The choice of ultrasonic inspection method for the detection of corrosion at inaccessible locations

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A R T I C L E   I N F O

Keywords:
Corrosion
Guided wave
Ultrasonic
Inaccessible locations
Defect sensitivity

A B S T R A C T

Inspection for corrosion and pitting defects in the petrochemical industry is vital and forms a significant fraction of the operating expenditure. Low frequency guided wave inspection is frequently employed as it gives large area coverage from a single transducer position. However, detection becomes problematic at inaccessible regions such as pipe supports or beyond T-joints since the low frequency guided waves produce a significant reflection from the feature itself, hence limiting the defect detectability of the method. This suggests testing at higher frequencies which helps to minimise the reflection from the feature and also improves the sensitivity to smaller defects. There are a number of guided wave and related techniques implemented for corrosion inspection including the S0 mode (at ∼ 1 MHz-mm), SH0 and SH1 modes (at ∼ 3 MHz-mm), CHIME, M-skip and Higher Order Mode Cluster (A1 mode at ∼ 18 MHz-mm). This paper presents a systematic analysis of the defect detection performance of each method with sharp and gradual defects, as well as their sensitivity to attenuative coatings, liquid loading, surface roughness and ability to test beyond features such as T-joints. It is shown by finite element analysis backed up by experiments that the A1 mode provides the best overall performance when dealing with surface features such as T-joints and coatings because of its low surface motion. Additionally a combination of two or more methods is suggested for corrosion inspection at inaccessible locations: The A1 mode in reflection for severe, sharp, pitting type defects; long range guided waves in reflection for large-area thinning and the SH1 mode in transmission for shallow, gradual defects.

1. Introduction

Detecting corrosion and pitting defects is vital in the petrochemical industry. These defects can occur at many locations in pipes and vessels and inspection and mitigation operations form a significant fraction of the operating expenditure [1]. When there is easy access to the locations of concern, spot ultrasonic thickness gauging can be employed, though this is very slow if a large number of locations must be tested. Guided wave inspection [2–9] allows large areas to be covered from a single transducer location and is commonly deployed on pipework. However, while it detects and locates damaged areas reliably, it does not give an accurate estimate of the maximum defect depth and is typically limited to detecting defects removing about 3–5% of the cross sectional area of the pipe, though this can be reduced in pipe that is in generally good condition, or if the system is permanently installed [10]. Unfortunately corrosion under pipe supports (CUPS) is problematic for guided wave inspection as at the low frequencies required to detect gradual wall thinning, the support itself gives a significant reflection [11–13], and the locations of concern are inaccessible for conventional ultrasonic thickness gauging. Similar issues arise when testing the floor of storage tanks from the small region of the floor protruding outside the tank wall. Also, deep defects with relatively small plan area are sometimes a concern as shown in Fig. 1a [14]. This suggests that it would be desirable to test at higher frequencies where the reflection from the support is negligible and sensitivity to smaller defects would be improved. Fig. 1b shows a typical pipe support involving pipework resting on a secondary structure. Corrosion and pitting are known to develop at the contact area between the support and the pipe which compromise the integrity of the structure; hence, establishing a reliable method for inspecting such regions is crucial.

There has been a number of guided wave and related techniques proposed to address these issues:

- S0 mode Lamb wave at ∼ 1.5 MHz-mm [15–17].
- SH0 and SH1 modes at ∼ 3 MHz-mm [18,19].
- Creeping Head-wave Inspection Method (CHIME) ∼ 20 MHz-mm [20,21].
- Multi-skip (M-skip) ∼ 20 MHz-mm [22–24].
Higher order mode cluster (HOMC) $\sim 18$ MHz-mm [25–28].

The operating points of the guided wave methods are shown on the dispersion curves for Lamb (Fig. 2a) and SH (Fig. 2b) waves. It is not clear from previous work which of these methods is the most appropriate in different circumstances. This paper undertakes a systematic analysis of their defect detection performance with sharp and gradual defects, and their sensitivity to attenuative coatings, liquid loading, surface roughness and ability to test beyond features such as T-joints. Most of the results are obtained analytically or with finite element simulations, key points being validated experimentally. Section 2 gives a brief description of each of the methods and the previous work done on them and section 3 then introduces the finite element analysis used to produce most of the results. Section 4 then studies the influence of different coatings, surface conditions etc. in turn on each of the inspection techniques, followed by an analysis of the sensitivity of the methods to different types of defect. The results with the most promising methods are validated experimentally in section 5 and the findings are summarised in Section 6, together with recommendations on the most appropriate method(s) in different circumstances.

2. Background to the inspection methods

The S0 mode Lamb wave at around 1 MHz-mm exhibits desirable properties such as being fairly non-dispersive at low frequencies and also for having a simple mode shape which provides roughly constant sensitivity to defects at different depths. Generic applications of the S0 mode for detecting various types of defect in pulse-echo and pitch-catch setups have been studied extensively [30–32]; however, the use of the method in more specific circumstances such as detection of CUPS is less well covered in the literature. Commercial users of this method include the Rosen Group [15] who employ electromagnetic acoustic transducers (EMATs) to inspect pipelines with limited accessibility e.g. at pipe supports; here various guided wave modes including S0 can be generated for optimal feature detection and in the case of pitting, for example, a 30% cross-sectional loss is reported to be the detection threshold for a probability of detection (POD) of 80%. Also Corrosion Inspection Technologies [16] use group velocity measurements of the S0 mode in transmission for CUPS monitoring in a guided wave to-mography configuration and claim a smallest detectable depth of 10% [17].

