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ORIGINAL ARTICLE

Ultrasonic guided wave testing on pipeline corrosion detection using torsional T(0,1) guided waves

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ABSTRACT – Ultrasonic guided wave testing is used in rapid screening to detect, locate and classify corrosion defects. This non-destructive testing technique can perform wide-range inspection from a single point, thus reducing the time and effort required for NDT. However, the mode conversion phenomena and the dispersive nature of the guided waves make corrosion detection difficult. Hence, the parametric studies on the response signals of a T (0, 1) wave from pipe defects were presented in this paper. Firstly, a mathematical model of 6-inch schedule 40 pipes was developed. The corrosion profile of various geometries was then constructed on the outer surface of the pipeline by varying the circumferential length and depth. The numerical study was performed to analyse the characteristics of the response signals when a torsional guided wave impinges on the corroded pipelines. A five-cycle Hanning tone-burst signal with a central frequency of 30k Hz was used throughout the study. The results demonstrated that mode conversion to a flexural mode F (1, m) occurs when the stimulated T (0, 1) strikes non-symmetric defects. Nonetheless, as the circumferential extent of the corrosion increased, the response signals tended to behave symmetrically, and there was less mode conversion detected. Thus, the presence of flexural mode F (1, m) can be used as the criteria to distinguish symmetric and asymmetric faults. In addition, the results demonstrated that the reflection coefficients increase monotonically with the defect's depth due to the increases in the estimated cross-sectional area loss. As a result, a more significant proportion of the transmission wave was reflected. These findings serve as guidelines for on-site inspections. With the known speed of guided wave propagation, it is possible to precisely forecast the position of faults.

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INTRODUCTION

Corrosion is characterised as a destructive attack by the reaction to its environment. It possesses a prospective natural hazard involving the oil and gas industry [1]. The continuous extraction of hydrogen sulphide (H_2S), carbon dioxide (CO_2), and free water through the oil and gas pipeline make the pipeline's internal surfaces suffer from corrosion effects [2]. Corrosion results in material degradation, which leads to the loss of mechanical properties in ductility and impact strength. Over time, material loss, reduction in thickness, and even failure will ensue.

The pipeline is defined as one of the most secure energy transport methods. However, it is believed that these pipelines typically operate in harsh conditions. A long operating duration has increased the likelihood of corrosion in the pipeline. Because of its non-destructive characteristics, ultrasonic guided wave testing (UGWT), as depicted in Figure 1, has been widely used in pipeline corrosion detection. Besides thin plates, rods, and tubes, guided waves can propagate in multi-layered elements. In guided wave ultrasonic testing, the detection concept often relies on the wave's reflection when it impinges on a defect. Using a guided wave for corrosion inspection has the benefit that the structure may be inspected from a single probe position. Various analyses of reflection signals based on various corrosion profiles have been undertaken. However, the characterisation of corrosion profiles on T (0,1) reflection remains unsolved. There is a limited publication on the reflection coefficients of the T (0,1) guided wave mode when it impinges on corrosion profiles of different geometry, such as on different circumference extent and depths.

In UGWT, some specific excitation modes are sensitive to the type of defects in a well-defined structure. Thus, selecting the appropriate excitation mode was essential in obtaining reliable results. In [3], the excitation mode selection criteria for UGWT was established. The dispersion, attenuation, sensitivity, excitability, detectability, and mode selectivity were investigated in the study. The speed of a single test, the testing instrument's design, and the data interpretation difficulty must be considered to satisfy the practicality of implementing testing techniques.

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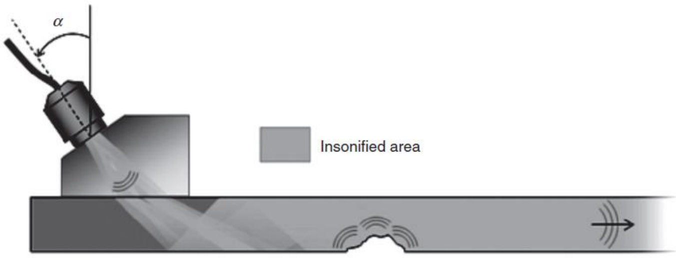


Figure 1. Ultrasonic testing: Guided wave testing [4]

The frequency of the transmitted guided waves is a vital parameter that must be calculated, as the smallest detectable defect size depends on the propagating guided waves' frequency. The guided waves sensitivity reduces as the frequency of the wave lowers. However, this effect is not always severe. Low-frequency guided waves are chosen for testing long pipes because of their low attenuation and longer propagation distance [5]. Besides, excessive unwanted modes will be introduced if the high-frequency wave is used. Fundamental modes such as T (0,1) and L (0,2) are frequently used for corrosion or fault identification because of their non-dispersive behaviour over a wide frequency range [3]. Non-dispersive behaviour denotes that the waves travel in a pipe at a constant velocity and that their phase velocity is insensitive to the wave number. This technology has several drawbacks due primarily to the usage of many modes concurrently with the principal mode, despite its extensive use in industry. Numerous studies have been undertaken, and the T (0,1) and L (0,2) modes have been used to mimic a vast array of potential faults [5-10]. The signal reflections were evaluated to determine the effectiveness of T (0,1) and L (0,2) modes in defect detection. The experimental results showed that the response of different wave modes interacts with defects, justifying the use of both modes to characterise the flaw.

