CORROSION DETECTION/QUANTIFICATION ON THIN-WALL STRUCTURES USING MULTI-MODE SENSING COMBINED WITH STATISTICAL AND TIME-FREQUENCY ANALYSIS

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ABSTRACT
In this paper, we present a multiple mode sensing methodology to detect active corrosion in aluminum structure utilizing the broadband piezoelectric wafer active sensors. This method uses ultrasonic Lamb wave complemented with the electro-mechanical impedance measurement to detect, quantify, and localize the corrosion progression in plate-like structures. The ultimate objective of this research is to develop in-situ multi-mode sensing system for the monitoring and prediction of critical aerospace structures that can be used during in-service period, recording and monitoring the changes over time.

The test experiments were conducted on an aluminum plate installed with a five sensor network using 7-mm piezoelectric wafer active sensors. The corrosion was emulated as material loss of an area of 50mm × 38mm on the other surface of the plate. Detection of corrosion and its growth was first conducted using the Lamb wave method in pitch-catch mode. The corroded area resulted in a thickness loss on the Lamb wave propagation and caused the amplitude and phase changes in the structural responses. The experimental data was first evaluated by the statistics-based damage indicator using root mean square deviation. Though the damage indicator is able to detect the presence of the corrosion and identify the corrosion location quantitatively, it failed in giving the right indication of corrosion development. A more corrosion signal processing based method, the cross time-frequency analysis, was proposed and used to analyze the phase characteristics of the data set. This cross time-frequency analysis was found more reliable and precise for detecting the corrosion progression compared with the damage indicator method.

1. INTRODUCTION
Corrosion is a serious problem in industrial applications such as pipeline and aircraft (Zhu et al. 1999) (Thomas et al. 2004). Dunn and Yacout (2000) used X-ray backscatter methods to perform a limited-scan backscatter technique for detecting hidden corrosion in aircraft. Uchanin and Tsirg (1991) discussed the detection problem of corrosion damage in inspection of aviation structures in the literature and proposed eddy current method to detect defects on the surface. Kathirvel et al. (2007) reported corrosion detection using eddy current array and ultrasonic phased array techniques for imaging the corrosion damage.

Guided Lamb waves have opened new opportunities for cost-effective detection of damage in structures. Lamb waves are guided waves that travel in thin-wall structures and they can facilitate efficient detection over large areas (Graff 1975) (Rose 2002). Of particular interest in this research is the use of Lamb waves for corrosion detection. Chahbaz et al. (1996) demonstrate the ability of Lamb waves to detect corrosion through material loss. Jenot et al. (2001) and Sicard et al. (2003) use wedge transducers to generate S0 Lamb waves which they sent along a copper plate to detect hidden corrosion in airframe structures. Zhu and Rose conducted experimental study on hidden corrosion detection by using the ultrasonic guided waves combined with boundary element method (BEM) numerical simulation (Zhu et al. 1999).

In this paper, we will propose use of propagating Lamb waves to detect material loss in thin aluminum plates. We will use piezoelectric wafer active sensors (PWAS) in a pitch-catch configuration to excite and detect Lamb waves. Since corrosion damage will change the material thickness, the propagating properties of the Lamb wave will be changed and shown in the collected signals. The changes are correlated to the damage
presence, growth, and/or extent. To identify these changes, several signal analysis methods including (1) damage indicator definition, (2) classic cross power spectrum, and (3) cross time-frequency analysis have been used to calibrate the corrosion damage.

2. LAMB WAVE METHODS WITH PIEZOELECTRIC WAFER ACTIVE SENSORS

This paper presents an in-situ diagnostics/monitoring of corrosion damage utilizing embedded piezoelectric wafer active sensors (PWAS) to excite and receive guided Lamb waves in thin wall structures. PWAS can be used as active sensing device, that provides the bidirectional energy transduction from the electronics into the structure, and from the structure back into the electronics. PWAS can be bonded to the structure or inserted into a composite structure, operated in propagating wave mode or electromechanical (E/M) impedance mode (Giurgiutiu 2008). As active sensors, PWAS can be used as either transmitter or receiver and connected to data concentrators and wireless communicators to generate or receive guided waves. PWAS can also be used as collocated E/M impedance sensor-actuators that permit effective modal identification in a wide frequency band. In an embedded sensing system, the PWAS can be embedded into the structures by mounting them directly on the outside surface and left in place to perform their structural health-monitoring task (such thing would be unthinkable with conventional ultrasonic transducers, which are bulky, obtrusive, and expensive).

