Corrosion monitoring using high-frequency guided waves

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Abstract

Corrosion can develop due to adverse environmental conditions during the service life of industrial structures, e.g., offshore oil platforms, ships, and desalination plants. Both pitting corrosion and generalized corrosion leading to wall thickness loss can cause the reduction of the strength and thus degradation of the structural health. The monitoring of corrosion damage in difficult to access areas can be achieved using high frequency guided waves propagating along the structure from accessible areas. Using standard ultrasonic transducers with single sided access to the structure, guided wave modes were selectively generated that penetrate through the complete thickness of the structure. The wave propagation and interference of the different guided wave modes depends on the thickness of the structure. Laboratory experiments were conducted and the wall thickness reduced by consecutive milling of the steel structure. Further measurements were conducted using accelerated corrosion in a salt water bath and the damage severity monitored. From the measured signal change due to the wave mode interference the wall thickness reduction was monitored. Good agreement with theoretical predictions was achieved. The high frequency guided waves have the potential for corrosion damage monitoring at critical and difficult to access locations from a stand-off distance.

1. Introduction

The corrosive marine environment can lead to thickness reduction in metallic structures, ultimately limiting the useful service life of ships (1). Nondestructive testing is required to predict and hence prevent failure. Both pitting corrosion and generalized, uniform thickness reduction are prevalent in ship hulls (1). Pitting corrosion is more difficult to detect nondestructively as it is a localized defect. Different ultrasonic techniques have demonstrated good sensitivity to detect small thickness changes and both surface and subsurface flaws. Advances have been made in the development of guided ultrasonic wave monitoring systems for large structures, such as oil storage tanks and pipelines (2). Such structures are subject to corrosion and fatigue damage during their service life (3, 4). Efficient structural health monitoring (SHM) of such structures can be achieved using guided wave array systems (5, 6). Guided ultrasonic waves can propagate over large distances in thin-walled structural components. Defects such as thickness reduction due to corrosion pitting, lead to scattering of the guided waves and reflected wave pulses propagating back towards the monitoring location. This can be employed for the efficient monitoring of large technical structures (7). Guided wave SHM systems typically operate at low frequencies below the cut-off frequencies of higher order wave modes to generate only the fundamental (A_0 or S_0) wave modes, simplifying signal interpretation. The low frequency operating range allows long propagation distances but necessitates larger wavelengths and thus limited sensitivity to small defects.

High frequency guided waves have been employed for non-destructive testing purposes (8, 9). The S_0 mode (around 5 MHz mm) was used for corrosion detection in aircraft structures (10), and longitudinal modes (above 15 MHz mm) were employed for plate inspection (11). This allows for the inspection of structures over reasonably long distances, and can be employed even if local access to the inspected part is not possible. The resulting wavelengths are comparable to those bulk wave ultrasonic testing (UT), possibly allowing good sensitivity for the detection of small defects (11). High frequency guided waves at around 6.75 MHz mm have been studied for the detection and localization of surface defects in stiffened plates (12). This wave type can be interpreted as the superposition of the first anti-symmetric A_0 and symmetric S_0 Lamb wave modes (13). The small difference between the phase velocities leads to a continuous shift in relative phase, causing the transfer of the wave energy between the plate sides. The significant distance for this energy exchange, is the so-called beatlength (14) or beat wavelength (15). This interference depends strongly on both the frequency and thickness of the structure.

This effect has been investigated to monitor the thickness reduction due to generalized corrosion in steel specimens. The concept was initially demonstrated using milled specimens to gain an understanding of the sensitivity of the methodology for uniform thickness reduction. Thickness reduction due to accelerated corrosion of steel specimens was monitored to verify the applicability for actual corrosion monitoring (16). The detection of hidden, simulated (milled) pitting corrosion using pulse-echo measurements with single sided access was investigated. The high frequency guided wave modes can be easily generated and received selectively above the cut-off frequencies of the higher Lamb wave modes using standard piezoelectric wedge transducers.