The guided wave experiment was conducted on an internal water-flowing pipeline [6]. During the investigation, UGWT was performed in L (0,2) and T (0,1) modes, and the results showed that the L (0,2) mode had a low signal to noise ratio, resulting in a low sensitivity in corrosion detection. In addition, there was a tendency for misleading signals to develop due to a natural occurrence known as the double mode conversion phenomenon, which created additional echoes. The longitudinal mode testing revealed more significant amounts of coherent noise in the reflected signals compared to the torsional mode testing. The low signal-to-noise ratio generated spurious signals that could be misinterpreted as flaws, or the actual defects could be missed. In identifying pipe corrosion, longitudinal and torsional testing modes were adopted to achieve greater sensitivity.

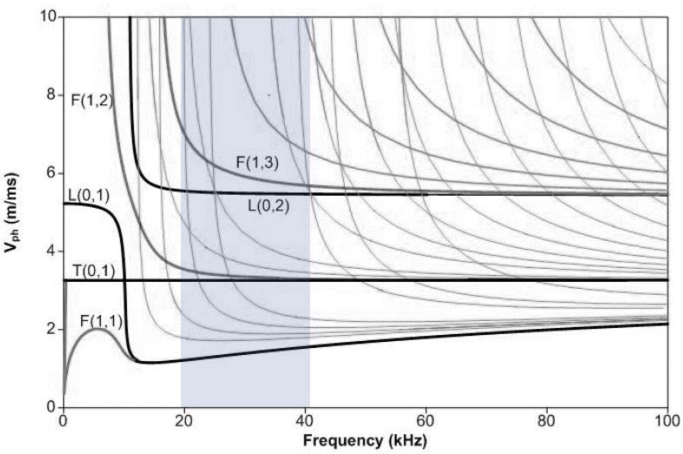
Nevertheless, this is often impractical, and if one relies on the testing findings in the torsional mode, testing in the L(0,2) mode is unnecessary. If both techniques exhibit the same sensitivity to defects and false alarm rates, a second pipe examination can be conducted. False signals can be embedded in the pipe by exciting the torsional guided wave from the pipe's edges. The erroneous defect call rate can be significantly lowered by comparing the two outcomes.

In general, the wave velocity of a guided wave is dispersive. Frequency variations will alter the mode shape, group and phase velocity. Therefore, a dispersion curve is necessary for determining the wave mode and frequency of excitation. The curve shows the correlation between frequency, mode shapes, group and phase velocities, and pipe wall thickness. The hollow cylinder dispersion curve was initially calculated by Gazis [11]. Since then, significant research has been undertaken to validate Gazis's theory. The solution of the frequency equation is retrieved as dispersion curves from the three-dimensional representation of the frequency equation to be an alternate way of visualising dispersion curves [12]. First, the real roots of the frequency equation are displayed in three dimensions, followed by the generation of dispersion curves using a suitable velocity–frequency plane cut. This method's merits include its simplicity, quickness, limited possibility for numerical inaccuracy, and presenting of data in a graphical format that facilitates interpretation. This method is not immediately applicable to problems involving solid damping or leaking waves. If the damping is not excessive, it may be a reasonable estimation of the precise dispersion curves.

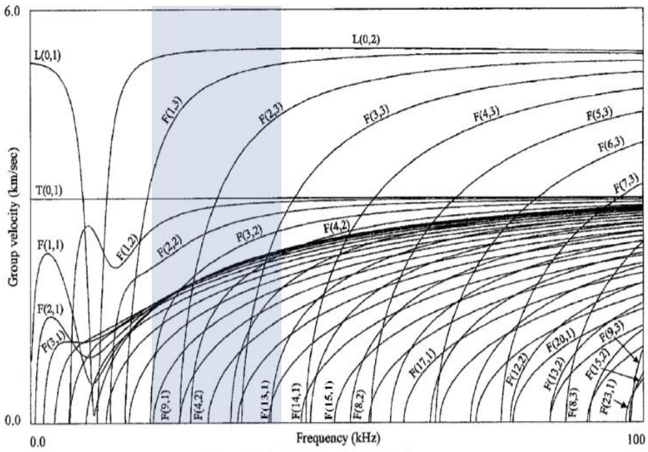
The properties of guided waves, including phase velocity, group velocity, attenuation, and wave structure, were illustrated using dispersion curves. Figure 2 depicts the dispersion curves for a 6-inch steel pipe. The phase velocity is the velocity of the wave packet's distinct peaks. In contrast, the group velocity is the frequency at which a guided wave packet moves. The phase velocity dispersion curves are crucial for selecting the optimal exciting mode. In addition, the group velocity dispersion curves were necessary for interpreting the reception modes in numerical simulations and experimental approaches [13].

