However, in the case of the A0 and S0 modes there is a trade-off between dispersion and bandwidth. A graphical approach, shown in Fig. 3, was taken to select feasible operating parameters for a guided wave mode in a 10 mm thick plate. In each of the figures shown in Fig. 3 a different limit is applied to the two Lamb wave modes:

a) Phase velocity curve: A1 and S1 Mode Cut Offs provide an upper boundary to prevent the excitation and mode conversion to higher order modes.

b) Group velocity curve: The dispersion of the mode is due to the different spectral components of the wavepacket propagating at different velocities, thereby causing the wavepacket to spread and decrease in amplitude. The A0 mode group velocity curve is relatively flat (non-dispersive) above 80 kHz and has a peak at 140 kHz [35]. The S0 is the least dispersive at low frequencies. Choosing a low centre frequency would, however, decrease sensitivity to small defects, due to a large wavelength, and limit the bandwidth.

c) Attenuation due to fluid loading is large at some frequencies. For both monitoring and rapid scanning to be practically viable they must be able to be performed when the pipes are full of fluid. The operating frequency ranges selected by steps a) and b) both have acceptable levels of attenuation, although the S0 significantly out performs the A0.

The most suitable operating parameters, as indicated by the analysis described by Fig. 3a–c, are shown in Table 1. Fig. 3d and e shows the A0 and S0 mode signals propagated over 500 mm. Due to the desire to limit dispersion, the bandwidth of the pulse has been limited to 3 cycles.

The SH0 mode is the fundamental shear horizontal wave mode and in a plate it is not dispersive. In order to prevent exciting the SH1 mode there is an upper frequency limit of 1.7 MHz mm, and attenuation due to fluid loading is less than 2 dB/m for frequencies below the SH1 cut-off. A centre frequency of 90 kHz was chosen to maximise the possible bandwidth. In a pipe the SH0 is dispersive, however, the effect is <0.5%
3. Extraction of normalised reflection amplitude

The signals are defined relative to either the transmitting (Tx) or receiving (Rx) transducer. The reflection measurements use the Tx signals. The signals, $s[n]$, are a function of $n$ samples. The Hilbert envelope is denoted by $\mathcal{H}[n]$ and was used for analysis.

When the defect is described as being in the central position the defect lies equidistant between and directly along the line between the Tx and Rx transducers. The defect position, $p$, is the distance of the defect away from the central line between the two transducers, along the locus between the two transducers. This is the equivalent in the pipe setup, shown in Fig. 1a, of the defect position being at the 6 o’clock position.

Baseline subtraction can be performed to clearly see the reflected signal when a defect is present in the plate. Although the FE model contains ALIDs the baseline subtraction approach was used to remove the input stimulus and other artefacts that may occur within the time trace, leaving just the reflected signal, Fig. 4e. The baseline subtracted signal at Tx, $s_{Tx, p}$ is defined as:

$$s_{Tx,p}[n] = s_{Tx,p,raw}[n] - s_{Rx,baseline}[n]$$  \hspace{1cm} (1)

where, $s_{Tx,p,raw}$ is the signal at Tx (Fig. 4a) with the defect at position $p$ (Fig. 4g).

The method by which the normalised reflection amplitude is calculated must be defined to compare the results from adjacent measurements as well as different modes.

Using the baseline subtracted signal, shown in Fig. 4e, the normalised reflection amplitude was defined as the ratio of the maximum amplitude of the reflected wavepacket (as shown in 4c) to the maximum amplitude of the baseline through transmitted wavepacket (as shown in 4c). The normalised reflection amplitude is therefore defined as:

$$A_{p} = \max\left(\frac{|\mathcal{H}(s_{Rx,baseline}[n])|}{|\mathcal{H}(s_{Tx,p}[n])|}\right)$$  \hspace{1cm} (2)