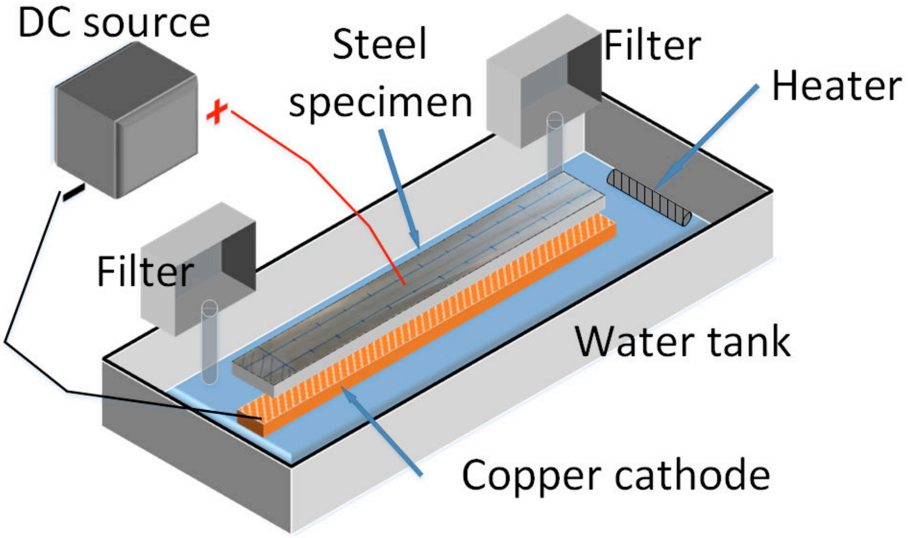

Figure 1. Accelerated corrosion setup impressing DC current on steel plate specimen in salt water, with steel specimen, copper cathode connected to DC source, water tank with filters and heater (16).

2. Experiments

Mild steel specimens (EN3B – AISI 1020) of size 650 mm x 100 mm were initially milled to 11 mm thickness. One specimen was then milled down in approximately 0.2 mm steps to a final thickness of 9.43 mm to achieve uniform thickness reduction. Two of the specimens were subjected to accelerated corrosion using reverse impressed current cathodic protection (16, 17). The setup consisted of a DC voltage source, the steel plate partially submerged as the anode in salt water solution, suspended above the copper cathode (Fig. 1). The DC voltage source supplied a current of approximately 5A at 6V. The thickness was monitored using longitudinal pulse-echo ultrasonic measurements at 5 MHz along the center line of the plate. The accelerated corrosion was interrupted approximately every 30 hours to perform guided ultrasonic wave measurements. An artificial defect was machined in one of the 11 mm thick steel specimen to simulate corrosion pitting (Fig. 2). A V-shaped notch with an opening angle of 90° and a maximum depth of 5 mm was milled.

High frequency guided waves were excited using a standard 90° wedge transducer with a center frequency of 0.5 MHz. Measurements for the first three specimens were conducted using a 10-cycle tone burst excitation (sinusoid in a Hanning window), generated in a programmable function generator and amplified using a broadband power amplifier. A heterodyne laser interferometer was used for point measurements of the out-of-plane displacement field along the propagation of the ultrasonic pulse (18) (Fig. 3). The interferometer head was moved parallel to the plate surface using a scanning rig with a step size of 1 mm for a distance of 450 mm from the transducer location. The signal was band pass filtered, averaged (50 averages) and recorded using a digital storage oscilloscope. Using Matlab the amplitude at 0.45 MHz was extracted using Fast Fourier Transform (FFT) from the time trace for each measurement location. For the 4th specimen containing the simulated pitting corrosion a standard ultrasonic pulser-receiver was employed to perform the pulse-echo (P/E) measurements of the reflections at the defects. The wedge transducer was placed on the plate surface opposite to the defect to investigate the potential for hidden corrosion detection. The stand-off distance from the transducer to the defect was varied between 50 mm and 250 mm in steps of 50 mm.

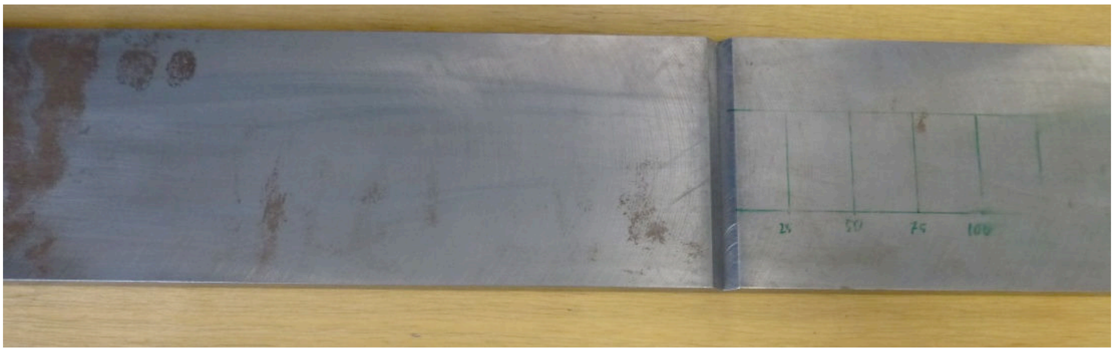

Figure 2. Photograph of steel specimen (11 mm thickness) with V-notch (maximum depth: 5 mm, opening angle: 90°).