An effective reflection of an ultrasonic guided wave requires reflectors with diameters equal to or greater than the wavelengths. Therefore, the higher the wave frequency, the greater the ultrasonic detection sensitivity. However, the high-frequency wave will cause a significant attenuation rate [14]. The ultrasonic guided wave examination reveals cross-sectional area (CSA) losses along a pipe's perimeter where it can scan the pipeline thoroughly. The pipe's CSA loss percentage depends on the geometrical features of the fault. Distinct reflection signals are expected when a wave interferes with defects of varied parameters, such as depth.

The reflection of the notches using the L (0,2) mode was first analysed by Alleyne et al. [15]. The reflection amplitude for various notch depths and circumferential lengths was studied. The results showed that the reflection coefficient in this mode is approximately a linear function of the notch's circumferential extent. The ratio of the through-thickness depth of the notch to the pipe wall thickness is of greater importance. The detection sensitivity is improved when the notch depth surpasses fifty percent of the wall thickness.



(a) Phase velocity dispersion curve



(b) Group velocity dispersion curve

Figure 2. Dispersion curves for 6-inch steel pipe [16]

Demma et al. [7] experimentally determined reflection coefficients from fractures and notches of varied depth, circumferential and axial extent when the T (0,1) mode travels through the pipe. The crack-like defects with various axial extents were modelled in the studies. This research concluded that asymmetric crack's reflection coefficients (RC) increase significantly with depth regardless of the signal frequencies. The RC value increases linearly with the increase of the circumferential extent of the defects. The experiment's findings revealed a crucial phenomenon where the reflection from axial defects was smaller than the reflection from circumferential defects.

The T (0,1) mode reflection from the axial defect on the pipe was discovered to be a series of wave pulses with progressively decreasing amplitudes based on computational analysis and experimental validation [17]. The phenomenon was caused by the distinct echoes resulting from the shear wave diffraction and repeated circumferential propagation. The reflection coefficient initially increases with the crack's length at all frequencies but soon approaches an oscillating regime. Due to the weak reflection from the axial defect, a focusing technique was used to boost the axially aligned defect reflection coefficients [18]. The wave focusing technique boosts the axial defect's reflection amplitude by two to four times, especially for through-thickness defects. Although the reflection amplitudes have increased, the sensitivity problem in identifying axial cracks remains unresolved since the signal amplitudes are too small to be recognised.

The research on ultrasonic-guided waves' characteristics has only been done for a defect with relatively simple geometry [15]. However, the question of determining the size of actual corrosion defects using ultrasonic guided waves remains unresolved because of the unpredictability of corrosion profiles. In lieu of reproducing defects with simple geometries such as notches, an experimental analysis of the reflection of the principal torsional mode T (0,1) from symmetrical defects using tapered notches was conducted [8]. The gradually fluctuating depth of the tapered defects revealed various tapered profiles. Wave reflection occurs at both ends of the taper. The tapered step's total RC is inconsistent due to the interference of the waves reflected from both sides of the defect. The results also indicated that the defect with a steeper taper improves the reflection coefficient. The effect becomes more prominent as the average defect length to wavelength ratio increases.

Localised corrosion is a severe attack that typically manifests as clusters of pits in the oil and gas industry [19]. Pits exist in various physical geometries, so their appearance is unpredictable. In order to examine the scattering behaviour of several randomly spaced defects, a model of localised corrosion was developed. A few small holes were drilled artificially in the pipe's circumferential and axial directions. The results showed that the reflection coefficient (RC) of the T (0,1) mode depends on the axial separation between pits.

A numerical simulation and experiment were conducted to investigate guided wave pipeline corrosion propagation [20]. Three levels of general corrosion were modelled, and the guided wave's interaction with various corrosion types was investigated experimentally. The general corrosion depth was observed to be proportional to the coherence noise generated and the guided wave rate of attenuation. A higher frequency decreases coherent noise for the same level of general corrosion. In parallel, the propagating guided wave's energy was lowered, resulting in a shorter testing range. Between the regions of the simulated deficiencies, two welds were incorporated. The results were qualitative because the reflected echoes from the welds and corrosions could not be distinguished. There was a significant congruence between the qualitative outcomes of numerical simulations and site inspections. For sequential detection of the ultrasonic guided wave, abrupt changes in the pipes' CSA were necessary, as the reflection coefficient increased with the depth of the defect.

Several experiments have been undertaken to study the effect of carbon steel pipe coating on the sensitivity of the guided wave in defect detection [21]. Three coatings for corrosion protection were evaluated: coal tar enamel (TGF-3), coal tar epoxy, and polythene-type coating (PRITEC). The 10 kHz wave exhibited significant attenuation on the coated surface regardless of the coating type. At a temperature of -7 degrees Celsius, the wave attenuation on the coated pipes was significantly reduced, allowing for a more precise differentiation of the coating layers and the corrosion over a vast area, enhancing the detection's precision.

