ABSTRACT

Structural health monitoring (SHM) is an emerging technology with great potential in structural diagnosis and prognosis. SHM systems can be passive or active. Active SHM systems rely on structural interrogation using active sensors (transducers) that can transmit and receive ultrasonic Lamb waves traveling at large distances in the structural material. Piezoelectric-wafer active sensors (PWAS) are small, inexpensive, non-invasive, transmitters and receivers of ultrasonic Lamb waves that can be permanently affixed to structures. The paper presents results on the dual use of PWAS for structural health monitoring through: (a) tuned traveling Lamb waves using the pitch-catch, pulse echo, and phased-array methods, and (b) broadband standing Lamb wave approach using the high-frequency electromechanical (E/M) impedance method. This paper shows that the traveling-wave and standing-wave approaches are complementary to each other and can be used with the same installation of PWAS transducers. Three examples are discussed: (a) detection of cracks in aircraft panel specimens; (b) monitoring of crack growth in an Arcan specimen under mixed-mode fatigue fracture testing; (c) disbonds detection in adhesively bonded specimens. In all three cases, both traveling waves and standing waves were used. The paper ends with conclusions and suggestions for further work.

Keywords: structural health monitoring, piezoelectric wafer active sensors, pitch-catch, pulse-echo, phased array, electromechanical impedance; damage detection, crack propagation, adhesives, joints, disbonds, diagnosis, prognosis, mixed-mode fracture, NDE, NDI, SHM, PWAS

INTRODUCTION

Structural health monitoring (SHM) is a method of determining the health of a structure from the readings of a number of permanently-attached sensors that are monitored over time. SHM can be performed in basically two ways, passive and active. Both approaches aim at performing a diagnosis of the structural safety and health, to be followed by a prognosis of the remaining life. Passive SHM consists of monitoring a number of parameters (loading stress, environment action, performance indicators, acoustic emission from cracks, etc.) and inferring the state of structural health from a structural model. This method uses passive sensors which only “listen” to the structure but do not interact with it. Therefore, passive SHM does not provide a direct measurement of the damage presence and intensity. In contrast, active SHM uses active sensors that interact with the structure and thus determine the presence or absence of damage. Active SHM performs proactive interrogation of the structure, detects damage, and determines the state of structural health from the evaluation of damage extend and intensity. The methods used for active SHM resemble the NDE methods only that they are used with embedded sensors. Hence, the active SHM could be seen as a method of embedded (or in-situ) NDE.

PIEZOELECTRIC WAFER ACTIVE SENSORS -- PWAS

Conventional ultrasonic transducers are inappropriate for active SHM applications due to their cost, weight, and size. Conventional ultrasonic transducers could not be embedded in large numbers into a structure without incurring important cost and weight penalties. For SHM applications, new types of ultrasonic Lamb-wave transducers must be developed; they must be small, light weight, unobtrusive, and low cost. In addition, they should have intelligence and communication capabilities.
integrated into a miniaturized system design. With such capabilities, they could do local signal processing and decision, and would be able to communicate a structural health bulletin wirelessly to a central station.

An essential element in an active SHM system is the piezoelectric wafer active sensors (PWAS)\cite{1}\cite{2} which provide the bidirectional energy transduction from the electronics into the structure, and from the structure back into the electronics. PWAS are small and lightweight. They are also relatively low cost. PWAS are inexpensive transducers that operate on the piezoelectric principle, which couples the electrical and mechanical effects (mechanical strain, $S_{ij}$, mechanical stress, $T_{kl}$, electrical field, $E_k$, and electrical displacement $D_j$) through the tensorial equations:

$$
S_{ij} = s_{ijkl}^E T_{kl} + d_{ijkl} E_k
$$

$$
D_j = d_{jkl} T_{kl} + \varepsilon_{jk}^T E_k
$$

where $s_{ijkl}^E$ is the mechanical compliance of the material measured at zero electric field ($E = 0$), $\varepsilon_{jk}^T$ is the dielectric permittivity measured at zero mechanical stress ($T = 0$), and $d_{ijkl}$ represents the piezoelectric coupling effect. PWAS are small and unobtrusive. PWAS couple their in-plane motion with the Lamb-waves particle motion on the material surface. Through the $d_{31}$ piezoelectric coupling, an applied oscillatory voltage excites the in-plane PWAS motion, which in turns excites Lamb waves into the structure. PWAS couple their in-plane motion with the Lamb-waves particle motion (Figure 1). Conversely, when ultrasonic waves reach a PWAS, the piezoelectric effect converts the mechanical displacement into electric voltage. PWAS act as both Lamb-wave exciters and Lamb-wave detectors. Optimum excitation and detection happens when the PWAS length is an odd multiple of the half wavelength of certain Lamb wave modes. This shows that PWAS are capable of geometric tuning. Rectangular shaped PWAS with high length to width ratio can generate unidirectional Lamb waves through half wavelength tuning. Circular and square PWAS excite omnidirectional Lamb waves that propagate in circular wave fronts.

