Monitoring and characterizing corrosion in aluminum using Lamb waves and attached sensors

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ABSTRACT

Corrosion is detrimental to the structural integrity of many critical components, and ultrasonic methods are routinely used in the field to make thickness measurements at points of interest. However, it is often difficult to assess the true extent of corrosion damage because of the likelihood of missing small corroded areas and the difficulty in mapping the extent of large corroded areas without an extensive number of time consuming measurements. Guided ultrasonic waves have the potential to both detect corrosion as early as possible and reduce the subsequent inspection time. This paper presents results from a study using Lamb waves to quantify the area extent of corrosion in an aluminum plate specimen. A sparse array of ultrasonic transducers was attached to an aluminum plate, and broadband excitation methods were used to generate both symmetric and anti-symmetric Lamb wave modes. As has been demonstrated in previous studies, the through transmission response recorded from each transmit-receive pair may be analyzed to determine if a defect exists and approximately determine its location. This paper presents a method to determine the exact location and quantify the extent of the corroded area using an acoustic wavefield imaging method. Lamb waves are generated using one of the permanently attached transducers as a source, and the acoustic wavefield is captured on the surface of the plate using an air-coupled transducer as a receiver. Full wavefield data are recorded as the receiver is scanned over the specimen surface, and wavefield images are processed to remove the strong incident wave and enhance the weaker scattered waves. The amplitude at the crest of the leading Lamb mode ($S_0$) is analyzed to produce spatial images of defective areas. Measured length and area results from these images compare very favorably with actual defect sizes. Results are also presented for scattering from a through hole with a simulated crack.

Keywords: Ultrasonics, Structural Health Monitoring, Corrosion Detection, Lamb Waves, Acoustic Wavefield Imaging

1. INTRODUCTION

This paper presents a method to determine the location and spatial extent of defects in plate-like structures using acoustic wavefield images obtained from ultrasonic guided waves propagating within the structure. Guided waves have been a cornerstone method for use in structural health monitoring (SHM) systems. Such waves are easily generated using permanently attached piezoelectric discs or patches, and many investigators have proposed using arrays of sensors to detect and image structural defects. Concepts considered have ranged from closely spaced, multiple transducer elements suitable for beamforming or tomographic algorithms to sparse arrays of widely spaced transducers distributed over the structure. Several studies have demonstrated that it is possible to detect structural changes and approximately determine defect locations under laboratory conditions. However, variable surface conditions and temperature effects complicate the analysis and can easily produce a high incidence of false alarms. Some investigators are conducting research to incorporate environmental factors into detection and localization algorithms to decrease the false alarm rate, but an inherently high false alarm rate would certainly limit the use of ultrasonic SHM methods. In fact, for any alarm on a critical structure, follow up inspections would be required.

Through transmission ultrasonic (TTU) methods are widely used for inspection of critical aerospace structural components because of their simplicity and high sensitivity to bonding and delamination defects. However, TTU inspection requires access to both sides of the part, so disassembly of the structure is usually required. Pulse echo (PE)
ultrasonic methods are often applicable when access is limited to one side of the part, but PE ultrasonic methods have limited penetration and generally do not have the sensitivity of TTU methods, especially when surfaces are non-parallel or for penetration of bonded interfaces. A non-contact acoustic wavefield imaging (AWI) method has been developed which approaches the sensitivity of TTU methods, but may be done without either extensive disassembly of the structure or using inconvenient coupling systems such as squitters, bubbler or roller probes\textsuperscript{11}.

This paper addresses methods for verifying, locating and quantifying defects using AWI methods. Specifically, the goal of this paper is to detect, locate and map the extent of areas affected by corrosion through analysis of acoustic wavefield images. Handheld instruments, such as ultrasonic thickness gauges, are effective for quantifying material loss. However, these are point measurement methods and ineffective for large area scanning. Maps of affected areas, or maps of where changes have occurred since previous inspections, would complement spot inspection methods and improve their effectiveness.

The AWI method uses one of the permanently attached transducers as a source, and the propagating wavefield is recorded on the surface of the structure using either an externally scanned air-coupled transducer or a scanning laser displacement interferometer system\textsuperscript{11-13}. Complete waveforms are recorded at each pixel location of the scan, and time slices represent a snapshot of the wavefield on the surface. Images of successive time slices can be assembled to produce a movie of waves propagating away from the source transducer and interacting with structural discontinuities. Previous studies by the authors have demonstrated that it is possible to directly image many structural defects using the AWI method\textsuperscript{11,14}.

