The Effect of Complex Corrosion Profiles on Remaining Wall Thickness Quantification Using Shear Horizontal Guided Waves

KONSTANTINOS TZAFERIS, MORTEZA TABATABAEIPOUR,
GORDON DOBIE, GARETH PIERCE,
MAYORKINOS PAPAELIAS, CHARLES MACLEOD
and ANTHONY GACHAGAN

ABSTRACT

Corrosion of plate and pipe structures is a major concern to many key industries, including power, maritime, and oil and gas. When there is a need to inspect large areas quickly or when access to the structure is limited, guided wave testing is often preferred over bulk wave measurements. In this work, shear horizontal guided waves are employed for wall thickness quantification. Specifically, the interaction of modes SH1 and SH0 with complex corrosion defects is investigated. The guided wave mode are selectively generated using a phased array-based approach. A pair of identical phased array probes are positioned before and after the simulated corrosion profile, to monitor the reflected and transmitted waves. The targeted mode is excited selectively using a 32-element 3 mm pitch array and guided wave modes are decomposed after a 2DFFT is performed. The cut-off frequency technique using mode SH1 is shown to be adequate when smooth wall thinning defects are considered. When sharp pits are present, mode SH0 proved sufficient to determine the pits depth.

INTRODUCTION

Monitoring wall thickness in critical structural assets, such as pipelines, tanks, and pressure vessels, is critical to prevent potential disasters. Traditionally, wall thickness is quantified in-service using either bulk wave ultrasonics or electromagnetic techniques. Despite their generally satisfactory accuracy, these methods involve local measurements immediately under the probe area. This limits the inspection only to areas of the structure where probe access is feasible. Unfortunately, in certain cases, direct access to the structure requiring inspection may be limited, or spot or scan measurements can be time-consuming when a large area needs to be inspected. Periodic inspection or continuous structural health monitoring of structures with limited accessibility can then be carried out using shear horizontal guided waves.

Recently, the research community has recently taken an interest in using a frequency-based technique for wall thickness quantification [1]. The technique utilizes the cut-off frequency of higher order guided wave modes. Specifically, a higher order mode is generated and travels circumferentially in pipes or linearly in plates. The mode is excited over a wide frequency-wavelength range, determined by the nominal thickness of the test sample and the capabilities of the transmitter and receiver probes.

By observing the split frequency between the reflected and transmitted waves from a defect, it is possible to determine the cut-off frequency and the remaining thickness of the wall.

Konstantinos Tzaferis, Morteza Tabatabaeipour, Gordon Dobie, Gareth Pierce, Charles MacLeod and Anthony Gachagan, Centre for Ultrasonic Engineering, Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, G11XW, UK

Mayorkinos Papaelias, School of Metallurgy and Materials, University of Birmingham, Birmingham, UK

To reduce mode conversion, it is preferable to operate in a region with fewer modes [1]. Typically, the first higher order mode, such as A1 for Lamb waves or SH1 for SH waves, is selected. SH1 is usually preferred because it does not leak into non-viscous fluids that may be in contact with the sample, and it can be excited using non-contact electromagnetic acoustic transducers (EMATs) [2,3].

In this work, modes SH1 and SH0 [4] are emitted and received using 32-element 3 mm pitch array probes. The array elements generated shear horizontal forces and can be seen as the elements of a phased array EMAT. The cut-off principle of mode SH1 is tested against three different corrosion profiles, namely uniform, pitting, and a more complex defect. Such corrosion profiles appear commonly in structures manufactured from mild steel [5]. Although the cut-off frequency technique is relatively simple when smooth wall thinning defects are considered, its validity is under question in the case of more complex corrosion profiles, where sharp pits might occur. However, in these cases, mode SH0 reflects strongly from the near vertical insonified face of the pit. Therefore, mode SH0 is also evaluated when sharp pits are present.

The organization of this paper is as follows. In Section 2, theory related to minimum remaining wall thickness quantification using the cut-off property of SH1 is briefly presented. In Section 3, simulations on different corrosion profiles are performed using the concept of shear horizontal phased array steering. Results are presented and discussed in Section 4. Finally, in Section 5, key conclusions are drawn.