where $\mathcal{H}(s_{baseline,Rx}[n])$ is the Hilbert enveloped of the through transmitted baseline signal, and $\mathcal{H}(s_{Tx,p}[n])$ is the Hilbert enveloped of the through transmitted signal with the defect at position $p$, both at Tx. When the defect is in the central position both the reflected and transmitted signal will have propagated over the same distance. As $p$ increases, the adjacent reflection amplitudes are therefore comparable with the defect in the centre position. Furthermore, the noise level and decision thresholds (used in section 5) are defined in relation to the maximum amplitude of baseline through transmitted signal (Fig. 4c):

$$A_{noise} = \frac{\max(|\mathcal{H}(s_{Rx,baseline}[n])|)}{10^{\frac{SNR}{10}}}$$  \hspace{1cm} (3)

where $A_{noise}$ is the maximum amplitude of the noise (band limited to signal bandwidth) and the SNR is the desired signal-to-noise ratio (in dB).

4. Reflection profiles from finite element B-scan simulations

Fig. 5a shows five normalised reflection amplitude profiles for a 30 mm diameter defect with five different depths (1, 2, 3, 4, and 5 mm), interrogated with a 90 kHz 3 cycle Hanning windowed S0 toneburst. The corresponding signals with the defect in the central position are also shown. The larger peaks in each signal are the direct reflections from the defect and the second smaller peaks are the reflections reflecting off the sides of the FE model, which have been dampened, although not removed, by the ALIDs. As the defect depth increases the peak reflection amplitude scales linearly. At any depth when the defect is in the central position the reflection amplitude is at a maximum. As the defect moves away from the centre the reflection amplitude decreases, as expected for two reasons: firstly, the incident and reflected wave must travel further; and secondly the incident beam has a finite width, therefore at large defect positions the wave incident on the defect will be less intense than at the central position.

In reflection the defect is effectively at the furthest point away from the transducer. This is because if the proposed guided wave system successfully took advantage of a directional transducer then it would be able to easily send directional waves either clockwise or anticlockwise around the pipe. Therefore, the maximum travel distance of the incident and reflected pulse occurs when the defect is at the 6 o’clock position in the pipe.

In reflection the profile is much wider than the width of the defect measured. These deviations will have implications on sizing, however, when considering just detection then a substantial difference from the baseline thickness value is an indication that a defect is present. The magnitude of the deviation from the baseline will dictate the sensitivity when compared to a baseline noise level. Therefore, a method needs to be devised to quantify this deviation from the baseline compared to different noise levels. The method also need to consider array or measurement pitch to derive an overall measure of sensitivity to different sized defects.

5. Model of probability of defect detection from reflection measurements as a function of measurement pitch

A method to quantify the detection capabilities of the different modes in reflection is described in this section. The approach is similar to other methods of extracting probability of detection (POD) and probability of
false alarm (PFA) that are reported in the literature [36–38]. This study is interested in the two setups illustrated in Fig. 1b and c, with the circumferential position of the defect fixed at the 6 o'clock position.

To calculate the POD and PFA in reflection for a certain defect two probability distributions must be derived, $p$(reflection|baseline) and $p$(reflection|defect); which describe the probability distribution of reflection amplitudes given that there is either no defect (baseline) or a certain defect is present.

These two distributions can be overlaid as shown in Fig. 6. To call a defect an arbitrary threshold must be chosen, if the change in measurement exceeds this threshold a defect (or wall thinning) is called. The values of the POD and PFA can then be calculated from the areas under the probability distribution curves which are above or below the threshold as follows [36,39,40]:

$$\text{POD} = \text{Sensitivity} = \frac{TP}{TP + FN}$$  \hspace{1cm} (4)

$$\text{PFA} = 1 - \text{Specificity} = 1 - \frac{TN}{TN + FP} = \frac{FP}{TN + FP}$$  \hspace{1cm} (5)

where the true positive (TP), false positive (FP), true negative (TN) and false negative (FN) represent the integrals of the two measurement distributions either side of the threshold, as shown in Fig. 6.