Detection of cracks around fastener holes is a concern for many metallic plate-like structures. This paper also presents wavefield imaging results for scans of a simulated fastener hole where a saw cut was added to simulate cracking. A companion paper addresses detection of artificially induced hole and crack defects in the presence of varying temperature changes on the same specimen studied here\textsuperscript{15}. Specifically, robust algorithms have been developed which successfully detected and approximately located these artificial defects.

2. EXPERIMENTS

2.1 Specimen

A 6061 aluminum plate specimen, 610 mm x 610 mm x 4.8 mm, was used for this study. Figure 1 shows the specimen geometry, the location of artificial defects, and the location of six piezoelectric disc transducers, 2.25 MHz x 12.7 mm diameter, mounted on the back surface of the specimen with conductive epoxy. Coordinates of these transducers are listed in Table 1 and those of the artificial defects in Table 2. A total of 8 wavefield scans were performed, designated as W01, W27, W46, W49, W51, W146, W153 and W159, and Table 2 indicates which of the defects are present during which scans. Only transducer T1 was active for scans presented here, although any of the permanently mounted transducers could have been used as the source. The other passive transducers are impedance discontinuities on the back surface of the specimen which scatter the incident waves as shown in the wavefield images of Figure 2. These images were made from scan W159 after all the defects listed in Table 2 were present in the plate. Both the transducer and defect locations are visible on these images as scattering sites. The objective of this study is to analyze these scattering sites to determine the location and area extent of the defects.

The simulated corrosion was machined in the plate using a ball nosed cutter of 3 mm diameter. The plate thickness was reduced 25% from 4.8 mm to 3.6 mm to simulate corrosion. The beginning corrosion defect was a 7 mm circular spot prior to scan W27. Prior to scan W46 it was enlarged to an oval shaped area, 10 mm x 16 mm, with the major axis orientated vertically on the plate. The length was then increased to 30 mm for a total size of 10 mm x 30 mm prior to scan W49. The final enlargement of the corrosion defect was to a 30 mm circular spot prior to scan W51.

Prior to scan W146, a 6 mm diameter hole was added to the structure to simulate a fastener hole. A saw cut was made at the 9 o’clock position, relative to the orientation shown in Figure 1, to simulate cracking. The length of the saw cut was 3.2 mm prior to scan W153 and was lengthened to 9.5 mm before scan W159.
Table 1. Locations of piezoelectric transducers on the aluminum plate specimen.

<table>
<thead>
<tr>
<th>Transducer</th>
<th>Function</th>
<th>X (mm)</th>
<th>Y (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Transmitter</td>
<td>149</td>
<td>419</td>
</tr>
<tr>
<td>T2</td>
<td>Passive</td>
<td>316</td>
<td>495</td>
</tr>
<tr>
<td>T3</td>
<td>Passive</td>
<td>470</td>
<td>470</td>
</tr>
<tr>
<td>T4</td>
<td>Passive</td>
<td>483</td>
<td>165</td>
</tr>
<tr>
<td>T5</td>
<td>Passive</td>
<td>292</td>
<td>114</td>
</tr>
<tr>
<td>T6</td>
<td>Passive</td>
<td>140</td>
<td>191</td>
</tr>
</tbody>
</table>

Table 2. Locations of artificial defects and associated scan numbers.

<table>
<thead>
<tr>
<th>Scan Numbers</th>
<th>Feature</th>
<th>Geometry or Type</th>
<th>Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W01</td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W27</td>
<td>Corrosion</td>
<td>Circular</td>
<td>Diameter = 7</td>
</tr>
<tr>
<td>W46</td>
<td>Corrosion</td>
<td>Oval</td>
<td>10 x 16</td>
</tr>
<tr>
<td>W49</td>
<td>Corrosion</td>
<td>Oval</td>
<td>10 x 30</td>
</tr>
<tr>
<td>W51 – W159</td>
<td>Corrosion</td>
<td>Circular</td>
<td>Diameter = 30</td>
</tr>
<tr>
<td>W146 – W159</td>
<td>Hole</td>
<td>Through hole</td>
<td>Diameter = 6</td>
</tr>
<tr>
<td>W153</td>
<td>Hole with Notch</td>
<td>Notch at 9 o’clock</td>
<td>Length = 3.2</td>
</tr>
<tr>
<td>W159</td>
<td>Hole with Notch</td>
<td>Notch at 9 o’clock</td>
<td>Length = 9.5</td>
</tr>
</tbody>
</table>