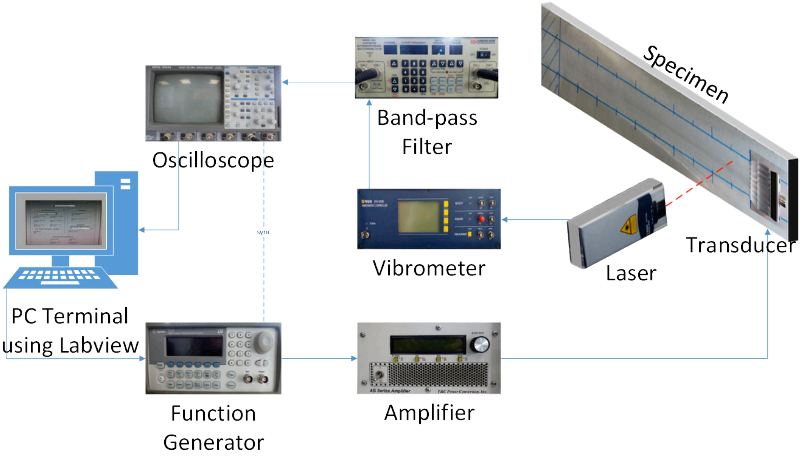

Figure 3. Experimental setup for laser measurement of high frequency guided ultrasonic wave propagation on steel specimen (16).

3. Guided wave measurement for thickness reduction

One mild steel plate specimen was milled down in uniform steps of approximately 0.2 mm from an initial thickness of 11.0 mm to a thickness of 9.43 mm. For each plate thickness the high frequency guided wave propagation along the specimen was measured using the laser interferometer. The amplitude at 0.45 MHz was extracted from each time trace using FFT and its variation with propagation distance analyzed. The beating effect between the two wave modes with similar phase velocity leads to a periodic amplitude variation (Fig. 4). The amplitude periodically decreases and increases as the wave propagates along the specimen. This beating effect depends strongly on the frequency-thickness product, so that in the time domain the amplitude variation is less pronounced as the wave pulse contains energy over a range of frequencies. The measured amplitude curves show some variation over shorter length scales due to the additional excitation of higher wave modes (19). The experimentally measured amplitude curves were fitted using Matlab with the theoretically predicted exponentially decreasing cosine curve and good general agreement can be observed in Fig. 4 for four different plate thicknesses. The experimental beatlength matched well with the theoretically predicted beatlength using Disperse (20) with a maximum error of less than 8% for all cases.

The accelerated corrosion for two mild steel plate specimens was interrupted regularly (approximately every 30 hours) and the plate thickness and high frequency guided wave propagation along the specimen measured. The variation of the amplitude with propagation distance was analyzed. Similar experimental amplitude variation to the results for the milled specimen with periodic amplitude increase and decrease due to the guided wave interference can be observed in Fig. 5 for one of the corroded specimens. The theoretical fit matches the measurements reasonably well, and the shorter beatlength for smaller plate thickness can be clearly seen. The deviation between theoretical and experimental beatlength is slightly higher than for the milled plate specimen, with a maximum error of about 10%. This slightly reduced sensitivity for the plate thickness determination would still be sufficient to detect generalized corrosion before it affects the structural integrity.

