Structural 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 damage detection and structural health monitoring (SHM) applications. This paper starts with a brief review of PWAS physical principles and basic modelling and continues by considering the various ways in which PWAS can be used for damage detection: (a) embedded guided-wave ultrasonics, i.e., pitch-catch, pulse-echo, phased arrays, thickness mode; (b) high-frequency modal sensing, i.e., the electro-mechanical (E/M) impedance method; (c) passive detection, i.e., acoustic emission and impact detection. An example of crack-like damage detection and localization with PWAS phased arrays on a small metallic plate is given. The modelling of PWAS detection of disbond damage in adhesive joints is achieved with the analytical transfer matrix method (TMM). The analytical methods offer the advantage of fast computation which enables parameter studies and carpet plots. A parametric study of the effect of crack size and PWAS location on disbond detection is presented. The power and energy transduction between PWAS and structure is studied analytically with a wave propagation method. Special attention is given to the mechatronics modeling of the complete transduction cycle from electrical excitation into ultrasonic acoustic waves by the piezoelectric effect, the transfer through the structure, and finally reverse piezoelectric transduction to generate the received electric signal. It is found that the combination of PWAS size and wave frequency/wavelength play an important role in identifying transduction maxima and minima that could be exploited to achieve an optimum power-efficient design. The multi-physics finite element method (MP-FEM), which permits fine discretization of damaged regions and complicated structural geometries, is used to study the generation of guided waves in a plate from an electrically excited transmitter PWAS and the capture of these waves as electric signals at a receiver PWAS. Wave diffraction from a hole damage is illustrated through time-frame snapshots. The paper ends with conclusions and suggestions for further work.

1. Introduction

Structural health monitoring (SHM) uses a set of permanently attached sensors to obtain on demand information about the structural performance and state of health. The benefits of monitoring the structural state include design feedback, performance enhancement, on-demand condition-based maintenance, and predictive fleet-level prognosis [1]. On-board structural sensing systems have been envisioned for determining the health of a structure by monitoring a set of sensors over time, assessing the remaining useful life from the recorded data and design information, and advising of the need for structural maintenance actions. An onboard SHM system could contain (a) sensors and sensor clusters; (b) electronics; (c) data processing and communications. The sensors can be either passive (strain, temperature, acceleration, impact, acoustic emission, etc.) or active (e.g., ultrasonic transducers that can interrogate the structure to detect damage presence, extent, and intensity).
Figure 1: Use of piezoelectric wafer active sensors (PWAS) as traveling wave transducers for damage detection: (a) pitch-catch; (b) pulse-echo; (c) thickness mode; (d) detection of impacts and acoustic emission (AE)

Structural health monitoring (SHM) is a multidisciplinary process involving several disciplines that must be closely coordinated. Guided-waves techniques for nondestructive evaluation (NDE) and structural health monitoring (SHM) applications are increasingly popular due to their ability to cover large areas with a relatively small number of sensors [2]. Piezoelectric wafers attached directly to structural elements, have gained large popularity due to low cost, simplicity, and versatility [3]. Piezoelectric wafer active sensors (PWAS) have emerged as one of the major SHM technologies because the same sensor installation can be used with a variety of damage detection methods such as: (a) embedded guided-wave ultrasonics, i.e., pitch-catch, pulse-echo, phased arrays; (b) high-frequency modal sensing, i.e., the electro-mechanical (E/M) impedance method; (c) passive detection, i.e., acoustic emission and impact detection. PWAS transducers couple 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

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

where, $s_{ijkl}$ is the mechanical compliance of the material measured at zero electric field ($E=0$), $e_{ijk}^T$ is the dielectric permittivity measured at zero mechanical stress ($T=0$), and $d_{ijkl}$ represents the piezoelectric coupling effect. PWAS utilize the $d_{31}$ coupling between in-plane strains, $S_{1}, S_{2}$, and transverse electric field, $E_3$. 

The main advantage of PWAS over conventional ultrasonic probes is in their small size, light weight, low profile, and inexpensive cost. By using Lamb waves in a thin-wall structure, one can detect structural anomaly, i.e., cracks, corrosions, delaminations, and other damage. PWAS transducers act as both transmitters and receivers of Lamb waves traveling through the structure. Upon excitation with an electric signal, the PWAS transmitter generates Lamb waves in a thin-wall structure. The generated Lamb waves travel through the structure and are reflected or diffracted by the structural boundaries, discontinuities, and damage. The reflected or diffracted waves arrive at the PWAS receiver where they are transformed into electric signals. PWAS transducers can serve several purposes [4]: (a) high-bandwidth strain sensors; (b) high-bandwidth wave exciters and receivers; (c) resonators; (d) embedded modal sensors with the electromechanical (E/M) impedance method. By application types, PWAS transducers can be used for (i) active sensing of far-field damage using pulse-echo, pitch-catch, and phased-array methods, (ii) active sensing of near-field damage 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 tip of advancing cracks (Figure 1).