Figure 1. Diagram of the aluminum plate, where the “x” symbols indicate transducer locations and the circles indicate simulated damage.
2.2 Data Acquisition System

The specimen was scanned with a Panametrics LSC automated ultrasonic scanning system, and a Panametrics 5058 pulser receiver was used to pulse transducer T1 with a 1000 volt spike excitation. RF waveform data were acquired by scanning with an air-coupled transducer (QMI AS400ARi, 400 MHz, 28.5 mm focal length) above the plate surface on the side opposite the attached transducers and simulated corrosion. The spatial increment was 1.27 mm in both directions, and RF waveforms were recorded at each pixel location at a sampling frequency of 5 MHz and with 8 bits of resolution. The recorded waveform length was set to capture from first activity at the source transducer to about 50 µs past the arrival of waves at the lower right hand corner of the specimen.

2.3 Wavefield Image Generation

Data records were organized in a 3D data array of RF waveforms recorded at the various 2D plate positions. The recorded time values were initially stored as times measured from the generation of the transmit sync pulse. These time values were converted to true propagation times by subtracting the time of first waveform activity on the specimen, which corresponds to the air path. Acoustic wavefield images were produced by taking 2D time slices through the 3D waveform data array at various propagation times to produce images as shown in Figure 2.

The broadband spike excitation produces both fundamental symmetric ($S_0$) and antisymmetric ($A_0$) guided wave modes in the specimen. Both of these modes are visible in the images of Figure 2, and the lead outward propagating wavefront is the faster $S_0$ mode. The $A_0$ mode is also visible on these wavefield images as disturbances with a smaller wavelength emerging from the source, reflecting from specimen boundaries and scattering from defects.

3. DATA ANALYSIS

As shown in Figure 2, all the passive transducer and artificial defects listed in Tables 1 and 2 scatter the acoustic wavefield. However, the outward propagating waves are the dominant image features and complicate analysis of these wavefield images. A source wave removal algorithm was used to remove the incident waves and thereby enhance the smaller amplitude scattered signals. A separate wave crest analysis algorithm was developed to directly trace the area extent of discontinuities as the leading crest of the incident wave traverses the specimen.

3.1 Source Wave Removal

Source wave removal algorithms have been developed to suppress the strong incident wave visible on acoustic wavefield images\textsuperscript{16}. For the isotropic aluminum plate specimen used in this study, circular wavefronts emerge from the source.

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Figure 2. Acoustic wavefield images at various propagation times from transmit from scan W159. (a) Wavefield image at 50 µs, (b) wavefield image at 65 µs, and (b) wavefield image at 100 µs.
The effective source location is obtained by first generating an early-time wavefield image after a propagation time of 10 µs in the plate, and then calculating the center of mass to determine the source location.

Next, a region of interest is identified for wave removal processing. Within this region, each pixel value is adjusted to remove the incident source wave by subtracting an average wavefield value. The average is computed for each pixel over a circular arc, typically 30 mm in length, where the arc radius is the distance from the pixel to the source location and the center of the arc is at the pixel location. Values along this arc are weighed by a linear tapered window with the minimum, central value at the center of the circular arc.

Figure 3 shows acoustic wavefield images before and after source wave removal for Region 1 of the plate specimen, which includes transducer T1 and the simulated corrosion defect. In Figure 3(c) the leading S₀ wave is incident at the corrosion defect and the leading A₀ wave is just entering the wavefield image from the left. The source removal processing has very effectively removed all the incident S₀ waves and most of the incident A₀ waves. What remains are images which show predominately A₀ waves resulting from the incident S₀ waves which have been mode converted and scattered by the discontinuities. This mode conversion from S₀ to A₀ is expected since both the attached transducer and the corrosion defect are asymmetric with respect to the plate thickness.

![Wavefield Images](image)

**Figure 3.** Acoustic wavefield images of Region 1 at various times from first transmit activity which show scattering from both transducer T2 and the 30 mm diameter simulated corroded area from scan W51. (a) Complete wavefield at 68 µs with Region 1 shown as the dashed rectangle, (b) wavefield at 62 µs, (c) wavefield at 66 µs, (d) wavefield at 68 µs, (e) wavefield at 62 µs with the incident wavefield removed, and (f) wavefield at 68 µs with the incident wavefield removed.
### 3.2 Wave Crest Amplitude Analysis