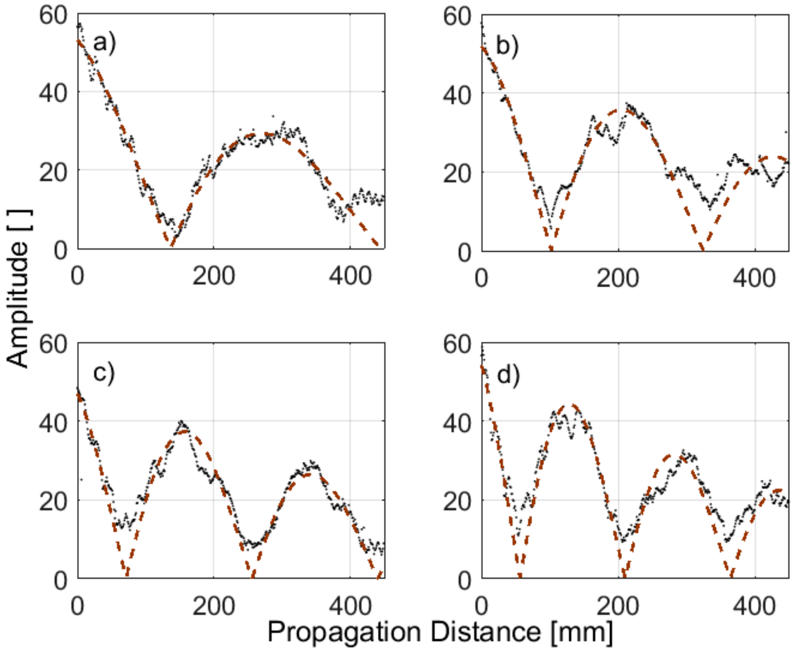

Figure 4. Experimental measurement of high frequency guided wave amplitude (0.45 MHz, FFT) on milled steel specimen; thickness: a) 11.00 mm; b) 10.39 mm, c) 9.80 mm, d) 9.43 mm; measured amplitude (laser interferometer, black dots) and exponential fit (brown, dashed line).

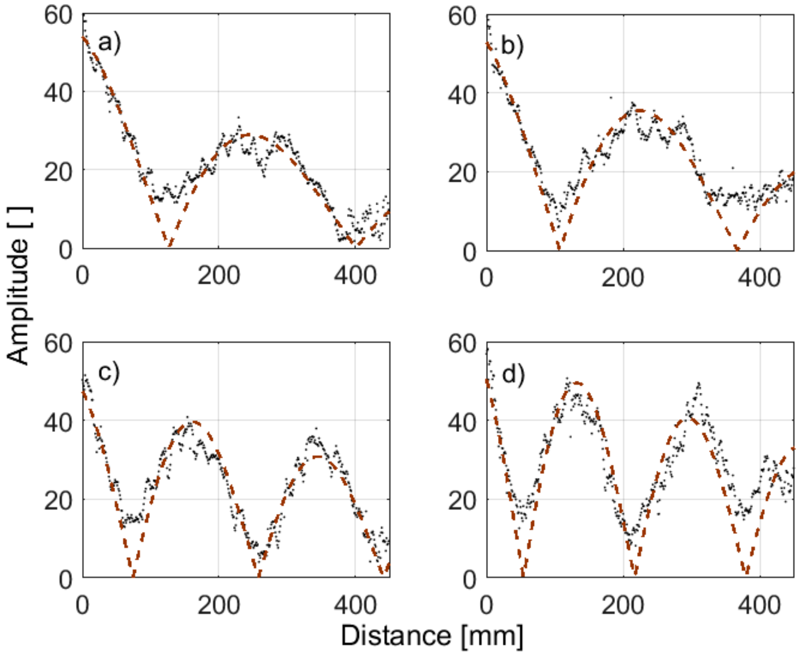

Figure 5. Experimental measurement of high frequency guided wave amplitude (0.45 MHz, FFT) on steel specimen with accelerated corrosion; thickness: a) 10.80 mm; b) 10.49 mm, c) 9.82 mm, d) 9.42 mm; measured amplitude (laser interferometer, black dots) and exponential fit (brown, dashed line).