Shear horizontal (SH) guided waves at around 3 MHz-mm provide an alternative inspection method since they are unaffected by non-viscous liquid loading of the structure and in the case of the fundamental SH mode (SH0), non-dispersive inspection can be carried out. Similarly to the S0 mode, general application of SH waves for detecting different types of defect has been studied in depth [33–37], but the use of these waves for more specific applications such as corrosion detection in inaccessible regions is less well described. There is a number of commercial users of SH waves such as Sonomatic [18] who employ EMATs for thinner walled pipes (< 15 mm) to excite both the SH0 and SH1 modes. The SH0 mode is non-dispersive so its arrival time can be used to determine the ratio of distance travelled to the shear wave velocity; all the higher order modes have a lower group velocity than SH0 and their arrival times are used to estimate the average remnant thickness between the probes. Sonomatic claim that localised corrosion
at 20% depth is detectable [18]; however, this is greatly influenced by factors such as the surface condition, coating type/thickness and defect morphology. Another example is Innerspec [19] who employ EMATs in an automatic inspection system to scan for defects in the axial and circumferential directions; a transmission configuration is used for the circumferential scan which can use the excitation transducer to receive waves that have travelled around the pipe circumference, while reflection in a pulse-echo configuration is measured for axial scans. It is reported [19] that the system is able to detect corrosion damage with 20% and 30% wall loss in the axial and circumferential directions respectively.

One of the more specialised methods of corrosion testing with up to 1 m range is the Creeping Head-wave Inspection Method (CHIME) which uses a conventional setup of a piezoelectric transducer mounted on a wedge at the critical angle to produce surface creeping, head and bulk waves [20,38]. In order to satisfy the surface boundary conditions, creeping waves must continuously produce head-waves which reflect multiple times from the plate/pipe surfaces and on each reflection the head wave partially mode converts back to a creeping wave [20,39]. The received signal therefore consists of a series of peaks made of the original creeping wave followed by the second creeping wave which is generated by mode conversion of the head wave which has done one full skip and so on; this allows complete volume inspection of the waveguide as the presence of a defect or a thickness change alters the arrival time and/or amplitude of these peaks [20]. If, however, the structure boundaries are not parallel, the head wave to creeping wave mode conversion cannot occur which limits the application of this method to pipes whose outer/diameter ratio is less than 1.19 [20]. The separation of the bulk waves and the creeping/head waves is also strongly dependent on the thickness of the structure which is the reason why CHIME is usually employed on structures thicker than 12 mm [20]. Raverscroft et al. [20] applied this method to test for machined notches, isolated pits and general corrosion on a pipe and reported that a corrosion patch of 50 mm width and minimum wall loss of 23% is detectable. Sonomatic [21] use CHIME to inspect inaccessible regions such as pipe supports and claim that the method is able to qualitatively rank the depth of corrosion into categories of < 10%, 10%–40% and > 40% corrosion.

Other methods of corrosion inspection with up to 2 m range include multi-skip (M-skip) which uses piezoelectric transducers mounted on wedges with an angle larger than the first critical angle in a pitch-catch configuration to produce shear vertical waves that reflect multiple times between the structure boundaries without mode conversion [22]. This therefore allows the inspection of the complete volume between the transmitting and receiving probes as the arrival time of each skip depends on the separation distance of the probes and the thickness of the material; since the shear wave cannot mode convert to longitudinal waves, the signal losses are minimised, hence enabling larger probe separation [22]. However, the presence of a secondary feature on the surface of the plate/pipe, such as an attenuative coating, causes energy leakage when the shear wave is reflected from the corresponding surface which is why, to avoid a large number of surface skips, M-skip is mostly applied to structures thicker than 12 mm [22]. Also the reflection of the shear wave from a boundary is strongly dependent on the surface condition which as a result limits the application of this method to test structures with uneven boundaries [23]. Burch et al. [22] studied the performance of M-skip on pitting type defects and provided a comparison between CHIME and M-skip for naturally corroded pipe support testing. They concluded that while M-skip is able to estimate the average wall loss between the probes, the maximum depth of an area of varying wall loss cannot be indicated. Shell [23] used the M-skip method for clamped saddle support inspection and suggested that the method is more suited to detect local wall loss, while CHIME can be used to identify the degree of general thinning. Other commercial users of M-skip include Sonomatic [24] who employ the method to test for corrosion in inaccessible areas such as pipe supports and, by using B-scans, they are able to estimate the depth of localised flaws while in the case of general degradation, the average remaining wall thickness can be approximated.

Balasubramaniam et al. [25–28] [40–42], have introduced a technique that they call Higher Order Mode Cluster (HOMC) that uses a conventional piezoelectric transducer mounted on an angled wedge in order to generate higher order Lamb modes at around 20 MHz-mm which are claimed, due to their similar group velocities, to form a non-dispersive cluster. Apart from being non-dispersive, the excited Lamb waves have reduced surface sensitivity since at higher frequencies the surface motion of the relevant modes reduces [40] while the sensitivity to small diameter, deep pits is improved. The low surface motion makes HOMC insensitive to surface features such as T-joints or supports, as well as surface roughness and attenuative coatings. This method has been applied to cases such as pipe support inspection and the testing of the annular ring region of storage tanks from outside the tank wall [25,27,28]. It is reported [25] that HOMC is able to detect localised flaws along the axial direction of the pipe while its detectability is barely affected by the addition of a weld patch on top of the defects; it was also able to detect rectangular notches with 0.5 mm width and at least 20% depth as well as machined pinholes with 1.5 mm diameter [28]. Recently Khalili and Cawley have shown that the features of HOMC are essentially those of the A1 mode in this frequency-thickness regime [43].