As the leading $S_0$ wave crest traverses a defect location, the amplitude along the crest is reduced as energy is removed from the incident wavefront. This observation has led to development of the imaging algorithm described here. Consider the leading $S_0$ wave crest as it traverses a defect as shown in Figure 4. The line superimposed on the wave crest represents a path along which image amplitude values are captured. Figure 4(a) shows the wave 10 $\mu$s before the defect and Figure 4(b) shows it 10 $\mu$s past the defect. The distance of travel of the wave crest is 104 mm, and thus the phase velocity of the crest of the wave is approximate 5.2 mm/$\mu$s. Next, an image is formed where the horizontal axis is the distance of the wave crest from the defect, i.e., $\pm$ 52 mm for the wave pattern shown in Figure 4, and the vertical axis is the distance along the crest of the wave; i.e. along the line superimposed on the leading wave crest. The image intensity is the amplitude on the crest of the wave. Figure 4(c) shows the corresponding image that results from applying this analysis method to the wavefield data shown in Figures 4(a) and (b).

![Figure 4](image1.png)

**Figure 4.** Illustration of the wave crest amplitude analysis as applied to the leading $S_0$ wave crest as the wave traverses the 30 mm diameter simulated corrosion. (a) Wave crest 10 $\mu$s before arriving at the defect (54 $\mu$s), (b) wave crest 10 $\mu$s past the defect location (74 $\mu$s), and (c) wave crest amplitude image.

### 4. RESULTS

Two regions of the plate were selected for detailed analysis as illustrated by the dashed rectangles in Figure 1. Region 1 contains the progressively enlarged corrosion defect and attached transducers T2 and T3. Region 2 contains a hole from which a saw cut was progressively enlarged to simulate a growing fatigue crack and attached transducers T5 and T6.

The corrosion defect was first introduced prior to scan W27 as a 7 mm diameter circular region within which the thickness of the plate was reduced from 4.8 mm to 3.6 mm. In subsequent scans it was progressively enlarged as shown in Table 2. Figure 5 shows snapshots of Region 1 wavefield images with the incident wave removed for each of the four corrosion conditions at a propagation time of 70 $\mu$s. Scattering is clearly visible from both transducer T2 in the upper left corner and the corrosion defect near the center of the image. At this propagation time the wave has not yet reached transducer T3, and thus scattered waves from T3 are not contained in the images.

Note that the scattered wave pattern from T2 is relatively constant in all the images while scattering from the corrosion defect has increased in intensity and spatial extent as the defect area was increased. Further note that predominately $A_0$ waves are scattered from both the attached transducer and the corrosion defect, which is expected since both the transducer and defect are asymmetric with respect to the plate thickness.
These waveform images with the incident wave removed are useful for detecting and visualizing scattered waves from defects, and also for determining the center location of the scattering site. It is also possible to see changes in defect geometry by analyzing the shape of the scattered wave patterns. Note the differences between Figures 5(a) and 5(b) when the defect was changed from a spot to a larger oval area. In Figure 5(b) the scattering wavefronts are no longer circular due to the oval shape of the defect, and this wavefront distortion is even more apparent for the larger defect of Figure 5(c). The scattered wave pattern is again circular in Figure 5(d) after the defect was enlarged to a 30 mm diameter circular spot. Additionally, an asymmetrical pattern is produced near the center as energy is geometrically focused and scattered from the back side of the defect.

**Figure 5.** Acoustic wavefield images of Region 1 captured at 70 μs after transmit which show scattering from transducer T2 (upper left) and the simulated corroded area (lower center). Plate thickness was reduced ~25% to simulate corrosion and the incident wave has been removed from the images. (a) 7 mm circular spot (W27), (b) 10 mm x 16 mm oval area (W46), (c) 10 mm x 30 mm oval area (W49), and (d) 30 mm circular spot (W51).

Results from the wave crest amplitude analysis method are shown in Figure 6 as the corrosion defect was progressively enlarged from a 7 mm diameter circular spot to a 30 mm diameter circular spot. These images are remarkable in that they trace out both the defect length parallel to the wave crest and the affected area. The oval geometry is accurately captured for both the 10 mm x 16 mm and the 10 mm x 30 mm defect shape, as well as the approximately correct angular deviation of the major axis from the vertical direction. Using the known source and defect coordinates listed in Tables 1 and 2, an off-axis angular deviation of approximate 8.5° is expected, which is within ±1° of the tilt amount shown in Figure 6.
The wave crest amplitude images were analyzed manually to measure the length and areas of each indication. Two measurements were recorded for each image, one using the outer boundary determined from the local peak just outside the dark interior region, and the other using the inner boundary based upon the edge of the dark interior region. Although these measurements are subjective, they provide useful information to determine if automated image analysis procedures could be effective for determining defect dimensions. Results are shown in Figure 7 where the uncertainty bars were established from the upper and lower measurement results.