An example of damage detection using PWAS phased arrays is given in Figure 2, which shows that broadside and offside cracks can be independently identified with scanning beams emitting from a central location. The main advantage of PWAS over conventional ultrasonic probes is in their small size, lightweight, low profile, and small cost. In spite of their small size, PWAS are able to replicate many of the functions performed by conventional ultrasonic probes. Extensive experimental data has been accumulated in using PWAS transducers for active structural sensing with guided waves. However, less has been achieved in the modeling and analysis of these active sensing methods.

![Simulated cracks (10mm slits)](image)

**Figure 2**: Crack-detection in a thin plate using two piezoelectric wafer active sensors (PWAS) phased arrays: (a) test schematic; (b) broadside crack imaging; (c) offside crack imaging

2. **Transfer Matrix Method Approach to Modeling the PWAS Detection of Disbonds**
Transfer matrix method (TMM) is an efficient analytical approach for solving 1-D vibration and wave propagation problems. TMM starts with the exact closed-form solutions describing the vibration and wave propagation in simple uniform segments and then uses a state-vector formulation and boundary matching to connect segments with different properties. The state vector at the right end of the beam is expressed in terms of the state vector at the left end of the beam using exact beam functions. Boundary conditions are matched at the left and right beam ends.

\[
\mathbf{z}_{BC}^R = \mathbf{P}_2 \cdot \mathbf{z}_{BC}^L + \mathbf{P}_1^F = \mathbf{P}_2 \cdot \mathbf{F}_1 \cdot \mathbf{z}_1^R = \mathbf{P}_2 \cdot \mathbf{F}_1 \cdot \left( \mathbf{z}_{BC}^L + \mathbf{P}_1^F \right)
\]

Hence, one writes

\[
\mathbf{z}_{BC}^R = \mathbf{U} \cdot \mathbf{z}_{BC}^L + \mathbf{T}
\]

\[
\mathbf{U} = \mathbf{P}_2 \cdot \mathbf{F}_1 \cdot \mathbf{P}_1 \quad \text{and} \quad \mathbf{T} = \mathbf{P}_2 \cdot \mathbf{F}_1 \cdot \mathbf{P}_1^F + \mathbf{P}_2^F
\]

**Figure 3:** TMM calculation of E/M impedance spectrum of a PWAS on bonded metallic coupon [9]

The TMM approach permits the modeling of branched structures, such as in the case of a disbond or split in an adhesively bonded structure. Cuc and Giurgiuțiu [9] used the TMM approach to simulate analytically the detection of disbonds in adhesive joints using PWAS transducers [9]. TMM was used for modeling a cracked multi-layer adhesively bonded beam with a PWAS attached to the top surface. The model starts with a single segment in the good-bond region. At point 2, the model splits into two branches representing the structure above and below the disbond. The two branches reunite when the disbond ends, and the rest of the beam is modeled with just one segment. The PWAS transducer is accommodated by making a separate segment for the structure above which the PWAS sits. Figure 3 shows the E/M impedance spectrum curves predicted for a small adhesively bonded coupon having
three PWAS transducers mounted on the upper surface. This analytical study (which was backed up by experimental measurements) was aimed at determining two things:

(a) the changes that occur in the spectrum when disbonds appear in the adhesive joint

(b) the sensitivity of the spectrum to changes in the PWAS location

The spectrum shown in Figure 3 corresponds to PWAS #2, which is placed directly above the disbond. Similar changes, though of lesser amplitude, were observed for PWAS #1 and #3, which are not placed on top of the disbond but in its vicinity. For the pristine specimen, the E/M impedance spectrum of PWAS #2 place exactly in the middle of the beam, shows three peaks in the 30–60 kHz range, i.e., at ~31 kHz, ~43 kHz, and ~56 kHz. When disbond damage was applied, these peaks shifted to ~38 kHz, ~42.5 kHz, and ~52 kHz. The changes in the first and third peak are major, and easily detectable; they are indicative of disbond damage presence. This answers point (a) by indicating that significant changes take place in the spectrum when disbond damage appears. To address point (b), we introduced a very small (1-mm) shift in the PWAS location. This 1-mm shift generated new small peaks at ~36 kHz, ~49 kHz, but left the three major peaks virtually unchanged. This answers point (b), i.e., it shows that the spectrum is also sensitive to changes in PWAS location, but changes are generally small. They do not impede our damage detection capability, because the changes due to disbonds are of much larger amplitude. In addition, during the SHM process, the PWAS location is fixed, and hence the differences between the pristine baseline and the damaged spectra will only be due to damage. The effect of modeling the exact PWAS location is nonetheless important when trying to compare theoretical predictions and experimental results. The study was continued with an investigation of how damage index (DI) values vary with the damage (Figure 4). Three damage index formulations were considered: root mean square deviation (RMSD), maximum absolute percentage deviation (MAPD) and correlation coefficient deviation (CCD). It was found that the MAPD formula seems be better because it increases monotonically with damage size.