For this study we define a call threshold equal to the noise level with 30 dB SNR as defined by Equation (3), this means if the normalised reflection amplitude change exceeds 0.031 then a defect is detected. To calculate the POD and PFA methods to derive $p$(reflection|baseline) and $p$(reflection|defect), need to be determined. In this study the PFA is fixed at 0.005 (0.5%). An SNR of 30 dB has been chosen as this has been experimentally observed by the authors [41].

5.1. Determination of the baseline probability distribution due to noise

To simulate the noise an array of random numbers with additive white Gaussian noise, which had the same number of samples as $s_{Tx,p}[n]$, was generated. The array was filtered in the frequency domain so that it had the same bandwidth as the input toneburst, scaled to the desired amplitude using Equation (3) and Hilbert enveloped. The amplitude at an arbitrary sample in the noise array, $s_{\text{noise}}[n]$, was logged. When performing a pulse echo measurement an operator searches for a reflection within a window in the time trace. However, it is not possible to incorporate all possible window widths within a value of the POD. Therefore, the amplitude of a single sample was logged since a single sample is the most conservative ‘window width’ possible. In this study, for computational convenience, the value at $n_{\text{max}}$ was logged (see Equation (6)). This process was repeated 1000 times and $p$(reflection|baseline) is then approximated from a histogram of noise amplitudes values. The amplitude variations of enveloped acoustic signals follow Rician distributions [38,42]. Rician distributions can be approximated to Rayleigh distributions or Gaussian distributions at low or high signal to noise ratios respectively [43,44].

5.2. Determination of the defect probability distribution variability due to noise in reflection

The probability distribution due to the presence of a defect, $p$(reflection|defect), is determined by two factors: the variability due to noise and the variability due to defect position. These are calculated separately and then combined.
5.2.1. Variability in reflection amplitude due to noise

Noise is repeatedly added to the Tx baseline subtracted signal (Equation (1)) with the defect in the central position ($p = 0$). The spread in amplitude values at the central position is then used to approximate the spread due to noise at all defect positions. First the position, $n_{\text{max}}$, of the maximum amplitude in $s_{\text{Tx},0}$ without noise is located:

$$n_{\text{max}} = \arg \max \left( \left| s_{\text{Tx},0} \right| \right)$$  \hspace{1cm} (6)

To simulate the different noise levels, filtered noise, $s_{\text{noise}}[n]$, with the corresponding signal to noise ratio (SNR) was added to $s_{\text{Tx},0}$. The noisy signal amplitude in the central position, $A_{\text{Tx,0,noise}}$, at $n_{\text{max}}$ can be logged.

$$A_{\text{Tx,0,noise}} = \left| s_{\text{Tx},0} \right|_{n_{\text{max}}} + s_{\text{noise}}$$  \hspace{1cm} (7)

This process was repeated 1000 times, with the value of $A_{\text{Tx,0,noise}}$.

Fig. 8. Example probability image used to display the POD results for a range of defect sizes. b) a recursive interpolation of a) by using a third order cubic interpolation. The example shown here shows the POD using S0 mode, via the average thickness method presented, for a range of defects with a pitch of 50 mm and 30 dB SNR.

Fig. 9. Probability of detection in reflection for the S0 mode (top row), SH0 mode (middle row), and A0 mode (bottom row) with pitches of 10, 50 and 100 mm, over a range of defect diameters (10–60 mm) and depths (1–5 mm), using the input toneburst parameters in Table 1 and 30 dB SNR.
logged each time. The standard deviation of the $A_{\text{TX,p}}$ set, $\sigma_{b}$, was then calculated.

5.2.2. Variability in reflection amplitude due to defect position

When a defect is present the distribution of the measured reflection amplitude does not solely depend on the noise level, defect type and defect size, but its position relative to the transducer(s) as well. The method by which the defect position is incorporated into the POD is illustrated in Fig. 7 using the reflection profiles from the finite element simulations, such as the examples shown in Fig. 5.