Figure 1: Typical structure of $S_0$ and $A_0$ Lamb wave modes, and the interaction of PWAS with the Lamb waves

PWAS have commonality with conventional ultrasonic transducers since both use the piezoelectric effect. However, PWAS are different from conventional ultrasonic transducers in several ways:

1) Conventional ultrasonic transducers are weakly coupled with the investigated structure through gel, water, or air. In contrast, **PWAS are strongly coupled with the structure** through an adhesive bond.

2) Conventional ultrasonic transducers are resonant narrow-band devices. In contrast, **PWAS are non-resonant broadband devices that can be tuned selectively into certain Lamb modes**.

3) Conventional ultrasonic transducers excite and sense the Lamb waves in the structure indirectly through acoustic waves impinging on the structural surface followed by the mode conversion phenomenon. In contrast, **PWAS excite and sense the Lamb waves in the structure directly through in-plane strain coupling**.
PWAS can be bonded to the structure (Figure 2a), or inserted into a composite structure. PWAS achieve direct transduction of electric energy into elastic energy and vice-versa. Figure 2b illustrates the use of PWAS in active SHM using transmitter-receiver (pitch-catch) and pulse-echo techniques.

Figure 2: (a) Four PWAS installed on an aircraft panel near a crack emanating from a rivet hole; (b) of active structural health monitoring principles with PWAS transducers

In recent years, the use of embedded PWAS for the detection of material damage with Lamb-wave techniques has experienced an ascending trend. This use of PWAS for SHM has followed two main paths:

(a) Wave propagation
(b) Electromechanical impedance

Chang and collaborators [3],[4] were among the early researchers to experiment with in-situ piezoelectrics for detection of material damage through wave propagation. Wang and Chang[5] extended this method to delamination damage identification in a composite plate. They showed that it is possible to detect impact damage in composite structures with four piezoelectric wafer transducers operating in a pitch-catch mode. The A₀ Lamb wave mode was excited and the location of the damage was determined through processing of scatter and time of flight data. More work in this area was reported by [6][7][8] and others. Similar work was done in Europe [9] [10] [11]. Lemistre et al. [12] studied the propagation of PWAS generated Lamb waves in laminated composite materials and their diffraction by defects. They showed that S₀ mode Lamb waves incident onto a delaminated region are diffracted as S₀, A₀, and SH₀ guided waves through the mode conversion phenomenon. The wavelet transform decomposition was used to extract the various guided wave modes generated by the diffraction process. The use of PWAS in conjunction with the electromechanical impedance has also been explored with considerable success [13][14][15].

Evaluating the use of PWAS for SHM, Giurgiutiu and collaborators [1],[2] have shown that PWAS can be used as both active and passive probes and thus can address four SHM needs:

1. **Active sensing of far-field damage** using pulse-echo, pitch-catch, and phased-array methods[16]
2. **Active sensing of near-field damage** using high-frequency impedance method[17]
3. **Passive sensing of crack initiation and growth** through acoustic emission [18]
4. **Passive sensing of damage-generating events** through detection of low-velocity impacts [18]

A series of successful experiments have shown that PWAS are positioned as one of the enabling technologies for active SHM implementation. Experimentation in this novel field continues in parallel with thoroughly conducted theoretical studies to identify the physical and mathematical modeling of the PWAS interaction with the Lamb waves in the structure. This will permit, in the near future, the construction of optimal configurations for enhanced excitation/detection performance [19][20].
PWAS-GENERATED TRAVELING LAMB WAVES FOR DAMAGE DETECTION

PWAS-generated traveling Lamb waves can be used in either pitch-catch or pulse-echo method. The pitch-catch method can be used to detect structural changes that take place between a transmitter transducer and a receiver transducer. The detection is performed through from the examination of the guided wave amplitude, phase, dispersion, and time of flight in comparison with a “pristine” situation. Guided wave modes that are strongly influenced by small changes in the material stiffness and thickness (such as the A\textsubscript{0} Lamb wave) are well suited for this method. Typical applications include: (a) corrosion detection in metallic structures; (b) diffused damage in composites; (c) disbond detection in adhesive joints; (d) delamination detection in layered composites, etc. Further advancements in this direction were achieved through acousto-ultrasonics (Duke, 1988). Pitch-catch method can also be used to detect the presence of cracks from the wave signal diffracted by the crack. The pulse echo method was developed in conventional NDE for through-the-thickness testing. For large area inspection, through-the-thickness testing requires manual or mechanical moving of the transducer over the area of interest, which is labor intensive and time consuming. As an alternative, guided Lamb-waves can be used. A guided-wave pulse echo approach allows wide coverage from a single location.