2.1. PWAS guided waves transducers

The modeling and understanding of interaction between surface-mounted piezoelectric-wafer active sensors and structures is essential for the successful development of proposed method (Figure 1) (Giurgiutiu 2008). This effort is essential to the generation of high-frequency guided waves of thickness type.

2.1.1. PWAS principles

The general constitutive equations of linear piezoelectric materials given by ANSI/IEEE Standard 176-1987 that describe a tensorial relation between mechanical and electrical variables (mechanical strain, $S_{ij}$, mechanical stress, $T_{ij}$, electrical field, $E_k$, and electrical displacement $D_j$) in the form

$$
S_{ij} = s^{P}_{ijkl}T_{kl} + d_{ijkl}E_k \\
D_j = d_{jikl}T_{kl} + e^{P}_{jk}E_k
$$

(1)

where $s^{P}_{ijkl}$ is the mechanical compliance of the material measured at zero electric field ($E = 0$), $e^{P}_{ijk}$ is the dielectric permittivity measured at zero mechanical stress ($T = 0$), and $d_{ijkl}$ is the piezoelectric coupling between the electrical and mechanical variables. As conventional ultrasonic transducers, PWAS can be used with propagation guided waves in pitch-catch or pulse-echo mode (as illustrated in Figure 2).

2.1.2. PWAS Lamb wave frequency tuning

The fundamentals of guided Lamb waves can be found in many textbook, such as Lamb (1917), Viktorov (1967), Graff (1975), and Rose (1999). For Lamb waves, there are at least two Lamb modes, A0 and S0, existing simultaneously for many SHM approaches, where the product of the wave frequency, $f$, and structure half-thickness, $d$, falls in the range of 0–1 MHz-mm. In this range of product, A0 mode is sensitive to damage associated with disbonds and corrosion while S0 mode is sensitive to crack damage (Giurgiutiu et al 2003). The frequency tuning of Lamb wave attempts to modify the excitation parameters such as to excite certain mode for detecting certain damage. With wedge-coupled conventional ultrasonic transducers, guided wave tuning is performed by varying the frequency and the wedge angle until a maximum response is recorded. The change in frequency modifies the wave speed of the dispersive guided wave, while the change of wedge angle modifies the wave conversion relationship in Snell’s law. It is shown that combinations of wedge-angles and excitation frequencies were able to generate increase response in certain guided-wave modes (Rose 2002).

PWAS are capable of geometric tuning through matching between their characteristic direction and the half wavelength of the excited Lamb mode. In this research, PWAS tuning means to tune the excitation at a frequency where S0 Lamb mode dominates and A0 Lamb mode is minimized. Giurgiutiu showed that given PWAS length $2a$, plate thickness $2d$, and material properties $\mu$ and $\lambda$, it is possible to find frequencies at which only one mode is excited (tuning frequency) (Giurgiutiu 2005). A plane-strain analysis of the PWAS-structure interaction using the space-domain Fourier analysis has been developed to illustrate the principle of PWAS Lamb wave
mode tuning; a selected Lamb mode can be tuned by choosing the appropriate frequency and PWAS dimensions. A plot of the strain solution in the 0~700 kHz bandwidth for an aluminum plate of 1 mm thickness installed with 7 mm round PWAS is presented in Figure 3a while Figure 3b presents the group velocity of PWAS Lamb waves. In Figure 3a, a S0 tuning frequency around 300 kHz can be found, where the amplitude of the A0 mode is minimized while that of the S0 mode is still strong. Therefore, we have tuning of the S0 mode and are able to reject the A0 mode at 300 kHz. These predictions have been extensively experimentally verified (Giurgiutiu 2005). We see that Lamb wave tuning offers considerable advantages, allowing us to select Lamb waves that are most appropriate for the particular application being considered.