The wave dispersion in coated pipes because of asymmetric defects was computed with a computational model [10]. Within the frequency range of 20 kHz - 120 kHz, the longitudinal L (0,1) modes have less attenuation than the torsional T (0,1) modes. The energy velocity of modes in coated pipes is comparable to that of equivalent modes in uncoated pipes. According to the results, the addition of the coating layer has no effect on the dispersion levels. When a defect scatters an incident wave, it was showed that the coating has no effect on the mode conversion compared to an uncoated pipe. Despite the benefit of screening a long pipe from a single faraway location, finding general corrosion remained challenging. General corrosion naturally affects a broader surface area but does not result in high CSA losses. As a result, the flaw's reflection signals were negligible, and the propagating wave may have missed widespread corrosion because it does not produce observable reflections in the recorded waveforms [7]. The energy of the guided wave will be reduced if corrosion is present, and the attenuation level can characterise the extent of corrosion. However, the increase in wave attenuation was also influenced by additional factors.

A laboratory experiment examined the attenuation characteristics of guided wave propagation in a buried pipe [22]. Two fundamental modes of torsional, T (0,1) and longitudinal, L (0,2) guided waves, were applied for different sand conditions, including loose, compacted, mechanically compacted, water-saturated, and drained sand. The results showed that the overburden pressure on the sand further increases the attenuation level. Both mechanically compacted sand and sand subjected to overburden pressure exhibit comparable attenuation. In sand completely saturated with water, the lower attenuation was recorded. However, the attenuation recorded in the dry and compacted sand is similar, which is relatively higher than in the sand completely saturated with water. In addition, when exposed to varied sand physical conditions, the T (0,1) mode exhibited more significant attenuation than the L (0,2) mode. Because of the considerable attenuation of the UGWT wave in underground pipelines, the test range was diminished. This attenuation was caused by energy dissipation into the embedding soil whenever the pipes directly interacted with the ground.

The wave attenuation in a pipe coated with fusion-bonded epoxy (FBE) and buried in loose and compacted sand was studied [23]. Polyethylene foam was coated onto the pipe as an ultrasonic isolation layer to limit energy loss in the sand. This low impedance coating successfully reduced the buried pipe's ultrasonic energy loss. This enhancement significantly increased UGWT's test ranges. In addition, the coatings applied to the pipelines might serve as a corrosion barrier to safeguard the pipeline.The above studies reveal that corrosion results in material degradation, which leads to the loss of mechanical properties in ductility and impact strength. Over time, material loss, reduction in thickness, and even failure will ensue. The corrosion will eventually lead to downtime and an increase in the cost of dealing with this issue. The critical consequence of corrosion has become a concern globally. This calls for the need to analyse the T (0,1) guided wave response signal in various pipeline corrosion profiles to predict the location of the corrosion. Hence, the objectives of this paper are to analyse the T (0,1) guided wave response signal in various pipeline corrosion profiles and to predict the location of the corrosion based on the pulse-echo guided wave inspection method.

MODELLING

As depicted in Figure 3, ANSYS software was used to construct a 6-inch Schedule 40 steel pipe model with a 2-meter length. The pipe has an outer diameter of 168 mm and an inner diameter of 154 mm, with Young Modulus of 216.9 GPa, density of 7932 kg/m^3, and Poisson ratio of 0.2865. As shown in Figure 4, a rectangular notch was created on the pipeline's outside surface to reflect the pipe surface's corrosion profiles. The dimensions of a corrosion defect can be described with axial length (a), depth (b), and circumferential extent (c).

The meshing procedure was carried out using the calculated element size so that the element size was less than 5% of the wavelength, λ [23]. The pipe was modelled along its axial length using 10-mm-diameter elements in this study. There were sixty elements around the circular and seven elements through the 7 mm thickness of the wall. The time step was set to one second. The T (0, 1) mode was actuated simultaneously at all nodes along the pipe end's outer circumference. A 5-cycle Hanning-window tone burst with centre frequency of 30 kHz was used. For pure torsional mode excitation, the circumferential segment of the pipe was divided into sixty elements around the circumference of the pipe's end. The

Implicit Newmark time integration method in ANSYS was used to analyse the transient responses. Using the mode extraction approach, the response signals were splited into single-mode waveforms to calculate the torsional mode, T (0, 1), and the flexural modes, F (1, m) amplitudes. Since the T (0, 1) wave is an asymmetric mode, the particles vibrate circumferentially. Excitation of guided waves in the cylindrical pipeline was applied to the 60 nodes on the outer diameter of the pipeline as a displacement loads of. In order to minimise the bandwidth of the excitation signals, 5-cycle Tone-burst signals were used instead of single-pulse signals. The single-pulse signal could potentially excite other undesired modes. The Hanning window was used since it decreased the undesirable peaks on the sides and boosted the energy level of the core frequency. The time-domain data were then extracted to analyse the wave response reflected from the defects after the model validation [24].

