Structural Health Monitoring and Damage Detection with Piezoelectric Wafer Active Sensors

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Abstract
Piezoelectric wafer active sensors (PWAS) are lightweight and inexpensive enablers for a large class of structural health monitoring (SHM) and damage detection applications. PWAS are multi-mode, i.e., they can be used for damage detection using both active and passive methods and utilizing both traveling guided waves (acousto-ultrasonics) as well as standing waves (vibration) techniques. After a brief review of PWAS physical principles and basic modeling, the paper considers several applications in the areas of: (a) embedded guided-wave ultrasonics, e.g., pulse-echo and phased arrays; (b) high-frequency modal sensing, i.e., the electro-mechanical (E/M) impedance method. The paper ends with conclusions and suggestions for further work.

Key words: Structural health monitoring; SHM; piezoelectric wafer active sensors; PWAS; electromechanical impedance; EMIS; acousto-ultrasonics; guided waves; Lamb waves; damage detection; modal analysis; high frequency; acoustic emission; AE; impact detection; pitch-catch; pulse-echo; phased-arrays; thickness mode

1. Introduction
Structural health monitoring (SHM) is an emerging technology with multiple applications in the evaluation of critical structures. The goal of SHM research is to develop a monitoring methodology that is capable of detecting and identifying, with minimal human intervention, various damage types during the service life of the structure. Numerous approaches have been utilized in recent years to perform structural health monitoring (1)(1)(2); they can be broadly classified into two categories: (a) passive SHM methods and (b) active SHM methods. Passive SHM methods (such as acoustic emission, impact detection, strain measurement, etc.) have been studied longer and are relatively mature; however, they suffer from several drawbacks which limit their utility (need for continuous monitoring, indirect inference of damage existence, etc.). Active SHM methods are of greater interest due to their ability to perform on-demand interrogation of a structure while the structure is still in service. One of the promising active SHM methods utilizes arrays of piezoelectric wafer active sensors (PWAS) bonded to a structure for both transmitting and receiving ultrasonic waves in order to achieve damage detection (3). When used to interrogate thin-wall structures, the PWAS are effective guided wave transducers which couple their in-plane motion with the guided wave particle motion on the material surface. The in-plane PWAS motion is excited by an applied high-frequency voltage through the $d_{31}$ piezoelectric effect. Optimum excitation and detection takes place when the PWAS length is in certain ratios with the wavelength of the guided wave modes. The PWAS action
as ultrasonic transducers is fundamentally different from that of conventional ultrasonic transducers. Conventional ultrasonic transducers act through surface tapping, i.e., by applying vibration pressure to the structural surface. The PWAS transducers act through surface pinching, i.e., strain coupling with the structural surface. This allows the PWAS transducers to have a greater efficiency in transmitting and receiving ultrasonic guided waves when compared with conventional ultrasonic transducers.

2. PWAS Principles

PWAS transducers are the enabling technology for active SHM systems. PWAS couples the electrical and mechanical effects (mechanical strain, $S_{ij}$, mechanical stress, $T_{ij}$, electrical field, $E_k$, and electrical displacement $D_j$) through the tensorial piezoelectric constitutive equations

$$S_{ij} = s_{ijkl} T_{kl} + d_{ijkl} E_k$$
$$D_j = d_{ijkl} T_{ij} + e_{ijkl} E_k$$

(1)

where, $s_{ijkl}$ is the mechanical compliance of the material measured at zero electric field ($E = 0$), $e_{ijkl}$ is the dielectric permittivity measured at zero mechanical stress ($T = 0$), and $d_{ijkl}$ represents the piezoelectric coupling effect. PWAS utilize the $d_{ij}$ coupling between in-plane strain and transverse electric field. A 7-mm diameter PWAS, 0.2 mm thin, weighs a bare 78 mg and costs around ~$1. PWAS are lightweight and inexpensive and hence can be deployed in large numbers on the monitored structure. Just like conventional ultrasonic transducers, PWAS utilize the piezoelectric effect to generate and receive ultrasonic waves. However, PWAS are different from conventional ultrasonic transducers in several aspects:

1. PWAS are firmly coupled with the structure through an adhesive bonding, whereas conventional ultrasonic transducers are weakly coupled through gel, water, or air.
2. PWAS are non-resonant devices that can be tuned selectively into several guided-wave modes, whereas conventional ultrasonic transducers are resonant narrow-band devices.
3. PWAS are inexpensive and can be deployed in large numbers on the structure, whereas conventional ultrasonic transducers are expensive and hence less likely to be deployed in as large a number as the PWAS transducers.

By using Lamb waves in a thin-wall structure, one can detect structural anomaly, i.e., cracks, corrosions, delaminations, and other damage. Because of the physical, mechanical, and piezoelectric properties of PWAS transducers, they act as both transmitters and receivers of Lamb waves traveling through the structure. Upon excitation with an electric signal, the PWAS generate Lamb waves which travel through the thin-wall structure and are reflected or diffracted by the structural boundaries, discontinuities, and damage. The reflected or diffracted waves arrive at the receiver PWAS transducers where they are transformed into electric signals.