Of particular interest is the phased-array implementation of pulse-echo method [16]. A PWAS phased-array can interrogate a wide structural area and detect structural damage using a steering-beam of ultrasonic Lamb waves similar to the way the phased-array radar uses a steering beam of electromagnetic waves to detect a flying target. This concept has been named embedded ultrasonic structural radar (EUSR) [16]. An aluminum plate was instrumented with a number $M$ of PWAS transducers arranged in a linear phased array. In order to implement the phased array principle, an array of $M^2$ elemental signals is collected. The elemental signals are obtained by performing excitation of one PWAS and detection on all the PWAS, in a round robin fashion. After the $M^2$ elemental signals are collected and stored in the computer memory, the phased array principle is applied in virtual time using the EUSR algorithm and the EUSR LabVIEW program described in [16]. The elemental signals are processed by the EUSR program (Figure 3) using the phased-array beam forming formulas based on the azimuthal angle $\theta$. The azimuthal angle $\theta$ is allowed to vary in the range 0° to 180°. Thus, a sweep of the complete half plane is attained. At each azimuthal angle, an A-scan of the Lamb wave beam signal is obtained. If the beam encounters damage, reflection/diffraction from the damage will show as an echo in the A-scan.

![Simulated crack (20mm slit)](a)

1220-mm sq., 1-mm thick 2024 T3
(48-in sq., 0.040-in thick)

PWAS array

![Crack image](b)

Figure 3: EUSR experiment in a square plate: (a) location and size of simulated crack; (b) imaging and echo of broadside crack in the EUSR algorithm

In Figure 3a, the damage is a 20-mm narrow slit simulating a through-the-thickness crack. The A-scan shown in Figure 3b indicates clearly the crack echo obtained when the scanning beam is oriented at 90°. Azimuthal juxtaposition of all the A-scan signals creates an image of the half plane. The damage is clearly indicated as darker areas. Using the wave speed, the time domain signals are mapped into the space...
domain. A measuring grid is superposed on the reconstructed image to determine the position of the crack. Thus, the exact location of the damage can be directly determined.

**ELECTROMECANICAL IMPEDANCE METHOD FOR DAMAGE DETECTION (PWAS-GENERATED STANDING LAMB WAVES)**

The electro-mechanical (E/M) impedance method [13],[15] is a PWAS-based damage-detection technology that measures directly the pointwise mechanical impedance of the structure through the real part of the electrical impedance measured at the PWAS terminals. The principles of the E/M impedance technique are illustrated in Figure 4. The drive-point impedance presented by the structure to the PWAS can be expressed as the frequency dependent variable, \(Z_{\text{str}}(\omega) = k_{\text{str}}(\omega)/i\omega = k_{\text{PWAS}}(\omega) - \omega^2 m(\omega) + i\omega c_\omega(\omega)\). Through the mechanical coupling between the PWAS and the host structure, on one hand, and through the electro-mechanical (E/M) transduction inside the PWAS, on the other hand, the drive-point structural impedance is reflected directly in the electrical impedance, \(Z(\omega)\), at the PWAS terminals:

\[
Z(\omega) = \frac{i\omega C \left(1 - \kappa_{31}^2 \frac{\chi(\omega)}{1 + \chi(\omega)}\right)^{-1}},
\]

where \(C\) is the zero-load capacitance of the PWAS and \(k_{31}\) is the electro-mechanical cross coupling coefficient of the PWAS transducer \((\kappa_{31} = d_{13}/\sqrt{\kappa_{11}\kappa_{33}})\), and \(\chi(\omega) = k_{\text{str}}(\omega)/k_{\text{PWAS}}\), with \(k_{\text{PWAS}}\) being the static stiffness of the PWAS.

