Title: Piezoelectric Wafer Active Sensors for Structural Health Monitoring – Recent Developments

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ABSTRACT

Piezoelectric wafer active sensors (PWAS) are inexpensive, non-intrusive unobtrusive devices that can be surface mounted on existing structures, or inserted in a new composite structure. The PWAS can be used in both active and passive modes. In active mode, the PWAS generate Lamb waves that can exist as either traveling waves or standing waves. As traveling waves, PWAS-generated Lamb waves can be used with the pitch-catch, pulse-echo, or phased-array methods that arrow far-field and some medium-field damage detection. This paper presents new results obtained in the use of PWAS for the structural health monitoring. In particular, it deals with recent advancements obtained in two aspects: (a) modeling and analysis of power and energy flow from transmitter PWAS through the structure and back into the receiver PWAS; and (b) exact solution of the shear-lag transfer between PWAS and structure in the presence of several Lamb wave modes at high frequency-thickness values.

PIEZOELECTRIC WAFER ACTIVE SENSORS (PWAS)

Piezoelectric wafer active sensors (PWAS) couple 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 piezoelectric constitutive equations

$$S_{ij} = s^{E}_{ijkl} T_{kl} + d_{klj} E_k$$
$$D_j = d_{jk} T_{kl} + \varepsilon^{T}_{jk} E_k$$

where, $s^{E}_{ijkl}$ is the mechanical compliance of the material measured at zero electric field ($E=0$), $\varepsilon^{T}_{jk}$ is the dielectric permittivity measured at zero mechanical stress ($T=0$), and $d_{klj}$ represents the piezoelectric coupling effect. PWAS utilize the $d_{31}$ coupling between in-plane strains, $S_1, S_2$, and transverse electric field, $E_3$. PWAS are transducers are different from conventional ultrasonic transducers because [1]:

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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 single-resonance devices.

3. Because PWAS are small, lightweight, and inexpensive they can be deployed in large quantities on the structure, which is not practical with conventional ultrasonic transducers, which are relatively bulky and expensive.

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.

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**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)
PWAS transducers can serve several purposes [1]: (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. 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.

**MODELING OF POWER AND ENERGY TRANSDUCTION BETWEEN PWAS AND STRUCTURE**

A systematic investigation of power and energy transduction between PWAS and structure during the structural health monitoring process was recently presented by Bin and Giurgiutiu[2]. 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 following energy conversion stages were consider: (a) piezoelectric transduction between source and 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 location; (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 by the electrical instrument. The model was used to simulate a pitch-catch SHM process; it can be also used to simulate energy harvesting from structural waves.

Figure 3  PWAS transmitter power and energy flow chart [2]

The analytical model was developed under the following assumptions: (a) 1-D propagation of axial and flexural waves; (b) ideal bonding (pin-force model) between PWAS and structure; (c) ideal voltage excitation source at the transmitter PWAS; (d) external impedance load at the receiver PWAS to represent the measuring instrument or the energy harvester, as appropriate.

The model was used to predict the frequency response functions for voltage, current, complex power, active power, etc. To facilitate understanding, the simpler case of a PWAS transmitter was considered first (Figure 3). 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 4a).

Figure 4  PWAS transmitter under constant 10-V excitation (a) power rating; (b) wave power; (c) axial wave power; (d) flexural power [2]

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 waves
excitation through tuning effects. Figure 4b,c,d, shows 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 receiver size, receiver impedance and external electrical load provides useful design guidelines for PWAS-based sensing and/or energy harvesting.

Finally, the power flow for a pitch-catch situation was considered: in this case, the power flows as follows: (a) from the electrical source into the transmitter PWAS; (b) through piezoelectric transduction, into the mechanical power; (c) into ultrasonic wave power through the interface between the transmitter PWAS and the structure; (d) the ultrasonic wave power travels through the structure to the receiver PWAS; (e) the wave power arriving at the receiver PWAS is captured at the mechanical interface between the receiver PWAS and the structure; (f) the captured mechanical power is converted into electrical power at the receiver PWAS through the piezoelectric effect; (g) the electric power is measured by electrical instrument connected at the receiver PWAS. Numerical simulation and graphical charts showed that power and energy flow have peaks and valleys that can be utilized for design optimization [2].

SHEAR-LAG ANALYSIS FOR STRUCTURALLY-ATTACHED PWAS

Giurgiu and Santoni-Bottai [3] developed a shear lag solution for the stress and strain transfer between a structurally attached PWAS and the support structure. Earlier studies of this subject [4] assumed axial and flexural vibrations with linear strain distribution across the thickness; this assumption is fine for low values of the frequency-thickness product $f_d$, but would not be appropriate for ultrasonic guided waves (e.g., Lamb waves) because the latter have complicated multi-mode strain distributions across the thickness. To overcome this limitation, Giurgiu and Santoni-Bottai [3] derived a generic shear lag solution which is not limited to the low frequency-thickness values. This generic solution takes into account the exact thickness distribution of displacements and stresses corresponding to the Lamb wave modes existing at a particular ultrasonic frequency-thickness product value. This study showed that essential parameters such as $\alpha$ and $\Gamma$ as well as the tuning curves depend on the frequency-thickness product [3].

![Figure 5: Bond-layer interaction between PWAS and structure: (a) micrograph; (b) modeling](image)

Santoni-Bottai and Giurgiu [5] extended this work to the case of multiple Lamb wave modes excited in the structure, the shear stress in the bonding layer depends on the number of modes present in the structure $M$, the PWAS size, $2a$, the modal wavenumbers, $\xi_m$, $m = 1,...,M$, and the shear lag parameter $\Gamma$, i.e.,
\[ \tilde{\tau}(\xi_n) = \frac{2i}{\Gamma^2 + \xi_n^2} \left\{ \Gamma^2 - \sum_{m=1}^{M} \eta_m \xi_m^2 \left[ \frac{2i e^{-i\xi_m a}}{\Gamma^2 + \xi_m^2} \left( \Gamma \cosh \Gamma a + i \xi_m \sinh \Gamma a \right) + 1 \right] \right\} \left( \Gamma \sin \xi_n a \cosh \Gamma a \right) \\
+ \sum_{m=1}^{M} \eta_m \Gamma \gamma \left[ \frac{2i e^{-i\xi_m a}}{\Gamma^2 + \xi_m^2} \left( \Gamma \cosh \Gamma a + i \xi_m \sinh \Gamma a \right) \right] \left( \frac{\sin(\xi_m - \xi_n)a}{\xi_m - \xi_n} - \frac{\sin(\xi_m + \xi_n)a}{\xi_m + \xi_n} \right) \right\] 

The use of the exact solution given by Equation (2) has shown a substantial improvement in the PWAS-Lamb wave tuning curves and an almost perfect match with the experimental measurements [5].

SUMMARY AND CONCLUSIONS

Piezoelectric-wafer active sensors (PWAS) are small, inexpensive, non-invasive, elastic wave generators/detectors that can be easily affixed to a structure. PWAS transducers are wideband non-resonant devices. They can be deployed into sensor arrays and sensor networks. However, the PWAS development is not yet complete, and a number of issues have still to be resolved. This paper has presented recent advancements in the modeling and design of PWAS for structural health monitoring including a thorough power and energy analysis and an exact shear-lag solution for the PWAS-structure interaction.

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