PWAS transducers can serve several purposes (3)(4)(5)(6): (a) high-bandwidth strain sensors; (b) high-bandwidth wave exciters and receivers; (c) resonators; (d) embedded modal sensors using the electromechanical (E/M) impedance method. The PWAS transducers have various modes of operation (Figure 1): (i) far-field active sensing using pulse-echo, pitch-catch, and phased-array methods, (ii) near-field active sensing using high-frequency E/M impedance method and thickness-gage mode, and (iii) passive sensing of damage-generating events through detection of low-velocity impacts and acoustic emission at the advancing crack tip. Damage detection using PWAS phased arrays can detect several cracks independently with scanning beam emitted from a central location.
3. Crack Detection with PWAS Pulse-Echo Method

Wave propagation experiments were conducted on an aircraft panel to illustrate crack detection through the pulse-echo method. The panel had a built-up construction typical of metallic aircraft structures: it features a vertical splice joint and horizontal stiffeners. Figure 2 shows photographs of PWAS installation on three structural regions of the panel which are increasingly more complex. 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 line of rivets. The first row of Figure 2 shows the situation with the lowest complexity, in which only the vertical line of rivets is present in the far left. 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. The echoes start to arrive at approximately 60 μs. The second row of Figure 2 shows the vertical line of rivets 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 2 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. 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. The use of archived signals is typical of SHM systems. Subtraction of these two signals yielded the signal presented in the last row of Figure 2. This differential signal shows a “loud and clear” echo due entirely to the crack. The echo, marked "reflection from crack" is centered at 42 μs, i.e., TOF = 37 μs which correlates very well with a 200-mm total travel from the PWAS to the crack placed at 100 mm (note that the wave speed is ~5.4 mm/us). The cleanness of the crack-detection feature and the quietness of the signal ahead of the crack-detection feature

Figure 1 -- Modes of operation of piezoelectric wafer active sensors (PWAS) transducers: (a) propagating guided Lamb waves; (b) standing guided Lamb waves; (c) PWAS phased arrays
are remarkable. Thus, we concluded that PWAS are capable of clean and un-ambiguous detection of structural cracks.

Figure 2 – Crack-detection laboratory experiments on an aircraft panel: left column represents specimens (40-mil 2025 T3) 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

4. PWAS Phased Arrays

The phased array ultrasonic transducers have been developed in conventional ultrasonic NDE for the inspection of very thick specimens, the sidewise inspection of thick slabs, etc. (7). These transducers employ pressure waves generated through normal impingement on the material surface. In our research (6), we have developed a phased array technology for thin wall structures (e.g., aircraft shells, storage tanks, large pipes, etc.) that uses guided Lamb waves to cover a large surface area through beam steering from a central location. We called this concept embedded ultrasonics structural radar (EUSR) and developed a simple proof-of-concept experiment (Figure 3a). A PWAS array was made up of a number of identical 7-mm sq. elements aligned at uniform 9-mm pitch. The PWAS phased array was placed at the center of a 4-ft square thin aluminum plate (Figure 3a).
The wave pattern generated by the phased array is the result of the superposition of the waves generated by each individual element. By sequentially firing the individual elements of an array transducer at slightly different times, the ultrasonic wave front can be focused or steered in a specific direction. Thus, electronic sweeping and/or refocusing of the beam without physical manipulating the transducers is achieved. We proved that inspection of a wide zone is possible by creating a sweeping beam of ultrasonic Lamb waves that covered the whole plate. Once the beam steering and focusing was established, the detection of crack was done with the pulse-echo method. During these proof-of-concept experiments, the EUSR methodology was used to detect cracks in two typical situations: (i) a 19-mm broadside crack placed at 305 mm from the array in the 90 deg direction; and (ii) a 19-mm broadside crack placed at 409 mm from the array in the 136 deg direction. Of these two, the latter was more challenging because the ultrasonic beam is not reflected back to the source but rather deflected sideways. Hence, the echo received from the offside crack is merely the backscatter signal generated at the crack tips. Figure 3b presents the front panel of the embedded ultrasonic structural radar graphical user interface (EUSR-GUI) displaying the
offside signals. The sweep is performed automatically to produce the structural defect image in the right pane. Manual sweep of the beam angle can be also performed with the turn knob; the signal reconstructed at a particular beam angle is shown in the lower pane. In Figure 3b, the lower pane show the signal reconstructed at the beam angle $\phi_0 = 136$ deg corresponding to the crack location.

5. Electromechanical (E/M) Impedance

Modal analysis and dynamic structural identification have become an intrinsic part of engineering practice. Structural frequencies, damping, and modes shapes identified through this process are subsequently used to predict dynamic response, avoid resonances, and even monitor structural change that are indicative of failure. Conventional modal analysis testing relies on two essential components: (a) structural excitation; and (b) vibration pickups. Structural excitation can be either harmonic sweep, or impulse. Vibration pickups can measure displacement, velocity, or acceleration; current technologies include miniaturized self-conditioning accelerometers and laser vibrometers. Due to limitation of structural excitation and accelerometer pickups, conventional modal analysis testing and structural dynamics identification is seldom done at frequencies higher than a few tens of kHz.