![Figure 4: Electro-mechanical coupling between PWAS and structure](image)

The electro-mechanical impedance method is applied by scanning a predetermined frequency range in the high kHz band and recording the complex impedance spectrum. During a frequency sweep, the real part of the E/M impedance, \(\text{Re}Z(\omega)\), follows the up and down variation as the structural impedance as it goes through the peaks and valleys of the structural resonances and anti-resonances [13]. By comparing the real part of the impedance spectra taken at various times during the service life of a structure, meaningful information can be extracted pertinent to structural degradation and the appearance of incipient damage. On the other hand, analysis of the impedance spectrum supplies important information about the PWAS integrity. The frequency range used in the E/M impedance method must be high enough for the signal wavelength to be significantly smaller than the defect size. From this point of view, the high-frequency E/M impedance method differs organically from the low-frequency modal analysis approaches.

**CRACK DETECTION IN AIRCRAFT PANELS**

The first example to be discussed is that of detecting cracks in realistic specimens representative of actual aerospace structures with aging-induced damage (Figure 5). These specimens have structural details typical of metallic aircraft structures (rivets, splices, stiffeners, etc.). The specimens were made of 1 mm (0.040") thick 2024-T3 Al-clad sheet assembled with 4.2 mm (0.166") diameter countersunk rivets. These structural details complicate the structural dynamics and make the damage detection task more difficult. Cracks were simulated with electric discharge machined (EDM) slits. We investigated crack damage and considered two specimens: pristine (Panel 0), and damaged (Panel 1). The objective

<table>
<thead>
<tr>
<th>Table 1: Position of PWAS on aircraft panels</th>
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<tbody>
<tr>
<td>Panel 0</td>
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<tr>
<td></td>
</tr>
<tr>
<td>Pristine</td>
</tr>
<tr>
<td>S1</td>
</tr>
<tr>
<td>S3</td>
</tr>
<tr>
<td>S5</td>
</tr>
<tr>
<td>S7</td>
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of the experiment was to detect a 12.7 mm (0.5”) simulated crack originating from a rivet hole (Figure 5). The panels were instrumented with eight PWAS (Table 1). On each panel there were four PWAS, two placed in the medium field (100 mm from the crack location), and two in the near field (10 mm from the crack location).

**Pulse-echo Method Applied to the Aircraft Panels**

Pulse-echo wave propagation tests were conducted to illustrate crack detection through this approach[2]. Figure 6 shows three photographs of PWAS installation on increasingly more complex structural regions of the panel. Adjacent to the photographs are the PWAS signals. All the experiments used only one PWAS, operated in pulse-echo mode. The PWAS was placed in the same relative location, i.e., at 200 mm to the right of the vertical row of rivets. The first row of Figure 6 shows the situation with the lowest complexity, in which only the vertical row of rivets is present in the far left.

The echoes start to arrive at approximately 60 µs. The second row of Figure 6 shows the vertical row of rivets. The signal to the right of this photograph shows the initial bang (centered at around 5.3 micro-sec) and multiple reflections from the panel edges and the splice joint. In the far left and, in addition, a horizontal double row of rivets stretching towards the PWAS. The signal to the right shows that, in addition to the multiple echoes from the panel edges and the splice, the PWAS also receives backscatter echoes from the rivets located at the beginning of the horizontal row. These backscatter echoes are visible at around 42 µs. The third row in Figure 6 shows a region of the panel similar to that presented in the previous row, but having an addition feature: a simulated crack (12.7-mm EDM hairline slit) emanating from the first rivet hole in the top horizontal row. The signal at the right of this photo shows features similar to those of the previous signal, but somehow stronger at the 42 µs position. The features at 42 µs correspond to the superposed reflections from the rivets and from the crack.

Figure 5: Aging aircraft skin panel with enlarged area of PWAS installation for E/M impedance tests
Figure 6: Crack-detection laboratory experiments on an aircraft panel (1-mm 2025 T3): left column shows areas with increasing complexity. Right column represents the pulse-echo signals. Fourth cell in the right column shows the crack detection through the differential signal method.

The detection of the crack seems particularly difficult because the echoes from the crack and from the rivets are superposed. This difficulty was resolved by using the differential signal method, i.e., subtracting the signal presented in the second row from the signal presented in the third row. In practice, such a situation would correspond to subtracting a signal previously recorded on the undamaged structure from the signal recorded now on the damaged structure. Such a situation of using archived signals is typical of health monitoring systems. When the two signals were subtracted, the result presented in the last row of Figure 6 was obtained. This differential signal shows a “loud and clear” echo due entirely to the crack. The echo, marked “reflection from the crack” is centered at 42 µs, i.e., TOF = 37 µs which correlates very
well with a 5.4 km/s 200-mm total travel from the PWAS to the crack placed at 100 mm. The cleanness of the crack-detection feature and the quietness of the signal ahead of the crack-detection feature are remarkable. Thus, we concluded that PWAS are capable of clean and un-ambiguous detection of structural cracks.