THEORY

One of the properties that higher order modes exhibit is a cut-off frequency-thickness product, which represents the minimum frequency-thickness value below which the mode cannot exist. The cut-off frequency of a shear horizontal mode can be calculated according to

$$f_{cut-off} = nC_T/2d_{min}, \quad (1)$$

where n, c_T and d_{min} are the wave mode order, shear velocity and minimum wall thickness, respectively.

Figure 1 depicts a 10 mm thick plate with a wall thinning defect. In the defect region, the minimum remaining wall thickness is 4 mm. Therefore, according to equation (1), the cut-off frequency of mode SH1 in the wall thinning region is 387 kHz. This implies that mode SH1 components with a frequency below 387 kHz cannot pass through the defect area and are thus reflected. Since the defect depth is not known beforehand, the quantification of the minimum remaining wall thickness involves exciting SH1 at a broad range of frequencies, utilizing multiple or a single capture. Once the cut-off frequency is identified, equation (1) can be employed to determine the remaining wall thickness.

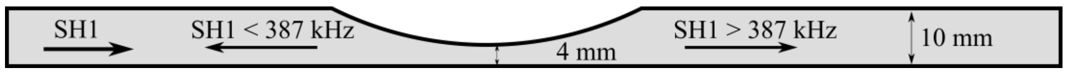


Figure 1. Wall loss quantification using the cut-off principle of SH1 mode. A uniform corrosion defect on a 10 mm thick plate is schematically illustrated. Frequencies below the cut-off are reflected, whereas higher frequencies propagate through the defect.

The discussed technique is successful when gradual wall thinning defects are employed. However, realistic corrosion profiles are often more complex. For example, sharp pits might appear in a region with general corrosion [5]. Due to their abrupt thickness changes, these pits might introduce mode conversion and reflection even at frequencies above the cut-off. In what follows, the validity of the method against corrosion profiles including sharp pits is examined.

SIMULATIONS

To test the interaction of different corrosion profiles with SH1, finite element simulations were conducted. 2D simulations were performed to accelerate simulation time and simplify the analysis. This assumes the defect length in the z-direction comparable than the beam with, which might not be the case, especially when pits are considered. However, this condition can be satisfied assuming a focused beam. The simulation setup is shown in Figure 2. The cross section of a linear elastic 10 mm thick sample with shear velocity $c_T = 3100$ m/s was modelled. The defect region is located between a pair of 32-element 3 mm pitch arrays. The center-to-center distance of the arrays is approximately 0.7 mm. To avoid edge reflections, the plate length was set to 1.2 m. Array 1 applies shear horizontal loads on the top surface of the plate. Both arrays act as receivers, to capture reflected and transmitted waves. To achieve high accuracy, the mesh size was set to 0.1 mm and the timestep to 10 ns.

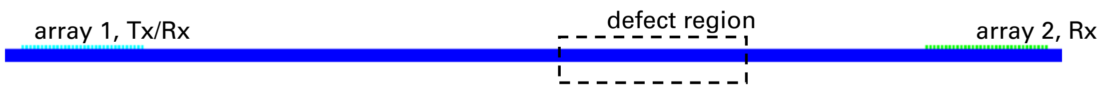


Figure 2. Simulation set-up.

The corrosion profiles of the three cases examined are given in Figure 3. Figure 3(a) shows a uniform corrosion profile with 4 mm remnant wall thickness and defect length 68 mm (measured on the top surface). In Figure 3(b), a pit is modelled, with 3 mm length measured on the top surface and 6 mm deep. A more complex profile is modelled in Figure 3(c), illustrating uniform corrosion and a pit [5]. The pit is 7 mm deep, and the minimum wall loss due to the uniform profile is 4 mm.

(a) (b) (c)

Figure 3. Simulated corrosion profiles: a) uniform corrosion b) a pit c) uniform and corrosion and a pit.

The excitation configuration for each defect case is summarized in Table I. In the case of uniform wall loss (see Figure 3 (a)), the cut-off frequency reads 387 kHz. Therefore, a broadband 3-cycle excitation with centre frequency at 387 kHz was selected and the elements of array 1 are phased appropriately [6] to excite SH1. In the when sharp pits are present, (see Figure 3(c) and (d)), an additional set of simulation was conducted, exciting mode SH0 in pulse-echo mode.