The methods introduced in this section are assessed against different criteria in Section 4.

3. Finite element analysis

In order to assess the performance of each method against a number of different criteria, Finite Element (FE) analysis was used. FE was found to be a suitable tool because it allows a variety of complex shapes/defects to be considered which otherwise would be costly to investigate experimentally. In general a two-dimensional (2D) model of a plate was used to simulate the propagation of the excited wave and for the cases of the guided wave methods, a Fourier transform in space and time (2D FFT) [43,44] was employed to measure the parameters of interest such as attenuation, reflection and transmission coefficients whereas due to the nature of the bulk wave methods, these parameters were obtained via surface amplitude comparison recorded from the out-of-plane time traces. 2D analysis has been used throughout this paper because it captures most of the important physics and is much more efficient computationally than full 3D analysis. Use of 2D analysis means that the attenuation values reported do not include the effects of beam spreading that will affect the lower frequency techniques more than the higher ones. Also the effects of diffraction around small defects are not captured and this again will affect the lower frequency methods more severely.

The majority of the FE simulations were performed using the Pogo software package [45], an FE solver which runs on graphics cards to greatly reduce the required simulation time. Pogo does not currently permit mixing of elastic and acoustic elements so ABAQUS CAE was employed in a 2D plane strain configuration for the liquid loading cases. Fig. 3 shows the overall FE setup, where a 10 mm thick steel plate was created using CPE4R elements (linear elastic material properties were considered); suitable element sizes and time steps were applied according to the frequency regime of each method to maintain stability and accuracy [46]. The excitation setup was also tailored for each method; in the case of the S0 mode, the mode shape was excited along the cross-section of the plate to ensure minimal intrusion of the other modes, the excitation signal being a 150 kHz centre frequency, 5-cycle Hanning-windowed toneburst. A similar mode shape excitation technique was also used for the SH0 and SH1 mode methods at a higher centre frequency of 250 kHz and 300 kHz respectively. For the CHIME method, the excitation simulated a 1-inch transducer on a fluid coupled 27° PMMA wedge; this was achieved by phased out-of-plane point
forces on the top surface of the plate and the excitation signal in time was at 2.25 MHz centre frequency, 5-cycle Hanning-windowed toneburst. Although, as mentioned above, CHIME is best suited for structures thicker than 12 mm [20], the simulations presented here were on a 10 mm plate for consistency with the other methods. M-Skip was simulated using the same setup as for CHIME with a wedge angle of 45°; the A1 mode method (similar to HOMC) was simulated in a similar way but with a 60° wedge angle, while the excitation signal in time was a 1.8 MHz, 5-cycle Hanning-windowed toneburst.

As shown in Fig. 3 and 200 mm line scans were utilised on each side of the defective region to enable 2D FFT analysis; the amplitude obtained from the modal decomposition was used to determine the reflection and transmission coefficients for a given mode compared to an undamaged/free plate. For the liquid loading and surface coating cases the transmission coefficient determines the attenuation level.

Fig. 3 also shows the monitoring points being placed on the opposite surface of the plate relative to the excitation; this was done specifically for the A1 mode method to eliminate the presence of the Rayleigh wave which tends to dominate the response due to its high excitability. This does not affect the absolute amplitude of the modes of interest since they are equal on either surface. In practice, where the excitation is carried out using a fluid coupled wedge, the Rayleigh wave is damped by leakage into the wedge and is not seen in the received signals. This was verified in FE by analysing one case in which the excitation was applied to a wedge, rather than by simply applying surface tractions to the plate.

4. Results

4.1. Effect of liquids

In most cases of guided wave and bulk wave testing, the structure is assumed to be within a vacuum. This is a reasonable approximation if the surrounding medium has an acoustic impedance very different to that of the structure material such as a pipe in air and/or carrying a gas. However when dealing with liquid interaction, the material properties tend to be much closer and the energy leakage of the propagating sound wave into the surrounding liquid cannot be neglected as before. In this section the attenuation of each method is predicted in a liquid loaded structure to establish their suitability in such conditions.

In this paper water loading is considered; while liquids such as oil may result in different attenuation levels, the difference is expected to be minimal compared with the overall effects of liquid loading [47]. Attenuation levels of the guided wave methods were predicted analytically using the DISPERSE [29] software, while an FE model was developed in ABAQUS CAE to predict the energy leakage of the bulk wave methods (CHIME and M-skip) into the surrounding liquid. In both the analytical and numerical studies, a 10 mm steel plate was created and the vacuum boundary on one side of the plate was substituted with a half-space of water. In FE, the water boundary was generated using AC2D4R elements which are acoustic elements that do not support shear waves; these elements were appropriately tied to the surface of the plate and to mimic a semi-infinite space of water, Absorbing Layers using Increasing Damping (ALID) [48] elements were placed adjacent to the acoustic element layer to absorb the leaked energy and prevent it from re-entering the plate structure.