The full reflection profile, $A_{\text{TX,p}}$, covers all the defect positions simulated in the finite element model, where $p$ is $-150$ mm to $150$ mm in $5$ mm steps. However, for a setup with a particular pitch, $X$, the reflection profile of interest is much narrower, $p$ is $-X/2$ to $X/2$ in $5$ mm steps, since we are only interested in the values with the largest normalised reflection amplitude values. Any transducer measuring a reflection outside that region will have a smaller response than the transducer within the central pitch, and is therefore ignored. $A_{\text{TX,p}}$ is cubically upsampled by a factor of 100 to increase the density of points, this is not shown in Fig. 7.

The assumption is made that the spread in amplitudes due to noise at $p$ from $-X/2$ to $X/2$ in $A_{\text{TX,p}}$ is the same as at $p = 0$ mm, but with a different value of the mean. Therefore, a Gaussian distribution was assumed at each data point in $A_{\text{TX,p}}$, each with a mean equal to the reflection amplitude and with the spread equal to $\sigma_{b}$, as shown in Fig. 7a. This assumption is in line with literature on high SNR signals [43]. While running validation simulations, the authors found that at low signal to noise ratios this assumption will start to break-down but only when the reflection amplitude, $A_{\text{TX,p}}$, is much less than the noise level.

By summing the individual Gaussian distributions (Fig. 7b), the variability due to defect position is taken into account, giving the probability distribution of the continuous reflection amplitude variable, $A_{r}$, for a certain defect, $p(\text{reflection|defect})$, Fig. 7c.

$$p(\text{reflection|defect}) = \frac{1}{\sqrt{2\pi} \sigma_{b}} \int_{-X/2}^{X/2} e^{-\frac{(p-A_{r})^2}{2\sigma_{b}^2}} dp$$

The POD can then be calculated using Equation (4).

5.3. Mapping the probability space with probability images

The POD of a particular guided wave mode with a particular array or scan pitch can be displayed in an image format, as shown by way of an example in Fig. 8a. The POD has been plotted for all defects depths (1–5 mm) and defect diameters between 10 mm and 60 mm, with a measurement pitch of 50 mm and a noise level of 30 dB SNR. Therefore, each pixel in Fig. 8a is the POD from an individual simulation, producing a map of the probability space for defects of various depths and diameters. All probability images presented in the results section have been interpolated since this allows for easier visual interpretation of the data. The example Fig. 8b is a third order cubic recursive interpolation of Fig. 8a. The sensitivity of a particular pitch and mode can therefore be assessed quickly by evaluating the ‘sensitivity coverage’ of the probability image. That is, what proportion of the defects modelled are detectable using the particular setup (SNR, measurement pitch, propagation distance).

6. Probability of detecting wall thinning defects using circumferential guided wave modes in either transmission or reflection

Fig. 9 shows the probability images using reflections to detect Hann profile defects, with array or scan pitches of 10 mm, 50 mm, and 100 mm. Across all guided wave modes, as the pitch increases there is little effect on the POD at all defect dimensions. This is due to the defects acting almost like point scatterers with the reflected wave radiating in all directions.

The S0 mode has the highest sensitivity to the defect dimensions simulated in this study. Using 0.95 POD as a threshold, the S0 mode can detect defects with a minimum depth of $3.5$ mm and an associated diameter of $30$ mm as well as defects with a minimum diameter of $20$ mm and an associated depth of $5$ mm. The SH0 has less coverage however it does have a higher sensitivity to narrower defects, being able to detect $20 \times 4$ mm Hann profile defects with 0.95 POD. The A0 is unable to detect many defects and the only defect it can detect with POD $>0.5$ is the $20 \times 5$ mm defect. It is therefore excluded from any further analysis. Fig. 9 also shows that in reflection guided waves are sensitive to a
finite range of defects diameters. Reflections of any waves occur when there is a change in acoustic properties in a material. With a Hanning profile defect this effect is much more gradual than with either a step, notch or part thickness hole. For defects with large diameters the change in acoustic properties will be very gradual and as a consequence little energy will be reflected, thereby providing an upper bound to reflection sensitivity [15]. As the defect diameter shrinks the gradient in acoustic properties will become more pronounced (increasing the reflection amplitude). As the diameter shrinks further the defect size as a percentage of the beam width will become very small. At these defect sizes little energy will be incident from the defect, greatly reducing the amplitude of the reflected pulse.