![Figure 3](image)

**Figure 3** Lamb wave S0 mode tuning on a 1-mm thick aluminum plate using 7-mm round PWAS within 0~700 kHz range. (a) strain curve; (b) group velocity (dispersion curves)

### 2.2. PWAS pitch-catch sensing for corrosion detection

The proposed PWAS pitch-catch sensing system will take advantage of PWAS ability to serve as guided wave transducer. As shown in Figure 4a, a sensor network using 7-mm round PWAS sensor is installed and a 50 mm x 38 mm area used to simulate the corrosion by removing material from the plate, as shown in Figure 4b. The corrosion is located exactly at the same position of PWAS #2 on the other side of the plate. To simulate different level of corrosion, 7 records of different depths of material are removed. Depth of corrosion is summarized in Table 1 in terms of each record. Then two pitch-catch experiments on the PWAS pair 14 (PWAS #1 as transmitter and PWAS #4 as receiver) and pair 04 (PWAS #0 as transmitter and PWAS #4 as receiver) are conducted. The pitch-catch experiment sends out a 3-count tone-burst signal from a HP 33120A signal generator to one PWAS and the received signal at the other PWAS is recorded by a TDS-210 digital oscilloscope. By using pitch-catch method for guided wave damage detection, if the wave travels through a region where there is a change in material properties, such as thickness decreasing in corrosion, the directly transmitted signal will be modified and the receiving signal will provide good information about the corrosion development across the transmitting and receiving transducer path.

![Figure 4](image)

**Figure 4** PWAS multi-mode corrosion detection system

<table>
<thead>
<tr>
<th>Records</th>
<th>ΔD (mm)</th>
<th>ΔD/D0 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0.38</td>
<td>11.81</td>
</tr>
<tr>
<td>2</td>
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<tr>
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<td>1.45</td>
<td>43.89</td>
</tr>
<tr>
<td>7</td>
<td>1.63</td>
<td>50.34</td>
</tr>
</tbody>
</table>

For Lamb wave applications, frequencies below 1 MHz:mm usually are selected where only two fundamental modes, S0 and A0, are excited to simply the analysis. Our previous study has found out that S0 mode is not significantly affected by surface damage such as corrosion (Giurgiutiu et al 2003). Hence, frequency tuning was first conducted to find out the “sweet spot” where S0 mode is minimized and A0 mode dominates, which was finally chosen at 57 kHz. Signals received on PWAS #4 when PWAS #0 sent at various corroded
depth are shown in Figure 5a while the received signals when PWAS #1 sent are shown in Figure 5b (only the electromagnetic coupling and the first arrival wave packets are shown). It can be noticed from Figure 5a that the first arriving A0 wave packet suffers shifting (being delayed) in time scale and the amplitude increased at first (from data set baseline 0 to record 4) and then decreased (for record 5 when thinning is about 40%). Note the first wave packets in Figure 5 are electromagnetic coupling signals caused by close wiring of PWAS transducers in the data collection system.

![Figure 5 Pitch-catch signals on aluminium plate at various corroded depth.](image)

Figure 5 Pitch-catch signals on aluminium plate at various corroded depth. (a) received signals at PWAS #4 when PWAS #0 sent; (b) received signals at PWAS #4 when PWAS #1 sent. The first wave packets are electromagnetic coupling signal, followed with arrival A0 wave packets.

3. STATISTICAL DAMAGE INDICATOR

In using pitch-catch method for guided wave damage detection, if the wave travels through a region where there is a change in material properties, such as thickness decreasing in corrosion, the directly transmitted signal will be modified and the receiving signal will provide good information about the corrosion development across the transmitting and receiving transducer path. The change can be obtained by subtracting the baseline data recorded for the structure without corrosion from the receiving data for the structure with the developing corrosion damage. The difference is a good indicator for the corrosion detection parameter since it carries information of both amplitude changes and the phased changes from the corrosion growth. The damage indicator (DI) is defined as the relative ratio of the difference between each measurement and baseline signals to the baseline signal:

\[
\text{Damage index (DI)} = \sqrt{\frac{1}{\sum_{j=0}^{N-1} s_j(j) - s_0(j)}^2} \sum_{j=0}^{N-1} s_0(j)^2
\]

where \(s_j\) is the \(j\)th measurement and \(s_0\) is the baseline signal, and \(N\) is the data length.