Table 1 shows the attenuation levels of each method at their respective centre frequencies. As expected the SW wave methods experience no energy leakage since the surrounding water layer cannot support shear waves. The A1 mode method exhibits relatively low attenuation compared with other Lamb wave methods such as the S0 mode; this is due to the low surface motion of the A1 mode at high frequency-thickness products as established previously [43]. The bulk wave methods performed particularly poorly as they rely on multiple boundary reflections for propagation, hence the condition of the surface and/or the presence of surface loading result in energy loss and scattering of the waves. The attenuation of CHIME was higher than that of M-skip since this method entails creeping waves propagating along the both surfaces of the plate that makes this method more susceptible to the presence of surface features.

4.2. Effect of coatings

In order to minimise corrosion, coatings are often used on pipe surfaces. Some of the materials used, such as bitumen, are highly attenuative and can cause significant damping of the propagating wave, so reducing the length of pipe that can be inspected from a given transducer position. In general this damping effect depends on the type of coating material and its thickness; however, since the coatings are sometimes applied manually there can also be variations in the coating thickness and the bonding between the surface and the coating [47].

In this study, bitumen coating was considered on one side of the plate-like structure in order to compare its damping effect for each method. Table 2 shows the bitumen material properties that were used in the analysis.

As with liquid loading, the attenuation levels of the guided wave methods were predicted analytically using the DISPERSE [29] software and the energy loss of the bulk wave methods were predicted using an FE model created in Pogo [45]. In both models, a 2 mm bitumen coating was placed on one side of a 10 mm steel plate. Table 3 shows the attenuation levels of each method at their...
Table 2
Properties of bitumen used in this study [47].

| Property          | Value |
|-------------------|-------|
| Density (kg/m³)   | 970   |
| Longitudinal Velocity (m/s) | 2200 |
| Shear Velocity (m/s)   | 700   |
| Longitudinal Attenuation (Np/λ) | 0.05 |
| Shear Attenuation (Np/λ)   | 0.50  |

Table 3
Predicted attenuation of each method in 10 mm thick steel plate due to presence of 2 mm bitumen coating; predictions obtained using DISPERSE [29] except where stated.

| Wave      | Centre Frequency (kHz) | Attenuation (dB/m) |
|-----------|------------------------|--------------------|
| S0        | 150                     | 2.6                |
| SH0       | 250                     | 19.2               |
| SH1       | 300                     | 27.6               |
| A1        | 1.8 MHz                 | 1.8                |
| CHIME     | 2.25 MHz                | 33.6 (FE)          |
| M-Skip    | 2.25 MHz                | 16.6 (FE)          |

respective centre frequencies. Unlike the liquid loading case, the SH wave methods experience much higher attenuation since the coating can support shear waves and exhibits relatively high shear attenuation; this energy loss is particularly high for the SH1 method due to the operating frequency being near a through-thickness resonance frequency of the bitumen layer (260 kHz) [49]. However, even at frequencies away from resonance, this mode experiences minimum attenuation of around 12 dB/m. The S0 method performs better as the coating provides lower longitudinal attenuation compared to the shear attenuation and the A1 method was the least affected by the coating as it exhibits very low surface motion that limits the energy leakage into the coating layer; as with liquid loading, the bulk wave methods show high attenuation.

4.3. Effect of rough surfaces

One of the often overlooked factors in ultrasonic inspection is rough surfaces due to general corrosion. It has been shown [50–54] that general corrosion of pipework can cause significant scattering of incident waves, resulting in higher background noise and also increased energy loss of the wave, limiting its inspection range. The signal to noise ratio is therefore decreased and the sensitivity of the method is reduced. Since it is often of interest to detect deep corrosion patches in the presence of modest generalised corrosion, the influence of shallow, general corrosion on the different methods is an important issue in selecting between them.

In this study, the effect of a 400 mm long section of rough surface on a 10 mm thick steel plate was investigated; the model was 2D so the surface simulated was a series of parallel troughs running normal to the plane of the elements. Fig. 4a shows the remnant thickness map of the rough surface; the profile was generated via a Gaussian distribution based on the parameters associated with a 30 year old generally corroded pipe sample that was obtained from industry in a previous investigation (normal distribution with a mean wall loss of 1.25 mm, standard deviation of 0.75 mm [50]). The surface grid was convolved with a Gaussian window that had a characteristic length equal to the correlation length of the surface roughness [50,54]. The correlation length, shown in Fig. 4b, is measured as the distance from the peak to the point at which the amplitude distribution drops to 1/e of the maximum. Fig. 4c illustrates the depth distribution of the simulated rough surface; the slight distortion of this distribution is because the depths less than zero were set to zero as the rough surface due to corrosion was modelled as thickness loss only. Further details of the generation of the surface are given in Ref. [50].

Table 4 shows the reflection and transmission coefficients for each method at their respective centre frequencies when interacting with the 400 mm rough surface described in Fig. 4a. All the guided wave methods show high transmission and low reflection coefficients; the SH1 mode at 300 kHz in the 10 mm thick plate is dispersive and so is very sensitive to thickness with high mode conversion explaining the low transmission coefficient compared to the SH0 mode. The bulk wave methods show minimal transmission past the rough surface as they require near-parallel boundaries to propagate. While some signal was transmitted, clear wave packets were not identifiable.

Other cases of rough surfaces with different correlation lengths and mean depths were investigated to check whether the results of Table 4 are generally representative of likely corrosion profiles. Similar results were found, though it was found that the reflection coefficient of the A1 mode was increased by any random outliers present in the profile with depths over 20% of the wall thickness; this would be expected from the mode shape [43] and is seen in the defect reflection results of section 4.5 below. The SH1 mode showed high sensitivity to the specific profile of the rough surface since it exhibits high motion close to the surface which in turn also makes it sensitive to shallow defects.