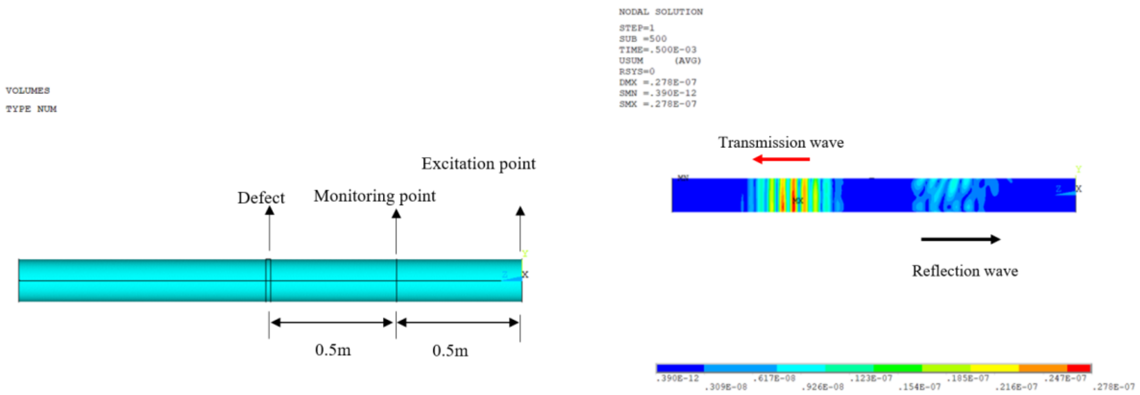


Figure 3. Guided wave defect detection model

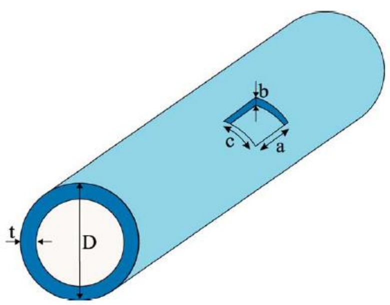


Figure 4. Geometrical parameters for pipe and defect size [9]

In some instances, a pipeline may contain several flaws. As depicted in Figure 5, two identical faults were created along the surface of the pipeline to examine the propensity of guided waves to detect numerous defects. The fault size is 25 per cent of the pipe's circumferential extent, and its depth is half of the pipe's thickness, which is 3.5mm.

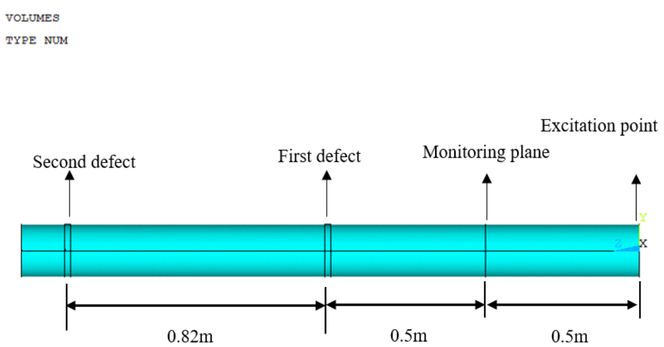


Figure 5. Model for two defects detection

RESULTS AND DISCUSSION

Defect Location Positioning

Figure 6 shows the time-response signal of a torsional mode T (0,1) propagated in a pipe with pre-define corrosion. A 5-cycle Hanning-window tone burst of 30 kHz central frequency was applied. Only one reflection wave packet is recorded 0.5 microseconds after the incident wave is recorded on the monitoring plane. This reflection wave indicated the presence of the defect on the pipe surface. The location of the defect can be estimated at the wave propagation speed of 3260 m/s and frequency of 30 kHz [22]. Based on the calculation, the defect was predicted at 0.49 m away from the monitoring plane when the actual distance was 0.5m with a small percentage error. This method can precisely determine the defect's location without a full-length inspection.