The results of damage index are provided against corrosion depth in Figure 6. Due to the corrosion development along the path of pair 04, the material depth change caused a change in the A0 wave velocity, as indicated by the wave speed curve of A0 in Figure 7. Therefore, a significant change on DI curve of pair 04 is observed. The change on DI curve of pair 14, on the contrary, was small comparatively since this path was not affected. However, in Figure 6 we see that for the DI curve of pair 04, the damage index works well from record 1 till record 4 but fail to increase with the growth of corrosion from record 5 to record 7. The reason is that the magnitude of A0 increase from record 1 to record 4 and then decrease from record 5 to record 7 as shown in Figure 6. Although both the change in magnitude and phase will affect the damage index, obviously the damage index is more sensitive to magnitude changes, which are not consistent with the corrosion levels. In the next section, phase related methods will be explored and used for corrosion detection.

![Figure 6 DI curves of PWAS pairs 04 and 14](image)

4. TIME-FREQUENCY ANALYSIS: THE PHASE DIFFERENCE DAMAGE INDICATOR

According to Giurgiutiu (2005), the wave speed of A0 wave pack depends on the product \(f\cdot d\) between the frequency, \(f\), and the plate half-thickness, \(d\), as shown in the wave speed curves in Figure 7.

![Figure 7 Wave speed curves for Antysymmetric modes Lamb waves in an aluminum plate (c_s=shear wave speed, d=half-thickness of the plate).](image)
In our experiment, the $f$ is tuning to 57 kHz to make the value of $f \cdot d$ lie inside the circled portion where the wave speed is very sensitive to the changes of the thickness of the plate, that is, the corrosion depths. It is obvious that the wave speed change will result in the phase difference of the A0 wave packs between the baseline and different corrosion depths. The theoretical value of the phase difference can be calculated as following:

$$\phi = 2\pi \left( \frac{L}{C_2} - \frac{L}{C_1} \right)$$  \hspace{2cm} (3)

Where $L$ is the length of the corrosion, $C_1$ is the wave speed before the corrosion while $C_2$ is the speed after the corrosion. Two methods, one based on the classical Fourier transform and the other based on the time-frequency analysis (Cohen’s class), will be used to evaluate the phase changes in each corrosion signal compared with the pre-corrosion baseline.

4.1. Traditional cross power spectral analysis

The classical Fourier-based cross spectral analysis is to analyze the frequency content of two signals and calculate phase difference for corresponding frequency. It takes the cross correlation of two signals and then calculates Fourier transform of the resultant.

Figure 8 shows the cross power spectrum and its phase spectrum of Pair 04 path for record 1. A theoretical curve is given based on Eq. (3) with $L=62.8$ mm (diagonal of the rectangular corrosion area) and $C_1 C_2$ as speeds corresponding to different product of $f \cdot d$ ($d$: corrosion depth). The power spectrum shows several peaks from 40 kHz to 70 kHz which implies existence of multiple frequency components in the signal, but only the one at 57 kHz is of interest which is the center frequency content of A0 wave packs. The phase difference of A0 wave packs between the record 1 and baseline can be found in the corresponding phase spectrum. The results of all corrosion records are summed up in Table 2 and plotted against corrosion depth in Figure 9 (dash line with square marker for experimental pair 04 data). In Figure 9, the phase difference of Pair 04 increase with the depth until record 6, while the phase difference of Pair 14 change around 0 radians. It can be determined from the results that the corrosion is located on the Pair 04 path, but can not tell the corrosion level because the discrepancy with the theoretical value increases with the growth of corrosion. The reason for that is the classical cross power spectral analysis utilizes the entire waveforms which have time dependant frequency content in this example. The E/M coupling wave pack and the noise in the waveforms will harm the accuracy of phase measurement of A0 wave pack.

<table>
<thead>
<tr>
<th>Records</th>
<th>Theoretical Value</th>
<th>Cross Spectral Analysis (Traditional Method)</th>
<th>Cross Time-Frequency Analysis (Proposed Method)</th>
</tr>
</thead>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
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<td>0.55</td>
<td>0.71</td>
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</tr>
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<td>3.35</td>
<td>1.64</td>
<td>3.22</td>
</tr>
<tr>
<td>7</td>
<td>4.07</td>
<td>1.47</td>
<td>4.15</td>
</tr>
</tbody>
</table>

4.2. Time-frequency analysis

Time-frequency analysis provides an effective tool for non-stationary signal analysis by a time and frequency localized signal representation. Various methods have been applied to a variety of applications; and Cohen’s class generalizes various types of the time-frequency distributions in terms of a kernel (Cohen 1989). The limitation of Cohen’s class in our application is that the traditional definition of the time-frequency distribution within Cohen’s class concerns a non-
stationary signal and to generate the time-varying energy spectrum. Thus, another critical feature of the signal, the phase difference, is not available in the real-valued time-frequency distribution function. In this research, we proposed the cross time-frequency distribution function to preserve the phase difference aspects of two signals (Williams 1998)(Shin et al 2000).