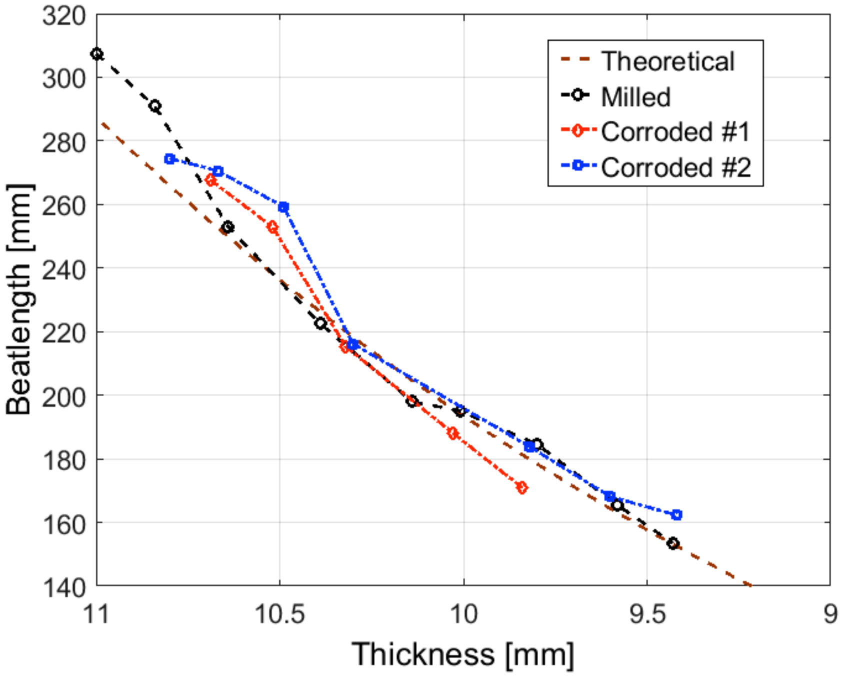

Figure 6. Comparison of theoretically predicted beatlength at 0.45 MHz (dashed, brown) against measured beatlength (fit from laser amplitude measurements at 0.45 MHz); milled specimen: black circles; corroded specimens: red diamonds (specimen #1), blue squares (specimen #2).

Shown in Fig. 6 is the measured beatlength (FFT, 0.45 MHz) for experiments using the milled and corroded specimens against the independently measured plate thickness. Good agreement with the theoretical beatlength can be observed with the beatlength decreasing with thickness. For the initial specimen thickness the guided wave propagation distance is comparable to the beatlength, leading to the fitting procedure being less accurate. For shorter beatlength the fitting procedure is more accurate as multiple minima and maxima occur over the propagation distance. A significant change in beatlength and good agreement can be observed in Fig. 6. The maximum change in thickness of about 1.6 mm (14%) leads to a change in beatlength by approximately 45% for the milled and corroded specimens. The sensitivity of the method for the determination of the plate thickness was estimated to give a resolution of about 0.3 mm (3% of plate thickness), which would be sufficient to detect generalized corrosion before it affects the structural integrity of corroded plate structures in marine applications.

4. Potential for Hidden Pitting Corrosion Detection

For one of the specimens an artificial defect (V-shaped notch, maximum depth: 5 mm, across specimen width) was machined to simulate pitting corrosion (Fig. 2). Standard P/E measurements using the wedge transducer were performed to investigate the reflection of the high frequency guided wave pulses and to ascertain the potential for the detection of hidden pitting corrosion from a stand-off distance, shown schematically in Fig. 7.

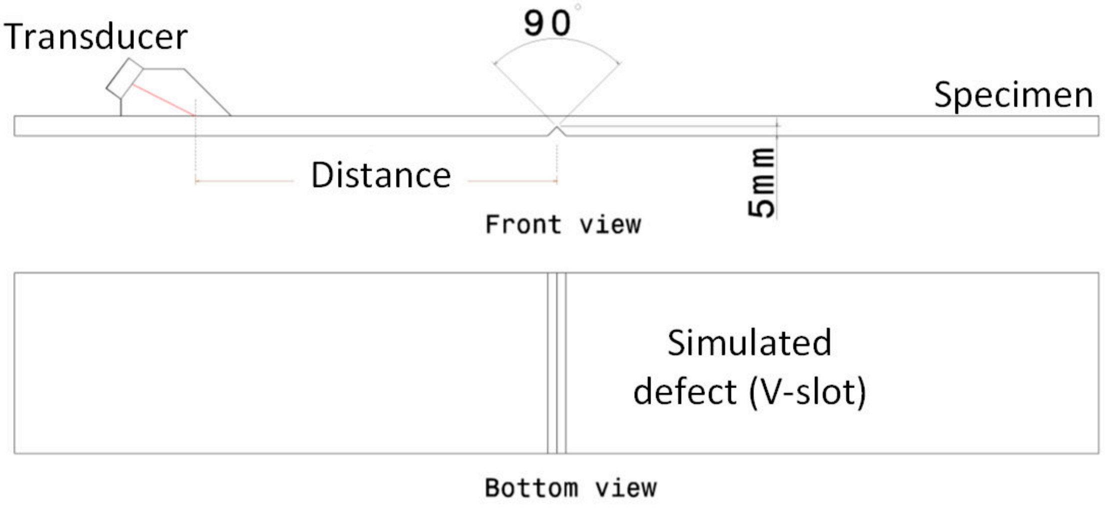

Figure 7. Schematic of experimental P/E measurements using wedge transducer at varying stand-off distances for detection of artificial defect (V-notch, 5 mm depth, 90° opening angle) in 11 mm thick steel plate on opposite specimen surface.