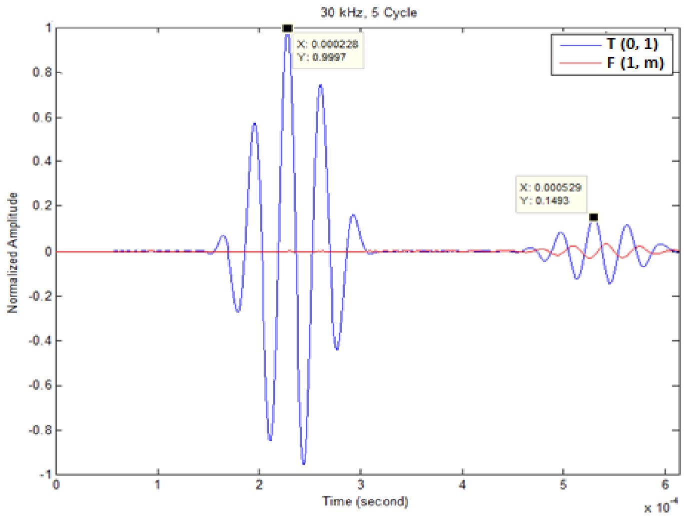


Figure 6. Corresponding simulation time of each wave packets

Effect of Corrosion Circumferential Extent on the Reflection Signal

Figure 7 shows the time responses of the incident wave and the response wave from the defect when a 30 kHz T (0, 1) wave propagates on the pipe with varying corrosion's circumferential extent, *C* and constant defect depth, 3.5mm (50 per cent of the wall thickness). The circumferential extent of the corrosion, *C*, is set to 25, 50, 75 and 100%, respectively, while the corrosion depth remains constant. The blue line represents the torsional mode, while the red represents the flexural mode. Based on Figure 7(a), when the circumferential extent of the corrosion is 25%, the incident wave is recorded at 1.5 – 3 seconds with the maximum normalised amplitude of 1. In contrast, the reflected wave is recorded at 4.5 to 6 seconds with the maximum normalised amplitude of 0.149. The flexural wave is detected in the deflected wave with an amplitude of 0.034. This result shows that the incident mode T (0,1) has partially converted to flexural mode F (1, m). The mode conversion is due to the reflection from the assymmetric crack. While the reflected waves only comprise scattered waves, the transmitted wave is a superposition of incident and dispersed waves. Therefore, it makes the transmission signal is significantly greater than the reflected wave from the corrosion.

The reflection coefficients of various circumferential extend of corrosion, and the flexural to torsional mode amplitude ratio F/T ratio, are shown in Figure 8 and tabulated in Table 1. The results also show that the T (0,1) reflected wave has a higher amplitude with the increase of the circumferential extent. However, the reflection coefficient for the flexural mode F (1, m) reaches the maximum value at C = 50% and decreases gradually to 0 at C = 100%. The results show an excellent agreement with the peer-published results [25]. The existence of the flexural mode indicated the presence of a non-symmetric feature, such as corrosion. This phenomenon is essential for distinguishing between a localised corrosion defect (typically non-symmetric) and a weld or connection, which are generally symmetrical. The flexural to torsional mode amplitude ratio (F/T) can be a valuable indicator for predicting the corrosion's circumferential extent and reducing the false detection on weld and connection.

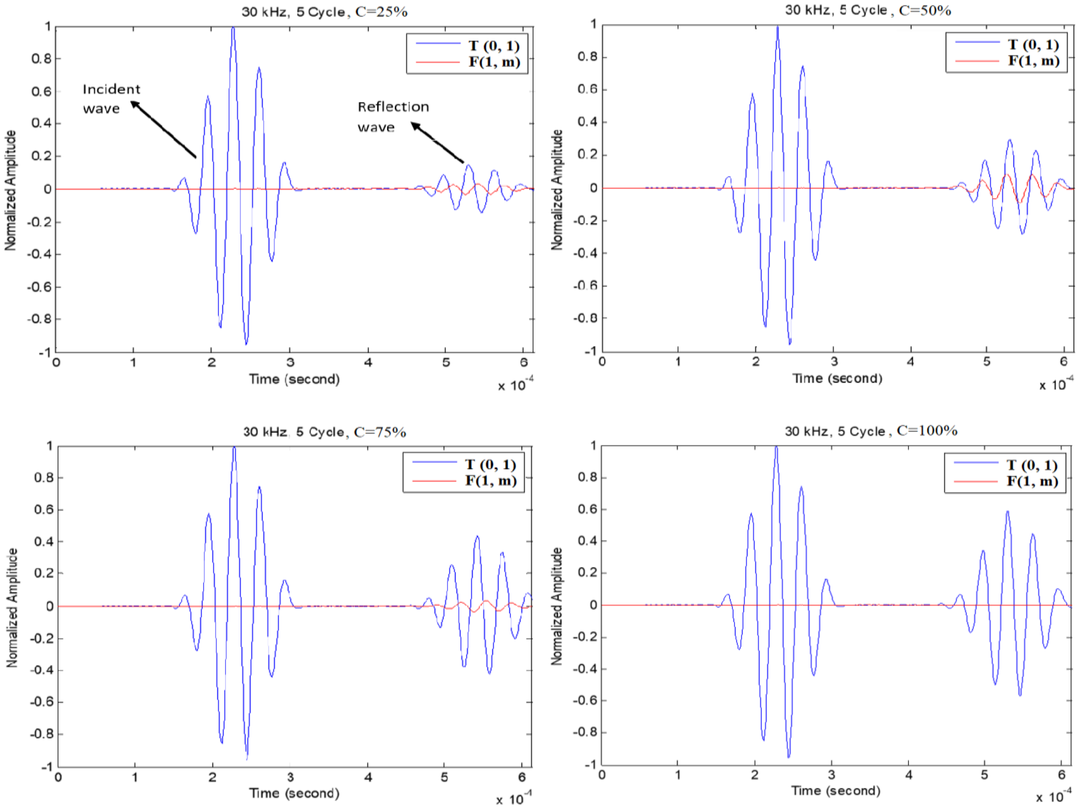


Figure 7. Guided wave and reflection signal from various corrosion circumferential extent