TABLE I. EXCITATION PARAMETERS FOR UNIFORM, SHARP PIT, AND COMPLEX CORROSION PROFILES

Corrosion profile / Technique	Uniform	Sharp pit	Complex
Cut-off principle	SH1 3-cycle sinusoid 387 kHz	SH1 3-cycle sinusoid 387 kHz	SH1 3-cycle sinusoid 387 kHz
Reflection	-	SH0 3-cycle sinusoid 350 kHz	SH0 3-cycle sinusoid 350 kHz

RESULTS AND DISCUSSION

Intact sample

First, a simulation on an intact sample was performed, targeting on mode SH1. The excitation signal was a 3-cycle sinusoid with 387 kHz center frequency. Array 2 received A-scan signals which where post-processed to obtain a 2DFFT map [7], presented in Figure 4**.** The bandwidth at -12 dB is around 150 kHz covering the frequency range 312-462 kHz.

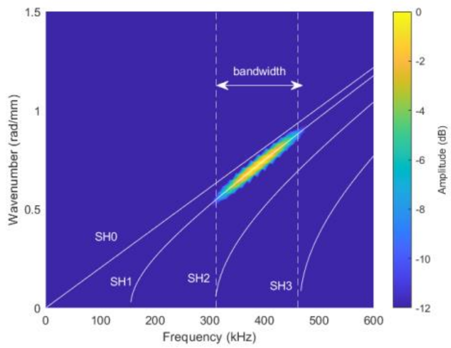
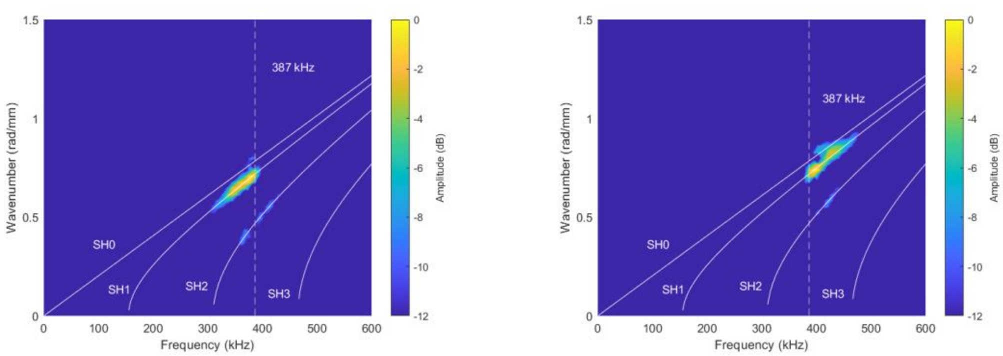


Figure 4. 2DFFT map on intact sample targeting mode SH1.

Uniform corrosion

Next, the 2DFFT maps obtained from signals captured by the two arrays are shown in Figure 5. Figure 5(a) relates to reflected waves captured by the array 1. As expected, only frequencies below 387 kHz are reflected. On the contrary, the transmitted waves contain only components above the cut-off, as shown in Figure 5(b). Therefore, in the case of uniform corrosion, it is straightforward to determine the split frequency and thus determine the minimum remaining wall thickness of the structure using equation (1).

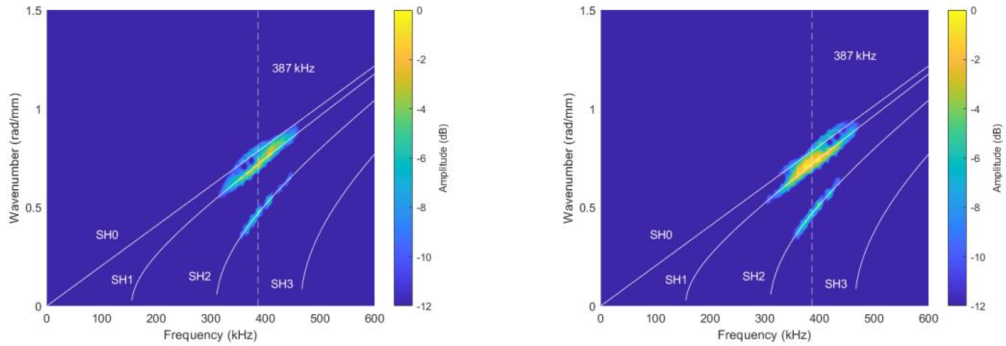


(a) (b)

Figure 5. Uniform corrosion: 2DFFT maps of (a) reflected waves and (b) transmitted waves. The frequency content between the reflected and transmitted waves is well-separated by the cut-off frequency line at 387 kHz.