4.4. Inspection of T-Joints

It is often necessary to inspect for corrosion beyond a feature in the structure. For example, pipes are sometimes welded to supports at the two support ends and it is necessary to detect corrosion in the middle of the supported region. Likewise it is desirable to detect corrosion in an oil storage tank by propagating waves along the floor plate from outside the tank; in this case it is necessary to test beyond the location where the tank wall is welded to the floor plate. These generic cases were investigated by studying propagation past a T-joint comprising a horizontal 10 mm thick steel plate rigidly attached to a similar plate in the vertical direction as shown in Fig. 5. A 2D FFT was used to predict the reflection and transmission coefficients of the guided wave methods while for the bulk wave methods, amplitude ratios of reflected and transmitted waves to the incident wave were used.

Table 5 shows the reflection and transmission coefficients for each method at their respective centre frequencies when interacting with the T-joint described in Fig. 5. Apart from the A1 mode, the guided wave methods experience noticeable energy loss when propagating past the T-joint; The A1 mode at 18 MHz-mm exhibits minimal surface motion which allows negligible reflection from the T-joint and also reduces energy leakage to the structure. CHIME showed poor transmission past the T-joint as the surface creeping wave was scattered significantly by the feature so clear wave packets were not detectable. In the case of the M-skip, the performance was found to be very setup sensitive; parameters such as the separation distance between the excitation region and the T-joint and also the angle of excitation, determine the level of interaction of the propagating shear waves with the T-joint.

The results presented here are for a single geometry of T-joint. While the many other possible geometries will give somewhat different results, the key finding that the A1 mode is essentially unaffected will remain since its lack of sensitivity to additions at the surface is a result of its very low surface motion.

4.5. Inspection of sharp defects

The more common types of damage to the pipe include wide area gradual thickness loss and sharp pitting type defects. In this section, testing for sharp defects is considered. Interaction of generic, low frequency guided waves with localised sharp defects has been studied extensively [2–9] but in order to improve sensitivity to such discontinuities it is of interest to raise the frequency; however, testing in the frequency-thickness region where multiple modes can exist is less well understood. This section studies the performance of the guided wave methods when interacting with sharp defects; the bulk wave methods were not considered in this case because of the poor...
Fig. 4. Simulated rough surface using the moving average method showing a) the surface morphology; b) the autocorrelation length of the surface in the x-direction; c) the distribution of depths. Surface shown has a mean depth of 1.25 mm and a correlation length of 20 mm.

Table 4
Predicted reflection and transmission coefficients of each method obtained using 2D FFT in 10 mm thick steel plate with the 400 mm rough surface described in Fig. 4.

| Wave  | Centre Frequency | Reflection Coefficient | Transmission Coefficient |
|-------|------------------|------------------------|--------------------------|
| S0    | 150 kHz          | 0.01                   | 0.98                     |
| SH0   | 250 kHz          | < 0.01                 | 0.96                     |
| SH1   | 300 kHz          | 0.01                   | 0.83                     |
| A1    | 1.8 MHz          | 0.01                   | 0.88                     |
| CHIME | 2.25 MHz         | –                      | –                        |
| M-Skip| 2.25 MHz         | –                      | –                        |

Table 5
Reflection and transmission coefficients for each method through equal thickness (10 mm) T-joint interaction.

| Wave  | Centre Frequency | Reflection Coefficient | Transmission Coefficient |
|-------|------------------|------------------------|--------------------------|
| S0    | 150 kHz          | 0.1                    | 0.82                     |
| SH0   | 250 kHz          | 0.1                    | 0.89                     |
| SH1   | 300 kHz          | 0.21                   | 0.81                     |
| A1    | 1.8 MHz          | 0                      | 0.95                     |
| CHIME | 2.25 MHz         | 0                      | –                        |
| M-Skip| 2.25 MHz         | 0                      | 0.75                     |

Fig. 5. Schematic of the 2D FE setup for T-joint.
performance of CHIME on the criteria above and also the performance of M-skip, as explained before, is very setup sensitive and therefore difficult to quantify.

Firstly the sensitivity of each method to the depth of defect was investigated by predicting the reflection and transmission coefficients when interacting with crack depths of 1%-50%; these were modelled by disconnecting nodes in the FE mesh. Then the performance of each method was studied when the length of defect was introduced; here the rectangular notches were modelled by removing elements in the mesh and to understand the physics of each method, the length of the notch was changed as a function of their wavelength where the reflection and transmission coefficients were obtained using a 2D FFT. It should be noted that the wavelengths of the methods are very different, hence the absolute length of notch in Figs. 7 and 8 is different where wavelengths range between 2 mm for the A1 mode to 35 mm for the S0 mode.

Fig. 6a shows the reflection coefficients of the S0, SH0, SH1 and A1 modes against the crack depth. Here it is clear that the cracks under 10% deep are difficult to detect through reflection while the A1 mode, in particular, cannot detect defects with 20% or lower thickness loss due to its mode shape that exhibits low surface motion at 18 MHz-mm. The S0 and SH0 modes allow a more linear response to the crack depth since their mode shape displacements are relatively constant across the thickness of the structure.

Fig. 6b illustrates the corresponding transmission coefficients where the drop in transmission coefficient was due to a combination of energy loss through reflection and mode conversion in transmission.

As suggested by Fig. 6a and b, the reflection and transmission coefficients of all the guided wave methods tend to a similar value of about 50% for the 50% crack depth; this is likely to be due to the symmetric energy distribution of the guided wave modes about the thickness centre line of the waveguide which leads to the similar reflection and transmission coefficients.