**ELECTROMECHANICAL IMPEDANCE APPLIED TO THE AIRCRAFT PANELS**

The E/M impedance tests were conducted with an HP 4194A impedance analyzer connected to a PC through the GPIB interface[21]. In these test, all the eight PWAS were measured. It was anticipated that PWAS placed in a similar configuration with respect to structural details (rivets, stiffeners, etc.) would give similar E/M impedance spectra. It was also anticipated that the presence of damage would change the PWAS readings. The PWAS # S1, S2, S3, and S5, S6, S7 were in pristine regions, and should give similar readings, while S4 and S8 were in damaged regions, and should give different readings. High frequency E/M impedance spectrum in the 200-550 kHz band was collected for each PWAS. During the experiment, both aircraft panels were supported on foam to simulate free boundary conditions. Two separate situations are considered: (a) medium field, i.e. PWAS # 1, 2, 3, 4, each placed at 100 mm from the site of interest; and (b) near field, i.e., PWAS #5, 6, 7, 8 placed at 10 mm from the site of interest. The medium field experiment was designed to estimate ability of PWAS to detect damage in a wider area. In this study, the medium field is called the area with a radius of about 100mm where the detection of damage is still possible, but the effect of damage does not manifested as drastically on the E/M impedance spectra as in the near field. The distance between PWAS and crack for the medium field experiment was 8 times bigger than for near field experiment. The relative size of near field and medium field of PWAS is depicted in Figure 7b. Two methods of spectral classification were used: (i) probabilistic neural networks; and (ii) overall statistics.

![Figure 7: Schematics of the aging aircraft panel specimens and PWAS configuration: (a) panel 0, sensors S1, S2, S5, S6; (b) panel 1, sensors S3, S4, S7, S8](image-url)
Probabilistic Neural Network Spectral Classification

To compare the PWAS spectra we used a probabilistic neural network (PNN) algorithm. The spectral features considered in the analysis were the resonance frequencies. A features extraction algorithm was used to obtain the features vectors. The 48 extracted features are shown graphically in Figure 8a for a “pristine” situation (S1) and in Figure 8b for a “damage” situation (S4). The resonance peaks picked by the feature extraction algorithm are marked with a cross in the data point. In total, four feature vectors, each 48 long, resulted for the medium field, and another four for near field. In each group of four feature vectors, three vectors represented “pristine” condition (S1, S2, S3, and S5, S6, S7) while the fourth vector represented a “damage” condition (S4 and S8, respectively). These vectors were used as inputs to the PNN.

Since the PNN was designed to classify data into two classes: “pristine” and “damage”, we used one of three “pristine” input vectors for training, and the other three vectors (two “pristine” and one “damage”) for validation. The results of the PNN study indicated that, regardless of choice of training vector for the “pristine” class, the PNN was able to correctly classify data into the correspondent classes. These results are presented in Table 2, where T indicates training, and V validation.

<table>
<thead>
<tr>
<th>Vector</th>
<th>Medium Field</th>
<th>Near Field</th>
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<tbody>
<tr>
<td>S1</td>
<td>T V V V T V V</td>
<td>V T V V V V</td>
</tr>
<tr>
<td>S2</td>
<td>0 0 1 0 0 0 1</td>
<td>OUT</td>
</tr>
<tr>
<td>S3</td>
<td>0 0 0 1 0 0 1</td>
<td>OUT</td>
</tr>
<tr>
<td>S4</td>
<td>0 0 0 1 0 0 1</td>
<td>OUT</td>
</tr>
<tr>
<td>S5</td>
<td>0 0 0 1 0 0 1</td>
<td>OUT</td>
</tr>
<tr>
<td>S6</td>
<td>0 0 0 1 0 0 1</td>
<td>OUT</td>
</tr>
<tr>
<td>S7</td>
<td>0 0 0 1 0 0 1</td>
<td>OUT</td>
</tr>
<tr>
<td>S8</td>
<td>0 0 0 1 0 0 1</td>
<td>OUT</td>
</tr>
</tbody>
</table>