A single sharp pit

Then, the effect of a pit in wall thickness quantification using SH1 is examined. In a similar manner to the previous case, 2DFFT maps related to a single deep pit are shown in Figure 6. However, in this scenario, as can be seen in the 2DFFT maps, there is no obvious split in the frequency axis between reflected and transmitted waves. This is due to the abrupt thickness change occurring from the pit. In fact, since the front face of the pit is near vertical, it is expected that a strong reflection will occur at all frequencies.



(a) (b)

Figure 6. Sharp Pit: 2DFFT maps of (a) reflected waves and (b) transmitted waves. The frequency content between the reflected and transmitted waves is not separated.

Due to the geometry of the sharp pit, it is expected that it can be sized based on the reflection of mode SH0 [8]. For this purpose, a separate set of 2D simulations was conducted, were SH0 was excited using a 3-cycle sinusoid at 350 kHz in pulse-echo mode. The depth of the pit varied from 5 to 8 mm with a 1 mm step, and each depth, the amplitude of the reflection of SH0 was recorded, as shown in Figure 7. The amplitude of SH0 is normalized, so that the amplitude of the 8 mm deep pit (80% wall loss) equals 0.8. The result indicates a linear relationship between the depth and the amplitude of SH0 [5]. This illustrates using a phased array-based approach, SH1 can be used for gradual thinning wall loss whereas SH0 can be used for sharp pits. It is not that the reflection of SH0 depends not only on depth but also the width (circumferential extent in pipes) [5] of the flaw, which in this work is assumed to be comparable to beam width.

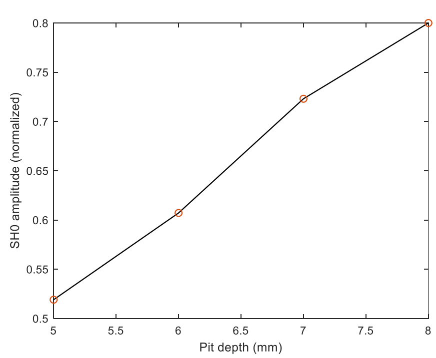
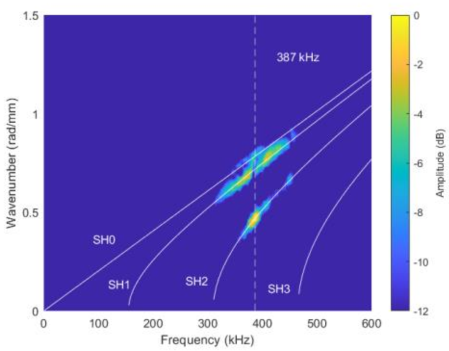


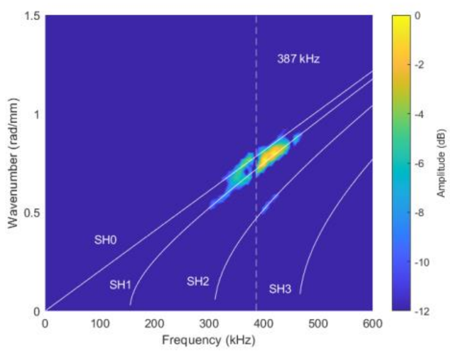
Figure 7. Pit depth vs SH0 reflection amplitude. A linear relationship exists between pit depth and the reflection of SH0.

Complex corrosion profile

The corrosion profile with a pit within an area of gradual wall loss is examined, see Figure 3(c). The pit is 7 mm deep, resulting in minimum remaining wall thickness of 3 mm. The uniform wall loss yields a minimum remaining wall thickness of 4 mm. Since the depth of the pit cannot be determined with the cut-off frequency technique, emphasis is placed on whether the gradual wall loss can still be quantified. Figure 8(a) displays the 2DFFT map obtained from reflected waves. Energy is spread uniformly across SH1, as it reflected at all frequencies from the front face of the pit. Mode conversion to mode SH2 is also observed. Figure 8(b) displays the 2DFFT map obtained from transmitted waves. In this case, there is an energy split at 387 kHz, suggesting a minimum remaining wall thickness of 4 mm.



(a)



(b)

Figure 8. Sharp pit and uniform corrosion: 2DFFT maps of (a) reflected waves and (b) transmitted waves. The frequency content between the reflected and transmitted waves is not separated.