![Figure 4: Variation of damage index (DI) with damage length for three damage index formulae: RMSD, MAPD, CCD [9]](image-url)
3. Power and Energy Transduction between PWAS and Structure

An analytical investigation of power and energy transduction between PWAS and structure during the structural health monitoring process was recently performed by Lin and Giurgiutiu [10]. This preliminary work uses an analytical approach applied to the simple model depicted in Figure 5. The study used a 1-D analytical model to capture the power and energy flow from the electrical source energizing the transmitter PWAS through various stages of transduction up to the signal captured by an instrument connected to the receiver PWAS. The model consists of a transmitter PWAS (A) and a receiver PWAS (B) bonded to a metallic beam. The following energy conversion stages were considered:

(a) piezoelectric transduction between the electric source and the transmitter PWAS
(b) mechanical transmission of shear stresses from the PWAS to the structure
(c) excitation of ultrasonic waves traveling through the structure from the transmitter to the receiver
(d) capturing of ultrasonic waves arriving at the receiver PWAS
(e) mechanical conversion of structural waves into shear stresses acting from the structure onto the receiver PWAS
(f) piezoelectric conversion at the receiver PWAS and measurement of the resulting signal by the electrical instrument.

We have developed two analytical approaches, one based on standing waves (vibration), the other based on traveling waves. The **standing-waves model** is appropriate for a finite-dimensional specimens; when excited harmonically, such a specimen will enter a state of vibration caused by the ultrasonic guided waves bouncing back and forth between the specimen boundaries in a standing-wave pattern. The **traveling-waves model** is appropriate for the study of large specimens in which the boundary effects can be neglected or for the study of wave-propagation events that happen before the waves bounce back from the reflecting boundaries. In order to account for the electronic effects, we considered a **voltage source** of voltage $V_A$, **source impedance** $Z_A$, and maximum current $I_{A\text{max}}$ and measuring instrument characterized by **instrument admittance** $Y_e$.

![Figure 5: PWAS transmitter power and energy flow chart [10]](image-url)
\[ \hat{V}_B(\omega) = \frac{k^2_{31}Y_{0B}}{Y_c + (1-k^2_{31})Y_{0B}} \times \frac{k_{iA}C_{AB}(\omega)}{R(\omega)k_{iA}k_{iB}[C_{AB}(\omega) - C_{AA}(\omega)C_{BB}(\omega)] + k_{iA}C_{AA}(\omega) + R(\omega)k_{iB}C_{BB}(\omega) - 1} \hat{V}_A(\omega) \]

where \( Y_{0B} \) is the admittance of PWAS B, \( k_{iA} \) and \( k_{iB} \) are the internal stiffnesses of PWAS A and B, \( k_{31} \) is the piezoelectric-transduction coupling factor of the PWAS material. The expressions \( R(\omega), C_{AA}(\omega), C_{AB}(\omega), C_{BB}(\omega) \) are defined in ref. [10].

The propagating-waves model assumes that axial and flexural propagating waves generated at PWAS A are felt at PWAS B and transduced into an electrical voltage which, in turn, will transduce into a reflected ultrasonic wave that will be felt back at A and will influence its ultrasonic output. Hence, the voltage \( V_B \) at B is found in terms of the voltage \( V_A \) at A in the following form

\[ \hat{V}_B(\omega) = \frac{k^2_{31}Y_{0B}}{Y_c + (1-k^2_{31})Y_{0B}} \times \frac{k_{iA}C_{AB}(\omega)}{R(\omega)k_{iA}k_{iB}[C_{AB}(\omega) - (k_{iA}C_{AA}(\omega) - 1)(R(\omega)k_{iB}C_{BB}(\omega) - 1)]} \hat{V}_A(\omega) \]

The coefficients \( C_{AA}(\omega), C_{AB}(\omega), C_{AB}(\omega), C_{BB}(\omega) \) are expressed in terms of propagating waves and are different from those of Equation (6) (see ref. [10] for details).