PWAS transducers offer structural dynamics identification at hundreds of kHz and low MHz through the electromechanical (E/M) impedance method (8). This approach is ideally suited for detecting minute damage because high frequencies imply small wavelength. PWAS-based electromechanical impedance spectroscopy (EMIS) is able to detect subtle changes in the high frequency structural dynamics at local scales. Such local changes in the high frequency structural dynamics are associated with the presence of incipient damage, which would not be detected by conventional modal analysis sensors that operate at lower frequencies. EMIS is also suited for monitoring small parts of machinery that have high natural frequencies.

It has been shown by theoretical modeling and experimental measurements (8) that the real part of the E/M impedance has essentially the same modal peaks and resonance frequencies as the frequency response function (FRF) under mechanical excitation (Figure 4a). Furthermore, the theoretical model developed to predict the E/M impedance spectrum was shown to give very good agreement with the measured spectrum (Figure 4b). Thus, EMIS method was found to have great potential for in-situ damage detection.

![Figure 4](image-url)  
(a) Experimental and calculated spectra for a pristine circular plate specimen: (a) FRF compared with measured E/M impedance; (b) theoretical and measured E/M impedance (8)

The use of EMIS method for the detection of disbonds in adhesively assembled parts is illustrated in Figure 5. Three PWAS transducers (a1, a2, a3) were attached to an L-section stiffener bonded to a test panel. A disbond (DB1) was intentionally created during panel manufacturing. The PWAS a2 was mounted on top of the disbond, whereas PWAS a1 and
a3 were mounted on regions of the stiffener were the bonding was in pristine condition (Figure 5a). The impedance spectrum from PWAS a1, a2, and a3 is presented in Figure 5b. It can be seen that the E/M impedance spectra for PWAS a1 and a3, which are located in areas with pristine bonding, are almost identical, as expected. However, the spectrum of PWAS a2, which is located on top of the disbond DB1, is entirely different, showing strong new resonant peaks and a clear increase in the response amplitude. These spectral changes are due to the changes in the local dynamics of the structure close to the disbond. Note that the frequency range where these changes are observed is in the hundreds of kHz (250—600 kHz); such high frequencies are not attainable with conventional modal analysis equipment but it is easily attained with the PWAS EMIS method.

![Figure 5 -- PWAS a1, a2, a3 located on L-section stiffener bonded to test panel (a2 is above the disbond DB1); (b) E/M impedance spectrum showing radical changes (increased amplitude and new peaks) for PWAS a2 located on the top of disbond DB1. Consistency of a1 and a3 spectra should also be noted.](image)

A systematic study of EMIS damage detection capabilities was performed on a set of circular plates with manufactured cracks (10-mm EDM slit) placed a various radial positions (Figure 6a). As shown in Figure 6b, five damage groups were considered: the baseline group consisted of pristine plates (Group 0) and the other four groups consisted of plates with cracks manufactured at decreasing radial distances (40, 25, 10, 3 mm) from the PWAS location in the plate center (Group 1 through Group 4). Each group contained five nominally ‘identical’ specimens. Thus, the statistical spread within each group could be also assessed.
Figure 6 Experiments on dependence of the E/M impedance spectra on the location of damage on metallic plate specimen, E/M impedance in 0.5–40 kHz frequency range: (a) the aluminum plate specimen with PWAS installed in the center; (b) E/M impedance spectra at various crack situations (8)

The EMIS experiments were conducted over three frequency bands: 10-40 kHz; 10-150 kHz; 300-450 kHz. The data for the 10-40 kHz band are shown in Figure 4. When damage was introduced in the plate, resonant frequency shifts, peaks splitting, and new resonances were noticed. As the damage became more severe, these changes became more profound. The most profound changes are noticed for Group 4. For the higher frequency bands, similar behavior was observed.

6. Summary and Conclusions

This paper has made a succinct presentation of structural health monitoring (SHM) and damage detection with piezoelectric wafer active sensors (PWAS). The PWAS transducers are lightweight and inexpensive enablers for a large class of SHM and damage detection applications. PWAS can work in multiple modes, i.e., they can be used for damage detection using both active and passive methods and utilizing both traveling guided waves (acousto-ultrasonics) as well as standing guided waves (vibration) techniques. After a brief review of PWAS physical principles and basic modeling, the paper considers several applications in the areas of: (a) embedded guided-wave ultrasonics, e.g., pulse-echo and phased arrays; (b) high-frequency modal sensing, i.e., the electro-mechanical (E/M) impedance method. The paper concludes that the PWAS technology offer great opportunities for SHM applications. However, substantial further work is required for PWAS SHM technology to achieve the degree of maturity attained by the conventional ultrasonic NDE systems.
References


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