The probability images for the transmission method using dispersive guided waves are shown in Fig. 10, for the S0 and SH1 guided wave modes with pitches of 10, 50 and 100 mm. As the pitch increases the sensitivity of both guided wave modes decrease, because more guided wave beam paths, which either pass through the thinner sections of the defect or miss the defect entirely, are incorporated into the calculation of the POD. The A0 mode is unable to detect any defect using the same criteria as the S0 and SH1 modes and is therefore not shown.

When comparing the two guided wave modes it is clear that the SH1 mode has a much higher sensitivity coverage than the S0 mode for the range of defects shown. The S0 modes is unable to detect any defect below 40 mm in diameter, whereas the SH1 can still detect defects of half that diameter. At defect depths below 1.5 mm, however, the SH1 mode is unable to detect any defect.

Fig. 10 also highlights the lower bound in sensitivity (in terms of defect diameter) for each guided wave mode.

6.1. Probability images normalising for defect diameter

It is important to note that each of the reflection probability images for S0 and SH0 modes have a similar shape, with each having a peak in sensitivity at 0.5–0.6 wavelengths, \( \lambda_{\text{eff}} \) (the wavelength at the toneburst centre frequency using the reflection input toneburst operating characteristics, S0 – 60 mm, SH0 – 36 mm). The contouring probability image, Fig. 11a, shows the equivalent of the S0 and SH0 10 mm pitch colour probability images but highlights lines of constant probability (in this case 0.5 and 0.95 POD). The defect diameter is expressed in terms of the wavelength at the input toneburst’s centre frequency. At depths of 5 mm both the modes are sensitive to 0.2\( \lambda_{\text{eff}} \) and 1.2\( \lambda_{\text{eff}} \) diameter defects at 0.5 POD. Fig. 11a further demonstrates that guided waves in reflection are only sensitive to a range of finite width defects (e.g. patches of corrosion). In general, these defects (relative to wavelength) can be classed as narrow and deep defects.

Fig. 11b shows contoured probability images for the through transmission detectability, with the defect diameter normalised to \( \lambda_{\text{trans}} \) (the wavelength at the toneburst centre frequency using the through transmission input toneburst operating characteristics, S0 – 25 mm, SH1 – 13 mm). The through transmission contours of the S0 or SH1 modes are comparable in shape, with either 0.5 or 0.95 POD. At diameters greater than 1.5\( \lambda_{\text{trans}} \) with 5 mm depth both modes are 95% sensitive (0.95 POD) to defects, whereas below that diameter there is no sensitivity. As the defect depth decreases the 0.5 and 0.95 POD contours for each mode follow the same trend. Both modes have a 0.95 POD at defect depths around 2 mm defects with 2.5–3\( \lambda_{\text{trans}} \) diameters. It is therefore possible to state that relative to wavelength, guided waves in transmission are suitable for detecting wide areas of wall thinning, either shallow or deep.

6.2. Design implications and discussion on the limitations of short range guided waves

Fig. 11 highlights the similarities in the sensitivity of the S0 and SH0/1 modes using either measurement method when the defect diameter is normalised for wavelength. It also shows the limits of sensitivity and differences of both measurement methods (reflection and transmission) as a function of wavelength.

Although the results in Fig. 11 suggest that one could optimise the setup by changing the wavelength to increase the sensitivity to a given defect, it is not that straightforward. That is because at different frequencies guided waves have different characteristics (especially dispersionseness and attenuation due to fluid loading) which will dramatically reduce the sensitivity for either measurement method.

Section 3 highlighted the considerations that must be made when choosing the most suitable operating characteristics and consequently the authors believe that the results presented here are close to the maximum sensitivity potential of short range guided waves, with a 6–8” pipe and 30 dB SNR.