**Figure 6**: PWAS transmitter under constant 10-V excitation (a) power rating; (b) wave power [10]
The model was used to predict the frequency response functions for voltage, current, complex power, active power, etc. At the input side, it was found that the reactive electric power is dominant and hence defines the size of the energizing power supply/amplifier (Figure 6a). At the PWAS structure interface, it was found that only the active electrical power gets converted into mechanical power, which is transmitted across the PWAS-structure interface and energizes the axial and flexural waves propagating into the structure. A parametric study was conducted w.r.t. the transmitter PWAS size: it was found that proper size and excitation frequency selection facilitates ultrasonic wave excitation through tuning effects. Figure 6b displays peaks and valleys that depend on frequency and PWAS size. It is apparent that a larger PWAS does not necessarily ensure more power transmission -- careful frequency-size tuning is necessary! Similar tuning effects were also found at the receiver PWAS where a parametric study of the receiver size, receiver impedance and external electrical load provides useful design guidelines for PWAS-based sensing and/or energy harvesting. This preliminary analysis shown here needs to be validated and verified through experiments and then extended to cover multi-modal Lamb waves, various structural situations (structural variability, structural joints, flaws/damage, nonlinear friction in joints and cracks, adhesive bonding/delamination, etc.), and more complicated excitation and detection electronic circuitry.

4. Multi-Physics Finite Element (MP-FEM) Simulations
Gresil and Giurgiutiu [12] have explored the use of multi-physics finite element method (MP-FEM) to model the generation of elastic waves from an applied electric field applied to a surface-mounted PWAS transmitter (T-PWAS) and the reception of the elastic wave as electric signal recorded at a PWAS receiver (R-PWAS). In these preliminary studies, we used the ANSYS and ABAQUS commercially available codes and explored the comparative behavior of the available elements such as brick, plate, and shell. We found that different elements and mesh sizes might give quite different wave propagation results. Subsequently, we performed a study on modeling the guided wave generation and reception in a rectangular metallic plate containing a through-hole defect. This benchmark problem has been examined by many investigators and is quite well documented in literature. We modeled 7-mm PWAS transducers bonded to the top of the plate on both sides of the hole. The PWAS transducers operated in pitch-catch mode. A 3-count smoothed voltage tone burst with \( f = 141 \text{ kHz} \) was applied to the T-PWAS and received by the R-PWAS. The presence of the hole in the plate modified the transmitted signal through wave scatter and mode conversion.

Figure 7 shows image snapshots of the guided wave pattern in the plate taken at 10-\( \mu \text{s} \) intervals. At the excitation frequency of \( f = 141 \text{ kHz} \), two guided wave modes are present, S0 and A0. The A0 mode is considerably slower than the S0 mode. The A0 mode is also much more dispersive than the S0 mode. At \( t = 10 \ \mu\text{s} \), one sees the waves just starting from the T-PWAS. Wave scatter from the hole becomes apparent at \( t = 20 \ \mu\text{s} \), with mode conversion very clear at \( t = 30 \ \mu\text{s} \). The interaction of the waves with the R-PWAS and the boundaries start to be observable from \( t = 40 \ \mu\text{s} \) onwards. By \( t = 80 \ \mu\text{s} \), most of the wave power has dissipated into the boundaries. In the future, we will simulate the sensor signals that would be measured on a flawed/damaged realistic structure in comparison to signals that would be measured on a pristine structure. The main difficulty in addressing realistic specimens representing actual structures is one of scale of complexity.

We have also modeled and developed electronic hardware for multichannel PWAS SHM systems [13], as well as a compact DSP-based electromechanical impedance analyzer[14][15] and other instrumentation and signal processing algorithms for compact active SHM systems.

5. Summary and Conclusions
This paper started with a presentation of the piezoelectric wafer active sensors (PWAS) basic principles damage detection capabilities and continued with the presentation of the various ways in which PWAS can be used to detect damage. Subsequently, the paper focused on analytical and finite
element method (FEM) modeling of PWAS structural health monitoring. The electromechanical (E/M) impedance spectrum for a partially disbonded adhesive joint was modeled with the transfer matrix method (TMM) allowed important parameter studies. The analytical modeling of the power and energy flow between a transmitter PWAS and a receiver PWAS showed very interesting tuning opportunities. Multi-physics finite element method (MP-FEM) was used to simulate the traveling of guided waves from a transmitter PWAS to a receiver PWAS while being scattered by a hole defect.

![Figure 7: Multi-physics finite element method (MP-FEM) simulation of guided waves generate by a 7-mm PWAS transmitter and scatter from a 12-mm through hole.]

However, the results presented here are just preliminary. Future work should attempt to combine the efficiency of analytical methods with the detailing capability of the FEM approach such as to developed a hybrid method for modeling realistic structures with sufficient computational efficiency as to permit parameter studies. In this way, we will be able to advance from an empirical approach into an analytical rational development of structural health monitoring systems and maintenance strategies.
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