Fig. 7a shows the reflection coefficient of the A1 mode against the notch length for depths of 20%-50%. As expected, the reflection coefficient was predicted to increase for deeper notches and it is also evident that for a given depth of notch its value remains relatively constant with the notch length meaning the detectability of the notch is independent of its lateral dimension. This behaviour is due to the significant mode conversion to higher order modes which minimises the interference effect as a result of reverberations within the notch area. This contrasts with the behaviour seen when the SH0 mode at low frequency interacts with rectangular notches. Here a sinusoidal variation in reflection coefficient is observed with a maximum when the notch length is a quarter wavelength and minimum at half wavelength; this is due to the constructive and destructive interference of reverberations of the SH0 mode in the notch length [9]. In the SH0 case at low frequency it is the only propagating mode so no mode conversion occurs; with the A1 mode at high frequency, extensive mode conversion can occur so there is no clear periodicity of reverberations.

Fig. 7b illustrates the transmission coefficient of the A1 mode against the notch length for depths of 20%-50%; here it is clear that the transmission coefficient reduces for longer notches. Through further investigation, it was found that when the incident A1 mode interacts with the step-down part of the notch, it partially mode converts to the Rayleigh mode which propagates along the base of the notch, so the transmitted A1 mode past the step-up part of the notch is formed by a combination of the remnant A1 mode and the mode conversion of the Rayleigh mode back to the A1 mode. As the notch becomes longer, the group velocity mismatch between the Rayleigh and A1 modes causes an interference effect which results in the reduction of the transmission coefficient recorded in this study.

Fig. 8a shows the reflection coefficient of the S0, SH0 and SH1 modes against the notch length at a fixed 30% depth. Here it is clear that the reflection coefficient of these modes varies significantly with the notch length because of the interference effect created through reverberations in the notch [9]; this can limit the detectability of the methods as the reflection coefficient is highly dependent on the lateral length of the notch meaning that at some lateral lengths, minimal reflection is obtained even from very deep defects. In this comparison, the reflection coefficient of the SH1 mode is generally larger than that of the other modes and comparable even at worst as this mode at 300 kHz in the 10 mm thick plate is highly dispersive and so is very sensitive to the thickness of the structure; this higher thickness sensitivity however causes stronger interference effects resulting in larger variation of the reflection coefficient with notch length.

Fig. 8b shows the corresponding transmission coefficients; here the S0 mode exhibits the highest transmission coefficient even compared with the SH0 mode since there is higher dissimilarity between the mode
shapes of the S0 and A0 modes than there is between the SH0 and SH1 modes which results in lower mode conversion and therefore higher transmission coefficient.

4.6. Inspection of gradual thinning

As mentioned above, corrosion patches sometimes involve wide area, gradual thickness loss which can significantly affect the performance of an inspection technique [11,12]. In this section, the interaction of each method with a large gradual defect is considered.

The defect was modelled as a 60 mm × 5 mm Hanning shaped notch in FE, shown in Fig. 9 and to study its effect on each method, the reflected and transmitted time traces were obtained with a setup similar to the excitation setup of the corresponding method; for instance, in the case of the A1 mode the reception with a 1-inch transducer on a fluid coupled 60° PMMA wedge (as used for excitation) was simulated by phased addition of out-of-plane surface displacements. Mode shape excitation was used for the S0, SH0 and SH1 modes, reception being done by summing the displacements across the cross-section weighted according to the corresponding mode shape.

Table 6 shows the reflection and transmission coefficients for the S0, SH0, SH1, A1 and M-skip methods. Here it is clear that all the guided

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![Graphs showing reflection and transmission coefficients for different methods at various notch depths and lengths.](image)

Fig. 7. 2D FE predictions of reflection (a) and transmission (b) coefficients of the A1 mode at different depths (20%-50%) and lengths (0 to 2\(\lambda\)) of notches (Points joined with straight lines to aid clarity). The reflection and transmission amplitudes obtained from experimental results in Fig. 12 are also included.

Fig. 8. 2D FE predictions of reflection (a) and transmission (b) coefficients of the other guided wave methods at a fixed notch depth of 30% and lengths (0 to 2\(\lambda\)) of notches in 10 mm thick plate. The results are for the following methods at their corresponding centre frequencies (fc): S0 at fc = 150 kHz (Blue), SH0 at fc = 250 kHz (Red), SH1 at fc = 300 kHz (Yellow). (Points joined with straight lines to aid clarity). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
wave approaches, apart from the SH1 mode, experience minimal reflection from the large Hann-shaped notch because the notch length (60 mm) is significantly larger than even the largest wavelength (32 mm for the S0 mode) \[11\]; this behaviour is due to the reflection coefficient being highly dependent on the wavelength of the propagating mode in the case of the fundamental torsional mode T(0,1) in pipes or SH0 in plates, the reflection was predicted to be minimal for Hann-shaped notches which are over 1.5λ long \[11\]. In transmission, due to the change in the remnant thickness of the structure, the guided wave methods all experienced mode conversion. The SH1 mode shows a significant reflection from the gradual defect as the remnant thickness is 50% at its lowest which is below the cut-off frequency-thickness product of this mode, resulting in the large reflection and reduced transmission recorded in this study. As explained before, the performance of the M-skip method is dependent on a number of factors; in this case, no reflection was recorded and the scattering of the angled shear waves from the gradual notch contained various guided wave modes and surface waves, so a very complex signal was obtained in transmission.