Legend: T = training, V = validation, 0 = pristine; 1 = damage

Overall Statistics Metrics for Spectral Classification

The overall statistics metrics used in this study were: root mean square difference (RMSD), mean absolute percentage difference (MAPD), and correlation coefficient difference (CCD), i.e.,

$$RMSD = \sqrt{\frac{\sum_{j=1}^{N} [Re(Z_j) - Re(Z_j^0)]^2}{\sum_{j=1}^{N} [Re(Z_j^0)]^2}},$$

(3)
\[ MAPD = \sum_{i=1}^{N} \left| \frac{\text{Re}(Z_i) - \text{Re}(Z_i^0)}{\text{Re}(Z_i^0)} \right|, \]
\[ CCD = 1 - CC, \quad \text{where} \quad CC = \frac{1}{\sigma_Z \sigma_{Z^0}} \sum_{i=1}^{N} \left[ \text{Re}(Z_i) - \text{Re}(Z_i^0) \right] \left[ \text{Re}(Z_i^0) - \text{Re}(Z_i^0) \right], \]

where \( N \) is the number of frequencies in the spectrum and the superscript 0 signifies the pristine state of the structure. The symbols \( Z, Z^0 \) signify mean values, while \( \sigma_Z, \sigma_{Z^0} \) signify standard deviations.

Figure 9a shows the superposition of the spectra obtained from the near field PWAS (S5, S6, S7, S8). Figure 9b shows the dereverberated (DR) curves extracted from the Figure 9a spectra using 9th order polynomial fit. It is clear that three DR’s for “pristine” situation (S5, S6, S7) are very similar. In contrast, the DR for the “damage” scenario, S8, is clearly different. To quantify these DR differences, we used the overall-statistics damage metrics RMSD, MAPD, CCD defined by Equations (3)–(5). The results indicated that the RMSD and MAPD values for the “damage” case are almost double that for the “pristine” case. This indicates good damage detection capability. However, the CCD values indicate an even better detection capability, since the value for the “damage” case was an order of magnitude larger than for the “pristine” case (6.64% vs. 0.55%). This confirms that CCD is a potentially very powerful damage detection metric.

However, the analysis of the dereverberated response did not yield practical results for medium field PWAS, since their E/M impedance spectrum changed much less due to damage than for the near-field PWAS.

CRACK MONITORING IN AN ARCAN SPECIMEN

The second example to be discussed is that of monitoring crack propagation in an Arcan specimen [22]. The specimen was made of 1.2mm thick galvanized mild steel sheet with yield stress of 231 MPa, ultimate tensile stress (UTS) of 344 MPa, and fracture toughness (\( K_{IC} \)) of 140 MPa.m\(^{0.5}\). The Arcan specimen was loaded for mixed mode I/II fracture testing. The specimen was instrumented with nine circular PWAS as shown in Figure 10a. Fatigue load was applied using an MTS 810 Material Test System with 1 Hz to 10 Hz loading rate. After Mode I precracking, the specimen was loaded in mixed mode I/II and a fatigue crack was propagated in stages. After each fatigue-loading stage, a digital image of the specimen and readings of the PWAS were taken. The PWAS data was taken with two methods (i) the E/M impedance method; and (ii) the Lamb wave propagation method. For the impedance method, a
Hewlett Packard 4194A Impedance Analyzer was used. The E/M impedance signatures of the 9 PWAS transducers affixed to the specimen was taken and stored in the PC. In initial trials, the frequency range 100 kHz to 500 kHz was determined as best suited for this particular specimen.

For the Lamb-wave propagation method, the pitch catch approach was used. A three-count tone burst sine wave at a frequency of $3 \times 158$ kHz = 474 kHz and 10 Vpp amplitude was generated with a HP33120 function generator. In a round-robin fashion, the excitation signal was applied to one of the PWAS working as a transmitter. The signals received at the other PWAS were recorded with a Trektronix TDS210 digital oscilloscope. Damage quantification and control was performed using the crack length. The maximum crack length ($a_{\text{max}} = 17.3$ mm) was taken to correspond to maximum damage and was assigned a value of 100% damage. The other intermediate damage cases were assigned damage values proportional with the relative crack size (i.e., \% damage = $a/a_{\text{max}}$). Thus, the damage values 3%, 5%, 8%, 19%, 33%, 42%, 47%, 58%, 69%, 77% and 100% were obtained. At each damage value, the readings of the E/M impedance signature of the nine PWAS transducers stored in the PC were analyzed. Also analyzed were the readings taken of the pitch-catch transmission of Lamb waves between various PWAS (#3 to #1; #3 to #4; #3 to #7; #6 to #1; #6 to #4; and #6 to #7). The process was repeated for each crack length up to the maximum value (17.3 mm at 94,000 cycles).