Fig. 11 shows that through transmission detects wide, shallow defects, whereas reflection is better suited to detecting narrow deep defects. Even at a pitch of 10 mm neither method can detect narrow (<2\( \lambda_{\text{trans}} \)) and shallow defects (<2 mm). Therefore, by combining the results of the two measurement methods for either mode the maximum theoretical sensitivity of either the S0 or SH modes can be found. This is based on the assumption that it is possible to build a transducer able to generate both the input operating parameters optimised for either measurement method.

6.3. Increasing sensitivity through the data fusion of probability images

There are many possible ways to combine multiple data sets [45–47].
In this case the reflection (Fig. 9) and transmission (Fig. 10) probability image data sets were fused using a simple OR-logic gate method which takes the larger value of the commensurate data points from the two probability image data sets. The SH0 reflection data is combined with the SH1 through transmission data, forming a hybrid SH mode.

Fig. 12 shows the data fused probability images for Hann profile defects with scan pitches of 10, 50, and 100 mm with the S0 and SH hybrid modes. The A0 mode is not shown since in both reflection and through transmission its sensitivity to Hann profile defects is much less than the S0 and SH modes.

At 10 mm pitch the SH hybrid has a higher sensitivity coverage than the S0, due to the high sensitivity of the dispersive SH1 mode to thickness changes. This pitch is more representative of a rapid screening or inspection tool, such as in Fig. 1c, since only a single transducer would be required and could slowly scan a pipe axially. At larger pitches of 50 and 100 mm then sensitivity of the SH hybrid reduces significantly, and although the S0 does likewise the greater coverage of the S0 in reflection compensates for this loss. A monitoring setup would take advantage of these larger pitches, such as in Fig. 1b, because fewer sensors would be required, thereby reducing the cost and complexity of the overall system.

6.3.1. Comparison of data fusion results with long range guided waves

By way of comparison between short and long range guided waves (LRGWs) it is possible to convert the defect into a value of cross sectional area (CSA). When viewing a cross section of the pipe though the deepest part of the defect, the CSA is defined as the area removed by the defect as a percentage of the entire cross section of the pipe. LRGWs is an established screening technique whose physical implementation is tried and tested in the field. The LRGW setup also has the benefit of 100% coverage.

In Fig. 12 two contours which approximately bound the maximum sensitivity coverage of either modes are overlaid on the data fused probability images (S0 – 0.75% CSA, SH – 0.6% CSA).

Long range guided wave techniques have a quoted sensitivity in 2001 of 5% CSA [3], however, recent strides have lowered this value to as low as 0.5% [48] when monitoring an area for an extended period of time. The measurement methods presented in this study are relatively simple compared with the more advanced methods studied with LRGWs, therefore it is reasonable to assume that appreciable gains could be made by employing more advanced signal processing.

In the introduction several assumptions had to be made about the short range guided wave setups, shown in Fig. 1, regarding the operation of the transducers. Depending on the physical implementation of the setups this could potentially reduce the sensitivity of the system. If overcome, however, in specialist/select scenarios then the setups and techniques presented may provide a new and commercially viable way of monitoring or screening of pipeline corrosion.

7. Conclusion

The suitability and sensitivity of three circumferential guided wave modes for detecting wall thinning defects has been studied. The guided wave modes were evaluated using two measurement modalities: 1. using the reflected signal; and 2. using the through transmitted signal. The A0 mode was excluded early in the study as it had a much lower sensitivity compared with the other two modes.

The selected input characteristics where chosen for each guided wave mode to boost sensitivity in either transmission or reflection. Results for the SH1 mode showed that it was sensitive to a much greater range of defects than the S0 mode in transmission, whereas in reflection the S0 mode was able to detect a greater range of defects compared to the SH0 mode.

Once the defect diameter was normalised to wavelength the sensitivity coverage was effectively independent of the guided wave mode. It was shown that in reflection the guided wave modes are more sensitive to narrow and deep defects but over a finite range of diameters. This contrasts with the transmission results where guided waves are sensitive to wider defects (either shallow or deep) and only have a lower bound of sensitivity. Neither measurement modality could detect narrow and shallow defects using the setup described in this paper: propagation distance, 500 mm; nominal wall thickness, 10 mm; and SNR, 30 dB.