Waveform images are shown in Figure 8 from Region 2, which contains transducers T5 and T6 and the hole/notch defect. These images are shown for the largest, final flaw condition. As was the case for the corrosion defect, these images accurately show the location of the defect and transducer T6 within the first arrival of the wavefield. However, note that the nature of the scattered wave pattern is different for the hole than it was for the corrosion defect. Specifically, the wavelength of the scattered field in Figure 8 is greater than it was in Figure 5. This is because the hole is a symmetrical defect with respect to the thickness direction of the plate and thus does not mode convert the leading S<sub>0</sub> wave to an A<sub>0</sub> wave as the hole scatters the incident wave.
Figure 7. Comparison of defect sizes measured from wave crest amplitude images to actual dimensions of the artificially induced corroded area. (a) Defect length and (b) defect area.

Figure 8. Acoustic wavefield images of Region 2 which show scattering from transducer T6 and a 6 mm diameter through hole with a 9.5 mm edge notch used to simulate a crack (Scan W159). (a) Wavefield at 60 $\mu$s (leading S$_0$ wave crest over defect), (b) wavefield at 62 $\mu$s, (c) wavefield at 66 $\mu$s, (d) incident wave removed at 60 $\mu$s, (e) incident wave removed at 62 $\mu$s (leading S$_0$ wave arrival at T6), and (f) incident wave removed at 66 $\mu$s.
Results from the wave crest amplitude analysis method are shown in Figure 9, where the direction along the wavefront, which is approximately horizontal in Figure 8, is vertical in Figure 9. Figure 9(a) is the wave crest amplitude image for the hole before the notch was inserted. Figure 9(b) is the image after a 3.2 mm notch was added to the edge of the hole at the 9 o’clock position for the plate orientation shown in Figure 1. This clock position points down in Figure 9(b) such that the total length of the hole plus the notch, measured parallel to the wave crest, is approximately 9 mm, which qualitatively agrees with the image. In Figure 9(c), the notch has been increased in length to 9.5 mm such that the total length of the hole plus the notch is approximately 16 mm, and this length qualitatively agrees with the image. The angle of the indication from the hole/notch combination in Figure 9(c) is tilted because the incident wave crest is not parallel to the notch, and the tilt direction and magnitude qualitatively agree with the actual specimen geometry.

![Wave crest amplitude images](image)

**Figure 9.** Wave crest amplitude images of the leading S₀ wave shown as the wave traverses a 6 mm diameter through hole with an edge notch used to simulate a crack. (a) 6 mm hole without notch (W146), (b) 6 mm hole with 3.2 mm notch (W153), and (c) 6 mm hole with 9.5 mm notch (W159).

### 5. SUMMARY

Algorithms have been presented for enhancing acoustic wavefield images scattered from defects in an aluminum plate specimen. Artificial defects were machined in the plate to simulate both back side corrosion and crack initiation and growth from fastener holes. A sparse array of piezoelectric transducers was attached to the plate as would be appropriate for structural health monitoring applications, and results are presented in a companion paper at this conference for *in situ* detection and localization of defects. This study has addressed verifying, localizing and sizing defects, which would take place after detection by *in situ* methods.

Acoustic wavefield images were recorded using one of the permanently mounted transducer as the wave source and an externally scanned air-coupled transducer as the receiver. Scattered wave patterns from the attached transducers and the introduced defects are directly visible on the acoustic wavefield images. However, scattered wave components are often obscured by the much stronger outwardly propagating incident wave from the source transducer. These images were enhanced by removing the strong incident wave, and the resulting images clearly show wavefields scattered from the defects. From these enhanced wavefields of scattering by an impedance discontinuity in the plate, it is possible to locate the defect and approximate its shape from the shape of the scattered wavefield. However, the area extent of the scattering site is often unclear.

A wave crest amplitude analysis method was developed which “paints” the spatial extent of the defect as it is traversed by the leading wave crest. It was demonstrated that this method was accurate within about ± 20% for determining both the length and area of the artificially induced corrosion defects. Although not shown in this study, it is expected that wavefield images from each of the permanently mounted transducers could be combined to improve the sizing accuracy. The methodology demonstrated here on an aluminum plate specimen is appropriate for application to critical metallic structural components as part of an integrated vehicle health management system.
REFERENCES