**Damage Effect on PWAS Readings**

In this specimen, the damage appeared in the form of a progressive crack, initiated at the specimen boundary and propagating diagonally across the specimen under mixed mode fatigue loading. Figure 11a presents typical superposed plots of the impedance signatures obtained at various levels of damage. As the crack advances, the effective high-frequency mechanical impedance seen by the PWAS attached to the specimen changes, as indicated in the E/M impedance signature. Processing of these plots with the RMSD damage metric algorithm of (3) yielded the plot in Figure 11b. Examination of the damage metric plot shows that the RMSD values change monotonically with structural damage.
The crack propagation also induced changes in the path of Lamb transmission across the specimen and hence modified the signal waveform arriving at the receiver PWAS during the pitch-catch experiment (Figure 12). Examination of the pitch-catch signals presented in Figure 12 (vertical shifts were used to separate the signals vertically) indicates that the crack size strongly influences the transmission of Lamb waves in the specimen. At the beginning (0% damage) the transmission of Lamb waves from PWAS #3 to PWAS #7 is direct and unimpeded, resulting in a representative arrival signal in the 10 to 20 micro-sec region (see the 0% curve in Figure 12). As the crack extends, it progressively interferes with the direct wave path and the signal starts to change (see the 3% and 5% curves in Figure 12). These changes become stronger and stronger as the crack extends (see the 8% through 69% curves in Figure 12). Eventually, the crack has extended so much that it obliterates completely the direct wave path and no signal arrives any longer in the 10 to 20 micro-sec region (see the 77% and 100% curves in Figure 12). In this latter case, the waves arrive on a round about path, i.e. in the 20 to 30 micro-sec region. Also apparent in the signal is the effect of wave dispersion and scatter.
These two effects, E/M impedance change and Lamb wave transmission change, though different in nature, are complementary. The E/M impedance change is a high-frequency standing waves effect, while the Lamb-wave transmission change is due to waves being reflected and diffracted by the crack.

**DISBOND MONITORING IN ADHESIVE SPECIMENS**

The third example to be discussed is that of monitoring disbonds in adhesive joints. The wave propagation and E/M impedance methods have been successfully used to monitor adhesive disbonds.

![Figure 13](https://example.com/figure13.png)

**Figure 13** Pitch-catch method for joint inspection: (a) pristine joint carries the signal well from PWAS #1 to PWAS #2 through "leakage"; (b) Disbonded joint cannot carry well the signal resulting in degradation of signal received at PWAS #2

**PITCH-CATCH FOR DISBOND DETECTION**

Figure 13 shows the pitch-catch approach to disbond detection in a lap joint specimen. PWAS #1 transmits wave energy into the left side of the joint. This wave energy is propagated through the adhesive bond into the right side of the joint. This phenomenon is known as wave "leakage" through the bond. The amplitude of the transmitted signal can be a measure of the bond quality. For a healthy bond, the amplitude of the received signal is large. If disbonding has occurred, there will be a decrease in amplitude of the received signal proportional with the severity of the disbonding.

![Figure 14](https://example.com/figure14.png)

**Figure 14** Pitch-catch setup for disbond detection with PWAS was used to send and receive Lamb waves from one PWAS to another PWAS

In our investigation, two adhesively bonded specimens were used. Each specimen consisted of two 178 mm x 36 mm x 1.6 mm 2024 aluminum strips bonded together with cold-cured Loctite Hysol EA 9309.3NA epoxy adhesive system. One specimen was designated pristine specimen. The other specimen was designated specimen with disbond because it contained a 25 mm wide simulated disbond created during the bonding process, using a 25 µm (0.001 in) Mylar strip. Figure 14 shows a schematic of the specimen and of the instrumentation setup. A 120 kHz smoothed tone burst signal was transmitted from PWAS #1 and received at PWAS #3a and PWAS #3b, which are located on the top and
the bottom of the specimen. The received signals were captured on a digital oscilloscope and then stored in a laptop PC. During the experiments, it was observed that the presence of the disbond clearly modifies the signal characteristics.