4.2.1. Cross time-frequency distribution

Cohen’s class of time-frequency distribution is defined by the following equation:

\[
C_n(t, \omega; \phi) = \frac{1}{4\pi^2} \int \int x^*(u - \frac{\tau}{2}) x(u + \frac{\tau}{2}) \phi(\tau) \exp(-j\omega \tau) \exp(-j\theta) d\omega d\tau
\]

(4)

where \( \phi(\tau) \) is the kernel of the time-frequency distribution and \( x(t) \) is the analytic signal representation. The asterisk sign represent the complex conjugate. Cohen’s class can also be expressed in terms of a generalized ambiguity function where the distribution is based on the instantaneous autocorrelation function (Cohen 1998).

The cross time-frequency analysis starts with the instantaneous cross correlation function (Shin et al 2000). For a pair of signal \( x_1(t) \) and \( x_2(t) \), the instantaneous cross correlation is defined as

\[
R_{x_1x_2}(t, \tau) = x_1(t + \frac{\tau}{2}) x_2^*(t - \frac{\tau}{2})
\]

(5)

The ambiguity function then is found as

\[
A_{x_1x_2}(\theta, \tau) = \frac{1}{2\pi} \int x_1(t + \frac{\tau}{2}) x_2^*(t - \frac{\tau}{2}) \exp(j\theta) dt
\]

(6)

Similarly to the definition of Cohen’s class, the cross Wigner distribution is expressed in terms of the ambiguity function as

\[
W_{x_1x_2}(t, \omega) = \int \int A_{x_1x_2}(\theta, \tau) \exp(-j\omega \tau) d\omega d\tau
\]

(7)

From the cross Wigner distribution, other types of generalized cross time-frequency distribution function can be obtained in terms of a kernel as well as follows

\[
J_{x_1x_2}(t, \omega; \phi) = \frac{1}{2\pi} \int \int A_{x_1x_2}(\theta, \tau) \phi(\theta, \tau) \exp(-j\omega \tau) d\omega d\theta
\]

(8)

For more details of the derivation and properties of the generalized cross time-frequency analysis, please refer to the references (Shin et al 2000).

4.2.2. Detection by cross time-frequency analysis

When cross time-frequency analysis is applied to the corrosion data, study of the phase difference of the specific frequency, 57 kHz of excitation, and specific time duration where A0 arrives can quantify the relationship of the corrosion depth and phase difference.

The cross time-frequency analysis between the baseline and record 1 of pair 04 is taken and shown in Figure 10. Figure 10a shows the time domain waveform of the baseline and the record 1. Figure 10b shows the corresponding phase of the cross time-frequency distribution between the two signals as a function of time w.r.t. 57 kHz which indicates the phase difference of the two signals changes with time. As observed from the figure, the phase difference is basically a constant during the A0 wave packet existence as 0.73 radian. The calculation results are summarized in Table 2 and plotted against the corrosion depth in Figure 9 as well (solid line with star marker for experimental pair 04 data and solid line with square marker for experimental pair 14 data, respectively). It can be seen that the phase differences between different records and baseline of pair 04 are pretty close to the theoretical values and those of pair 14 changes around 0 radian. So the phase information obtained from cross time-frequency analysis can not only determine which path the corrosion is located, but also determine the extent of the corrosion damage. Cross time-frequency analysis is shown as a more powerful tool in this research by taking localized signal information.
determine the presence of corrosion damage. Results showed that though statistical damage indicator and classic cross power spectrum can indicate the presence of corrosion, they fail to determine the corrosion depth correctly. By utilizing time-frequency localized phase difference information, Cross time-frequency distribution can not only correctly evaluate the phase difference of specific frequency and time, it also carries useful information of phase difference, which strongly correlated to the physics of corrosion detection using Lamb waves.

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