Like the previous case, the depth of the pit was varied and the reflection of mode SH0 was recorded. The result is plotted in Figure 9. Again, a linear relationship exists between the depth of the pit and SH0.

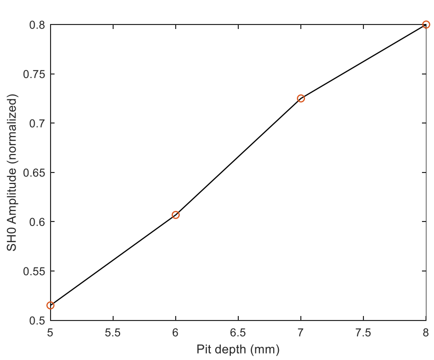


Figure 9. Pit depth vs SH0 reflection amplitude for complex corrosion profile.

CONCLUSION

The applicability of determining the minimum wall thickness using the cut-off frequency of SH1 and the reflection of SH0 on three different simulated corrosion profiles was examined. The use of an array allowed to excite these two modes dynamically, without altering transducer configuration. The results are summarized in Table II. As expected, the cut-off frequency principle provided accurate results in the case of gradual wall loss. However, it failed to estimate wall loss when testes against a sharp pit. Interestingly, in the case of a complex corrosion profile, when a sharp pit is present in a generally corroded region, although the reflected waves did not provide any sufficient information, the transmitted waves successfully evaluated the wall loss of the generally corroded region, but without giving information on the depth of the pit. Quantification of pit depth was shown to be possible utilizing the reflection of SH0, which exhibits a linear relationship with pit depth.

TABLE II. WALL LOSS QUANTIFICATION OF DIFFERENT CORROSION DEFECT TYPES AND PROFILES FOR FREQUENCY AND AMPLITUDE BASED TECHNIQUES

Corrosion profile:	Uniform	Sharp pit	Complex
Cut-off principle (SH1)	✓	✗	✗
Reflection (SH0)	-	✓	✓

REFERENCES

[1] Suresh N, Balasubramaniam K. Quantifying the lowest remnant thickness using a novel broadband wavelength and frequency EMAT utilizing the cut-off property of guided waves. NDT E Int 2020;116:102313. https://doi.org/10.1016/j.ndteint.2020.102313.

[2] McMillan R, Hampson R, Tabatabaeipour M, Jackson W, Zhang D, Tzaferis K, et al. Design and Manufacture of an Optimised Side-Shifted PPM EMAT Array for Use in Mobile Robotic Localisation. Sensors (Basel) 2023;23. https://doi.org/10.3390/s23042012.

[3] Trushkevych O, Tabatabaeipour M, Dixon S, Potter MDG, Dobie G, Macleod C, et al. Miniaturised SH EMATs for Fast Robotic Screening of Wall Thinning in Steel Plates. IEEE Sens J 2021;21:1386–94. https://doi.org/10.1109/JSEN.2020.3021526.

[4] Tabatabaeipour M, Tzaferis K, McMillan R, Jackson W, Dobie G, Edwards RS, et al. Ultrasonic Guided Wave Estimation of Minimum Remaining Wall Thickness Using Gaussian Process Regression. Mater A 2022;221:110990. https://doi.org/10.1016/j.matdes.2022.110990.

[5] Carandente R, Cawley P. The effect of complex defect profiles on the reflection of the fundamental torsional mode in pipes. NDT E Int 2012;46:41–7. https://doi.org/10.1016/j.ndteint.2011.11.003.

[6] Tzaferis K, Tabatabaeipour M, Dobie G, Lines D, MacLeod CN. Single-mode Lamb wave excitation at high-frequency-thickness products using a conventional linear array transducer. Ultrasonics 2022:106917. https://doi.org/10.1016/j.ultras.2022.106917.

[7] Haywood-alexander M, Dervilis N, Worden K, Dobie G, Rogers TJ. Informative Bayesian tools for damage localisation by decomposition of Lamb wave signals. J Sound Vib 2022;535:117063. https://doi.org/10.1016/j.jsv.2022.117063.

[8] Clough M, Fleming M, Dixon S. Circumferential guided wave EMAT system for pipeline screening using shear horizontal ultrasound. NDT E Int 2017;86:20–7. https://doi.org/10.1016/j.ndteint.2016.11.010.