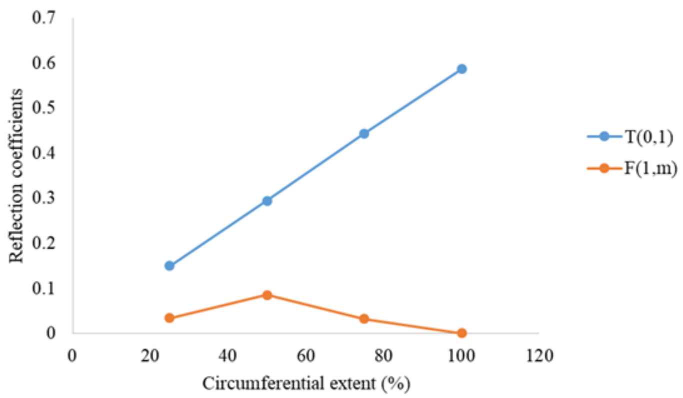


Figure 8. Graph of reflection coefficients of reflection wave against the circumferential extent

Table 1. Reflection coefficients of various circumferential extend of corrosion when the corrosion depth is 3.5mm

Circumferential Extent (%)	Reflection Coefficient		F/T Ratio	Estimated cross-sectional area loss (ECL)
	Flexural F (1,2)	Torsional T(0,1)		
25	0.034	0.149	0.226	12.77%
50	0.086	0.294	0.291	25.54%
75	0.032	0.444	0.072	38.31%
100	0.000	0.586	0.000	51.09%

Effect of Corrosion Depth on the Reflection Signal

Figure 9 shows the guided wave and its reflection signal at varying corrosion depths b while a 30 kHz T (0, 1) wave propagates on the pipe. The perimeter extent of corrosion is unchanged at 25%. For all values of b, the reflected signal appears as the combination of the torsional T (0, 1) and flexural F (1, m) modes. The T (0,1) and F (1, m) waves grow as the corrosion depth increases. The coefficient of wave reflection is reported in Table 2. The reflection coefficients (RC) obtained are dimensionless and calculated as a peak-to-normalised-amplitude ratio. With increasing depth, the reflection coefficients increase monotonically. Although the amplitudes of reflection waves for both modes grew, it was noted that the T(0,1) mode had a greater amplitude than the flexural mode F (0, m). The result reveals that, although mode conversion happened, the propagating wave mode continued to dominate the torsional T (0, 1). The F/T ratio increases with crack depth showing that larger amonut of wave energy is transferred to flexural mode.

The data also indicate that the maximum reflection coefficients for a notch with a circumferential extent of 25% are within 0.3, in contrast to the highest RC measured at 0.586 when the circumferential extent was 100%, and the depth was 50%. (3.5mm). Although the RC value was frequently a function of the ECL, additional characteristics that composed the ECL must be considered. Since it is typically narrow, a relatively low reflection coefficient is anticipated. Therefore, if the wave impacting a crack-like defect has a minimal circumferential extent but is densely localised, the wave's reflection coefficient is relatively low.