The guided wave operating frequency/wavelength is constrained by physical factors (such as dispersion, higher order mode cut-offs and fluid attenuation), which restricts the ability to frequency sweep and thereby...
design a system to be optimally sensitive to certain defect dimensions. The data fused SH hybrid results show a higher sensitivity to a wider range of defects at 10 mm pitches compared to the data fused SO mode results, whereas the SO mode has a higher sensitivity at pitches of 50 mm and 100 mm. At 10 mm pitch the sensitivity of the data fused short range guided waves have a limit of 0.6% CSA and 0.75% CSA for the SH hybrid and SO mode respectively. This is comparable with long range guided waves, which have a quoted sensitivity in monitoring mode of 0.5% CSA.

The results shown in this paper will aid the future design of a short range guided wave system, detailing the defects to which the guided waves are most sensitive as well as highlighting some of the design implications which must be considered.

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Appendix

Table 2

| Mode | Centre freq (kHz) | Bandwidth (FWHMkHz) (kHz) | Wavelength (mm) at centre freq. | Attenuation due to fluid loading (dB/m) |
|------|-------------------|----------------------------|---------------------------------|---------------------------------------|
| A0   | 50                | 45 kHz–55 kHz (20%)        | 40                              | 37                                    |
| S0   | 200               | 193 kHz–207 kHz (7.5%)     | 25                              | 29                                    |
| SH1  | 300               | 289 kHz–311 kHz (7.5%)     | 13                              | 4                                     |