5. Experimental validation

In order to verify the FE predictions presented above, experimental measurements on a steel plate were carried out. For this section, the A1 and SH1 modes were chosen to establish their performance when testing for sharp notches at various depths as well as for wide-area gradual thinning by obtaining pulse-echo and pitch-catch time traces. The A1 mode was selected as it showed the best overall performance on the criteria above while its higher operating frequency improves the sensitivity to sharp, localised defects; in the case of the SH1 mode, it was considered to provide better detectability to shallower defects because of its dispersive nature while showing good performance on a number of criteria discussed above. It is noteworthy however that in practice, it is difficult to excite a pure SH1 mode at 3 MHz-mm, hence the test signal consists of both SH0 and SH1 modes.

5.1. Experimental setup

Fig. 10a illustrates the experimental setup for the SH modes when testing for 2-D 2 mm long sharp defects at depths of 10%–50% of the plate thickness which were machined on a 10 mm thick steel plate and Fig. 10b shows the setup for the A1 mode used to test a 2-D 60 mm x 5 mm Hann-shaped notch. Excitation for the A1 mode was performed at 1.8 MHz centre frequency with a 5-cycle Hanning-windowed toneburst via a 1-inch diameter 2.25 MHz centre frequency piezoelectric compression wave transducer (Panametrics A104S-RB) mounted on a gel coupled 60° PMMA wedge (\(c_L = 2710\) m/s, and \(\rho = 1188\) kg/m³ \[43\]); the excitation for the SH modes was carried out at 300 kHz centre frequency with a 5-cycle Hanning-windowed toneburst via single-loop SH wave EMATs \[55\] where the reflection was recorded via a separate EMAT placed around 250 mm after the excitation EMAT (as shown in Fig. 10a).

The toneburst was generated and amplified via a custom-built amplifier which was then fed into the transducer. To record the reflections from the defect, in the case of the A1 mode, the excitation transducer

### Table 6

| Wave  | Centre Frequency | Reflection Coefficient | Transmission Coefficient |
|-------|------------------|------------------------|--------------------------|
| S0    | 150 kHz          | 0.04                   | 0.99                     |
| SH0   | 250 kHz          | 0.01                   | 0.98                     |
| SH1   | 300 kHz          | 0.94                   | 0.14                     |
| A1    | 1.8 MHz          | 0                      | 0.99                     |
| M-Skip| 2.25 MHz         | –                      | 0.2                      |

Fig. 10. Schematic of the 2D FE setup for gradual thickness loss.
Fig. 11. (a) Experimental baseline SH signals at 3 MHz-mm on undamaged section of 10 mm thick steel plate; (b) predicted (red) and experimental (black) signals reflected from sharp notch 10% of plate thickness deep normalised to maximum amplitude in (a); (c) experimental signal as (b) for 20% deep notch; (d) as (c) for 30% deep notch; (e) as (c) for 40% deep notch; (f) as (b) for 50% deep notch. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
was positioned before the defect and used as a receiver in a pulse-echo configuration, while for the SH modes, a separate EMAT was employed after the excitation EMAT to record the reflections. To obtain the transmitted signals a second transducer similar to that for the excitation was placed after the defect and employed in a pitch-catch configuration. The signals received for both methods were amplified and then captured on a digital oscilloscope. In order to improve the SNR, 1000 averages were used when testing with the SH modes due to the lower amplitudes generated by the EMATs, while 10 averages or fewer were required for the A1 mode.

Table 7

Performance of the each inspection methods along with the long range guided wave methods (not covered in this paper) for the different areas investigated in this paper.

| Inspection method                  | Long range | S0/SH0 | S0  | SH0 | SH1 | A1  | M-Skip | CHIME |
|------------------------------------|------------|--------|-----|-----|-----|-----|--------|-------|
| Centre frequency × Nominal thickness (MHz-mm) | < 0.5      | 1.5    | 2.5 | 3   | 18  | 22.5| 22.5   |
| Effect of liquid loading           | Very low [29,56] | Average | Very low | Very low | Low | Very high | Very high |
| Effect of surface coatings         | Very low [29]  | Low    | Very high | Very high | Very low | Very high | Very high |
| Effect of rough surfaces           | Average [50]    | Average | Low | Average | Very low | Very high | Very high |
| Effect of T-joint/welded patch     | Very high [5,7]  | Average | Low | Average | Very low | Average | Very high |
| Sensitivity to sharp shallow defects | Very poor [9,30] | Average | Good | Very poor | Case dependent | – | – |
| Sensitivity to sharp severe defects | Good [9,30]      | Good | Average | Very good | Case dependent | – | – |
| Sensitivity to wide-area gradual thinning in reflection | Good [11,12] | Poor | Poor | Good* | Poor | Very poor | – |
| Sensitivity to wide-area gradual thinning in transmission | Poor [55]        | Average | Poor | Very good | Good | Poor | – |

Bold text indicates desirable performance; italic text indicates poor performance.

*When mode cut-off is possible.

- Not investigated due to poor performance on other factors.
5.2. Sharp notch results

The measured A1 mode reflection and transmission coefficients are shown alongside the FE predictions in Fig. 7 and show good agreement. The amplitudes were normalised to the transmitted wave that was obtained in a separate test on an undamaged section of the plate. As expected the reflection amplitude is shown to increase while the transmission amplitude decreases as the notch becomes deeper. Also as predicted by the FE results, the notches with 20% or lower thickness loss are difficult to detect through reflection due to the low surface motion of the A1 mode at 18 MHz-mm.