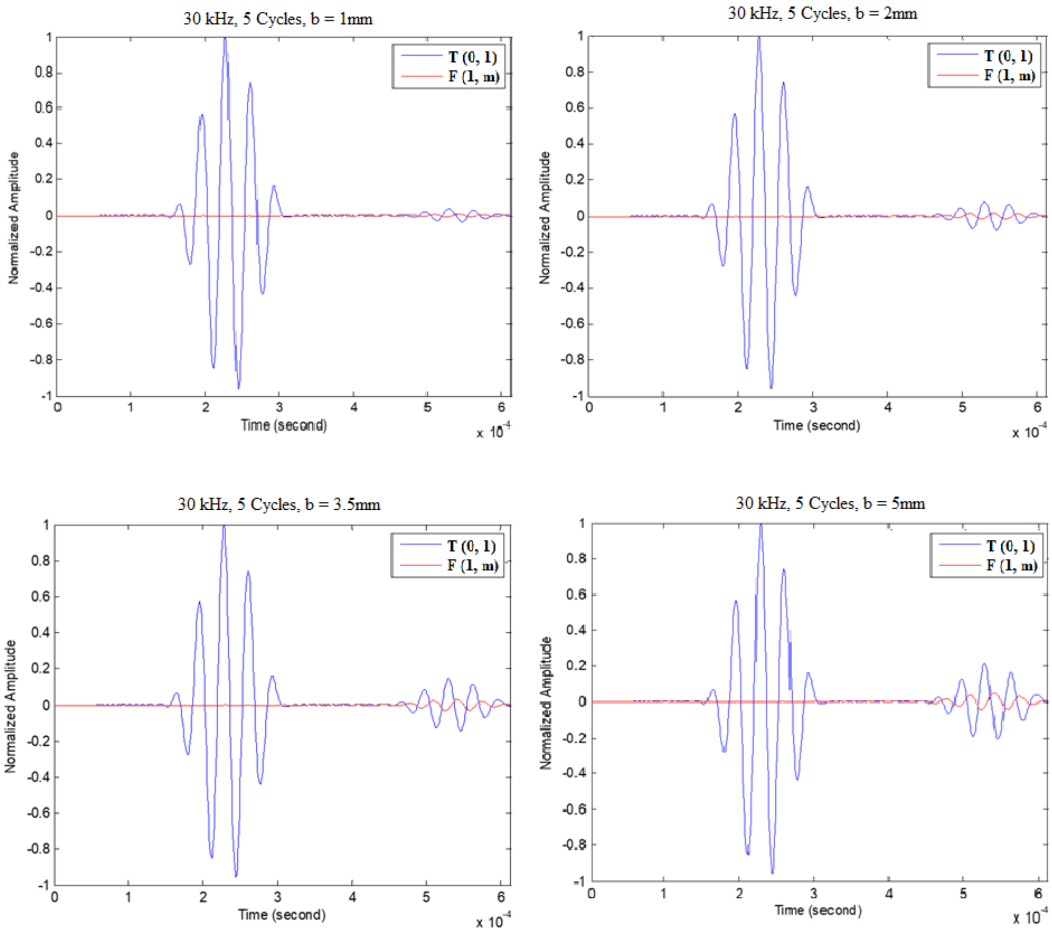


Figure 9. Graph of guided wave and reflection signal from various corrosion depths

Table 2. Reflection coefficients of various corrosion depths with circumference extent of 25%

Depth, *b* (mm)	Reflection Coefficient		Ratio of F/T	Estimated cross-sectional area loss (ECL)
	Flexural F(1,2)	Torsional T(0,1)		
0.0	0	0	0	0
1.0	0.008	0.034	0.235	3.70%
2.0	0.018	0.077	0.234	7.36%
3.5	0.034	0.149	0.228	12.77%
5.0	0.048	0.215	0.223	18.07%

The Effectiveness of the Guided wave in Positioning Multiple Defects

Figure 10 depicts the guided wave signal in the time domain when a torsional mode T (0,1) propagates in a pipe containing two flaws. According to the graph, five-wave packets were captured. At 0.2 milliseconds, the first wave packet was identified as the incident wave. The second and third wave packets were determined to be the first defect's reflected echoes. The second wave packet is the direct reflection of the incident wave. In contrast, the third wave packet is the reflection of the excitation point when the reflected wave from the first defect strikes the excitation point. The fourth wave packet recorded at one millisecond is the reflection of the second fault, which is 0.82 metres away from the first defect. And the final wave packet is the end-of-pipe reflection. As the ECL is 100 per cent, the pipe end reflection has a rather significant amplitude. The results demonstrate high concordance with the peer-reviewed literature [25]. Additionally, the reflection of the second flaw tends to blend with the reflection from the pipe end, making it harder to detect the signals. If two defects or features were adjacent to one another due to the constructive-destructive character of the wave, excessive reverberation would result from the interference between the reflecting waves, which results in erroneous signal detection. If the faults were close, they could only be noticed qualitatively and not numerically.

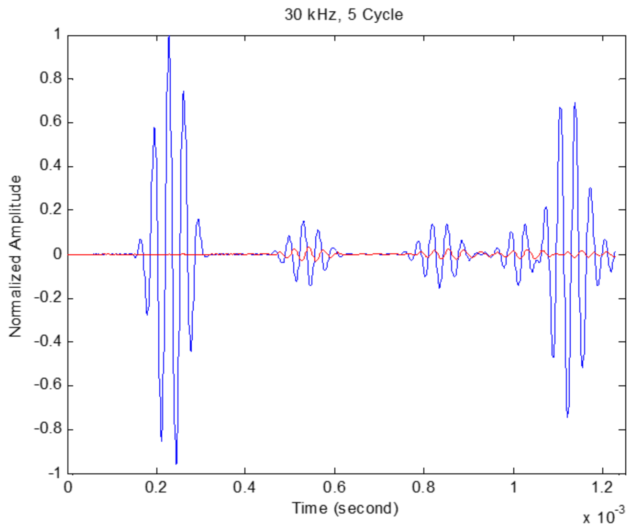


Figure 10. Time-domain signals for two defects

CONCLUSION

This work describes the first attempt to investigate the features of T (0, 1) wave response signals from pipe faults. The mode change from torsional mode T(1,0) to flexural mode F(1,2) occurs when a directed wave interacts with a non-symmetric structure, such as a flaw or corrosion. When the circumferential extend and depths grow, the ECL and reflection coefficient increase. However, the F/T ratio value fluctuates depending on the defect's circumferential extent and depth. This characteristic enables the identification of the defect's nature and shape. Additionally, it prevents erroneous interpretations such as weld and connection. The specific position of defects can be determined depending on the time the reflection signal is received. However, identifying several problems is time-consuming. Excessive reverberation may result in the detection of a false signal due to interference between the reflecting waves. If the faults were close, they could only be noticed qualitatively and not numerically.

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