References

[1] Howard R, Cegla F. On the probability of detecting wall thinning defects with dispersive circumferential guided waves. NDT E Int 2017;86:63–72. http://dx.doi.org/10.1016/j.ndteint.2016.11.011.
[2] Gajdacsi A, Cegla F. High accuracy wall thickness loss monitoring. AIP Conf Proc 2014;1581:1687–94. http://dx.doi.org/10.1063/1.4869026.
[3] Alleyne DN, Cawley P, Pavlovic B, Lowe MJS. Rapid, long range inspection of pipes using long range guided waves. NDT E Int 2001;35:169–74. http://dx.doi.org/10.1016/S0963-8695(01)004017-0.
[4] Luo W, Rose JL, Van Velsor JK, Avioli M, Spanner J. Circumferential guided waves for pitting-type corrosion imaging in inaccessible pipe-plates using lamb waves generated and detected by ultrasonic phased array probes. J Acoust Soc Am 2002;111:1165–72. http://dx.doi.org/10.1121/1.1488399.
[5] Fletcher S. Guided waves for power plant applications. Imperial College London; 2012.
[6] Luo W, Rose JL, Van Velstor JK, Avioli M, Spanner J. Circumferential guided waves for defect detection in coated pipe. AIP Conf Proc 2006;920(1):165–72. http://dx.doi.org/10.1063/1.2184525.
[7] Shivraj K, Balasubramaniam K, Krishnamurthy CV, Wadhwan R. Ultrasonic guided wave methodology for pipeline screening and extending into quantitative defect measurements. In: AIP Conf Proc, vol. 1706; 2016. http://dx.doi.org/10.1063/1.4940618.
[8] Cawley P, Pavlovic B, Lowe MJS. Rapid, long range inspection of pipes using long range guided waves. NDT E Int 2001;35:169–74. http://dx.doi.org/10.1016/S0963-8695(01)004017-0.
[9] Cawley P, Pavlovic B, Lowe MJS. Rapid, long range inspection of pipes using long range guided waves. NDT E Int 2001;35:169–74. http://dx.doi.org/10.1016/S0963-8695(01)004017-0.
[10] Fromme P, Sayir MB. Measurement of the scattering of a Lamb wave by a through hole in a plate. J Acoust Soc Am 2002;111:1165. http://dx.doi.org/10.1121/1.1488388.
[11] Shrivastav B, Xu L, Wu Y, Wei S. Modeling of circumferential SH guided waves in pipeline for axial cracking detection in ILI tools. Ultrasonics 2015;56:325–31. http://dx.doi.org/10.1016/j.ultras.2014.08.018.
[12] Musa P, Dzoule M, Skelton EA, Lowe MJS, Craster RV. On the use of absorbing layers to simulate the propagation of elastic waves in unbounded isotropic media using commercially available finite element packages. NDT E Int 2012;51:30–40. http://dx.doi.org/10.1016/j.ndteint.2012.04.001.
[13] Rajagopal P, Lowe MJS. Short range scattering of the fundamental shear horizontal guided wave mode normally incident at a through-thickness crack in an isotropic plate. J Acoust Soc Am 2007;122:1527. http://dx.doi.org/10.1121/1.2764472.
[14] Rajagopal P, Dzoule M, Skelton EA, Lowe MJS, Craster RV. On the use of absorbing layers to simulate the propagation of elastic waves in unbounded isotropic media using commercially available finite element packages. NDT E Int 2012;51:30–40. http://dx.doi.org/10.1016/j.ndteint.2012.04.001.
[15] Demma A, Cawley P, Lowe MJS. Scattering of the fundamental shear horizontal mode from steps and notches in plates. J Acoust Soc Am 2003;113:1880–91. http://dx.doi.org/10.1121/1.1564739.
[16] Schueller P, Simonetti F, Instanes G. Corrosion and erosion monitoring in plates and pipes using constant group velocity Lamb wave inspection. Ultrasonics 2014;54:1832–41. http://dx.doi.org/10.1016/j.ultras.2014.01.017.
[17] Olin BD, Meeker WQ. Applications of statistical methods to nondestructive evaluation. Technometrics 1996;38:95–112. http://dx.doi.org/10.1080/00401706.1996.10484451.
[18] Millard DB, Hedges V. Non-destructive evaluation system reliability assessment. 1999. http://dx.doi.org/10.1016/j.ndteint.2016.11.011.
[19] Ogilvy JA. Model for predicting ultrasonic pulse-echo probability of detection. NDT E Int 1993;26:19–29. http://dx.doi.org/10.1016/0963-8095(93)90016-V.
[20] Haapalainen J, Leskelä E. Probability of detection simulations for ultrasonic pulse-echo testing. In: Proc. 18th World Conf. Nondestr. Test. 2012. p. 16–20.
[21] Schoefs F. Risk analysis of structures in presence of stochastic fields of deterioration: flowchart for coupling inspection results and structural reliability. Third Int Forum Eng Decis Mak Forum 2007:12–5.
[41] Howard R, Cegla F. Monitoring thicknesses along a line using SH guided waves. In: AIP Conf Proc; 2015. p. 1706. http://dx.doi.org/10.1063/1.4940486.

[42] Rice SO. Mathematical analysis of random noise. Bell Syst Tech J 1944;23:282–332. http://dx.doi.org/10.1002/j.1538-7305.1944.tb00874.x.

[43] Durgin GD. Space-time wireless channels. Upper Saddle River, NJ: Prentice Hall Press; 2003.

[44] Talukdar KK. Estimation of the parameters of the Rice distribution. J Acoust Soc Am 1991;89:1193. http://dx.doi.org/10.1121/1.400532.

[45] Hall DL, Member S, Llinas J. An introduction to multisensor data fusion. Proc IEEE 1999;87:6–23. http://dx.doi.org/10.1109/5.554205.

[46] Horn D, Mayo WR. NDE reliability gains from combining eddy-current and ultrasonic testing. NDT E Int 2000;33:351–52. http://dx.doi.org/10.1016/S0963-8695(99)00058-4.

[47] Lu Y, Michaels J. Feature extraction and sensor fusion for ultrasonic structural health monitoring under changing environmental conditions. Sens J IEEE 2009;9:1462–71.

[48] Liu C, Dobson J, Cawley P. Practical ultrasonic damage monitoring on pipelines using component analysis methods. In: 19th World Conf. Non-destructive test; 2016.