The experimentally obtained P/E signals are shown in Fig. 8. The initial pulses a 0 ms and 0.05 ms are transducer ringing internal reflections within the wedge. The measurements were conducted for different stand-off distances from the transducer to the defect, ranging from 50 mm to 250 mm with a step size of 50 mm. The red dashed line in Fig. 8 shows approximately the expected arrival time of the pulse reflected at the defect. A clear pulse can be seen for all stand-off distances at the expected times, allowing the detection of the simulated pitting corrosion.

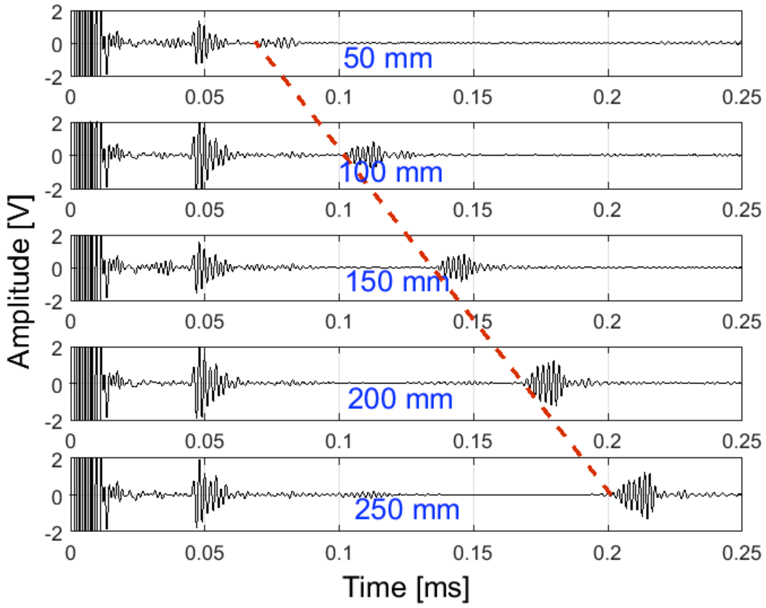

Figure 8. Experimentally measured P/E signals for V-notch (5 mm depth, 90° opening angle) in 11 mm thick steel plate; wedge transducer (0.5 MHz) placed on opposite specimen surface as defect at different distances to defect center; variation of stand-off distance transducer to defect.

The amplitude of the defect reflection increases with stand-off distance due to the interference of the wave modes. The reflected pulse at 50 mm stand-off distance is rather small as most of the guided wave energy is on the side opposite the defect where the transducer has been placed. For stand-off distances of 200 mm and 250 mm most of the incident wave energy is expected to be focused on the side of the specimen containing the part-thickness notch. A significant reflected pulse can be observed, allowing the detection of the simulated hidden pitting corrosion from a stand-off distance of about a quarter of a meter without access to the damaged plate side.

5. Conclusions

High frequency guided ultrasonic waves propagating along the structure allow for the monitoring of wall thickness reduction over reasonable lengths compared to through-thickness point measurements. Experimentally the high frequency guided waves were excited selectively using standard ultrasonic wedge transducers and measured using a laser interferometer. The amplitude beatlength due to the interference of the guided wave modes was calculated from the experimentally measured amplitude curves. Milling the plate specimen to achieve uniform thickness reduction, good agreement of the experimentally measured beatlength with theoretical calculations was obtained and the sensitivity of the proposed methodology quantified. Accelerated corrosion resulted in wall thickness loss and similar reduction of the beatlength and could be measured with comparative accuracy. The achieved sensitivity would allow the detection of generalized corrosion before it affects the structural integrity of plate structures. Standard P/E measurements employing the high frequency guided wave modes were conducted for a specimen containing simulated pitting corrosion. The potential for the detection of hidden pitting corrosion (opposite specimen surface to transducer) was demonstrated. The amplitude of the defect reflection depends on the stand-off distance of the transducer to the defect. It was observed that simulated typical hidden pitting corrosion defects can be reliably detected from a stand-off distance without access to the damaged plate side.

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