Figure 12 presents a plot of the results. Four signals are displayed. Vertical shifts were used to separate the signals vertically. The upper two signals represent the signals received at the top and bottom PWAS in the pristine specimen. It is apparent that the two signals are more or less identical. The lower two signals are the signals received at the top and bottom of the specimen with disbond. It is apparent that a clear difference exists between the top and the bottom signals. In addition, these signals are clearly different from the signals in the pristine specimen. The time of flight of the signal from the bottom PWAS is clearly longer than that of the signal from the top PWAS. It is clear that the pitch-catch method can detect disbonds using Lamb waves pitch-catch approach with embedded PWAS.

![Graph showing signal characteristics](https://example.com/graph)

**Figure 15** Lamb wave signals transmitted from top PWAS #1 and received at top PWAS (#3a) and bottom PWAS (#3b), in the pristine and disbond cases.

**E/M IMPEDANCE FOR DISBOND DETECTION**

Two aluminum strips, 178 x 37 x 1.55 mm, where bonded using an epoxy paste adhesive, Hysol® EA 9309.3NA. The disbonding of the two aluminum strips was simulated as a discontinuity of the epoxy paste in the middle of the specimen, having the length of 25 mm. This was done using a strip of Teflon tape. The specimen was instrumented with PWAS sensors and the location of the sensors is shown in Figure 16a.

![Experimental setup](https://example.com/setup)

**Figure 16** The aluminum bonded specimen: (a) experimental setup; (b) the E/M frequency response measured in three locations.
Using an HP4194A impedance analyzer the E/M impedance was measured in three locations as shown in Figure 16a. The E/M frequency response for the three PWAS is presented in Figure 16b. It can be observed that the frequency response is very similar for PWAS #1&3 which are located on a bonded area, but is different for PWAS #2 located on the disbond. We can clearly see new sharp peaks in the frequency spectrum due to disbond.

CONCLUSIONS

Structural health monitoring (SHM) is an emerging technology with great potential in structural diagnosis and prognosis. SHM systems can be passive or active. Active SHM systems rely on structural interrogation using active sensors (transducers) that can transmit and receive ultrasonic Lamb waves traveling at large distances in the structural material. Active SHM emulates the ultrasonic NDE methods for detecting structural damage, but have the advantage of doing on-demand structural interrogation as often as needed. Piezoelectric wafer active sensors (PWAS) are the enabling elements of the active SHM systems currently considered for implementation. PWAS-based SHM can emulate the conventional ultrasonic methods (pitch-catch, pulse-echo, phased arrays, etc.) using traveling Lamb waves. PWAS-based SHM also allows for novel interrogation techniques such as the broad-band electromechanical impedance method based on standing Lamb waves.

This paper has shown that the traveling-wave and standing-wave approaches are complementary to each other and can be used with the same installation of PWAS transducers. Three examples were given: (a) detection of cracks in aircraft panel specimens; (b) monitoring of crack growth in an Arcan specimen under mixed-mode fatigue fracture testing; (c) disbond detection in adhesively bonded specimens. In all three cases, both traveling waves and standing waves were used. It was found that the traveling-wave pulse-echo method can detect the echo due the presence of a crack and extract it from the background echoes using the signal differential method. The traveling-wave pitch-catch approach indicated that a definite change in the transmitted wave characteristics appears as the crack propagates. This change can be attributed to the diffraction of Lamb-wave by the propagating crack. Similarly, definite change in the transmitted wave was observed in the case of disbands. The standing-waves high-frequency E/M impedance approach indicated that the presence of damage produces a definite change in the E/M spectrum due to the presence of a crack or disbond. In the case of aircraft panels, near-field and medium-filed situations were independently studies. It was found that the complex E/M impedance spectra measured in the hundreds of kHz range can be classified into “damaged” and “pristine” using probabilistic neural networks (PNN) algorithms. It was also found that the near-field situation, which is stronger influenced by the damage, can be also classified with simpler overall-statistics metrics, such as RMSD, MAPD, and CCD. The same approach was also successfully applied to the Arcan specimen and the disbond specimen.

Further research needs to be conducted before PWAS-based SHM could be brought to full fruition. The electromechanical coupling between PWAS and the structural Lamb waves must be fully modeled and understood. This would permit the development of PWAS-based SHM solutions that are optimized for specific structural applications. The durability and survivability of the bond between the PWAS and the structure must be fully characterized. A model must be developed to estimate the bond survivability under various environmental/climatic conditions and to predict its durability in service. This is a complex electrical-mechanical-chemical problem that requires an interdisciplinary approach. In the long-term, the in-situ fabrication of PWAS transducers directly onto the structure is a long-term goal that should be explored. This goal could be pursued through an interdisciplinary effort involving microelectronics and nanotechnologies.

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