Fig. 11 illustrates the predicted (red) and experimental (black) reflection time traces for the SH modes when interacting with 2 mm long notches with depths of 10% (b), 20% (c), 30% (d), 40% (e) and 50% (f). It should be noted that the time traces were normalised to the incident wave (a) which was obtained separately on an undamaged section of the steel plate; the incident wave consists of both SH0 and SH1 modes since pure SH1 mode excitation is difficult to implement in practice in this frequency-thickness regime due to the proximity of the SH0 and SH1 modes at around 3 MHz-mm as shown in the dispersion curves of Fig. 2b. Therefore, additional FE simulations have been carried out to validate the experiments directly; these are shown as red coloured time traces in Fig. 11b and f for the shallowest (10%) and deepest (50%) notch cases respectively. The expected arrival time (at centre frequency) of each mode, generated through mode conversion of the incident modes, is indicated on Fig. 11c (The SH0-SH1 and SH1-SH0 frequency-thickness product of this mode as shown in Table 7. When testing for sharp but shallow defects, the SH1 mode is found to be the most suitable method because of its dispersive nature at around 3 MHz-mm which provides enhanced sensitivity to small thickness changes.

When inspecting for wide-area gradual thinning, low frequency guided waves offer higher detectability in reflection because of their longer wavelengths; detection in reflection can also be achieved with the SH1 mode for the cases when the remnant thickness is near the cut-off frequency-thickness product of this mode as shown in Table 7. The SH1 mode was also found to be suitable for detecting wide-area gradual thinning in transmission and it may be possible to obtain remnant thickness profiles of structures along a line [55], again because of the dispersive nature of this mode.

In addition to the performance, there are a number of limitations regarding the application of some of the methods which were not investigated in this paper. The excitation of a pure SH0 mode is not easy due to the presence of the SH0 mode and its relatively large wavelength at 3 MHz-mm. In the case of M-skip, the performance was found to be highly dependent on the number of surface "skips", hence in order to minimise the effect of surface features and increase the detectability of sharp defects, it was concluded to be more suited for inspecting thicker structures. Finally CHIME is often not practical for corrosion inspection at inaccessible locations as rough surfaces, welded patches and coatings are often present.

In conclusion, this paper recommends a combination of two or more methods when inspecting for corrosion at inaccessible locations such pipe supports. The A1 mode at around 20 MHz-mm in reflection should be used for severe, sharp, pitting-type defects; its short wavelength (~2 mm in a 10 mm thick plate) means that it is the only method among those studied that will be capable of detecting localised pitting where the defect diameter might be in the order of the pipe thickness [43]. Long range guided waves in reflection are most suitable for larger area thinning and the SH1 mode in transmission is particularly suitable for the detection of gradual, shallower defects, and can also be used in reflection over a range of defect morphologies.

6. Conclusions

The performance of the A1, S0, SH0, SH1, M-skip and CHIME inspection methods for detecting sharp and gradual defects was established via numerical predictions with selective experimental validation. The ability of the methods to cope with features such as liquid loading, surface coatings, rough surfaces and T-joints was also predicted via a mixture of analytical and numerical predictions. Table 7 summarises the performance of the methods along with the long range guided wave method that was not covered in this paper but has been extensively researched previously; desirable performance on each criterion is indicated with bold text.

When dealing with surface features such as liquid loading, coatings and welded T-joints, the A1 mode was very little affected due to its low surface motion at 18 MHz-mm and showed the best overall performance. The bulk wave methods (CHIME and M-skip) are predicted to perform poorly as they require multiple surface reflections to propagate so the presence of surface features has a significant effect.

With regards to the sharp defects, as suggested by Table 7, the A1 mode offers the best performance for inspecting severe (> 30%) thickness loss as it exhibits high spatial resolution because of its raised operating frequency and also, as shown by Fig. 7a, the detectability of the sharp notches is independent of their axial dimension which is in contrast to the other guided wave methods discussed in Table 7. When testing for sharp but shallow defects, the SH1 mode is found to be the most suitable method because of its dispersive nature at around 3 MHz-mm which provides enhanced sensitivity to small thickness changes.

When inspecting for wide-area gradual thinning, low frequency guided waves offer higher detectability in reflection because of their longer wavelengths; detection in reflection can also be achieved with the SH1 mode for the cases when the remnant thickness is near the cut-off frequency-thickness product of this mode as shown in Table 7. The SH1 mode was also found to be suitable for detecting wide-area gradual thinning in transmission and it may be possible to obtain remnant thickness profiles of structures along a line [55], again because of the dispersive nature of this mode.

In conclusion, this paper recommends a combination of two or more methods when inspecting for corrosion at inaccessible locations such pipe supports. The A1 mode at around 20 MHz-mm in reflection should be used for severe, sharp, pitting-type defects; its short wavelength (~2 mm in a 10 mm thick plate) means that it is the only method among those studied that will be capable of detecting localised pitting where the defect diameter might be in the order of the pipe thickness [43]. Long range guided waves in reflection are most suitable for larger area thinning and the SH1 mode in transmission is particularly suitable for the detection of gradual, shallower defects, and can also be used in reflection over a range of defect morphologies.

Acknowledgements

This research was partially supported by the UK research centre in non-destructive evaluation (RCNDE) through Engineering and Physical Sciences Research Council (EPSRC) grant no. (EP/L022125/1).

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