Title: Recent Advances in the Use of Piezoelectric Wafer Active Sensors for Structural Health Monitoring

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ABSTRACT

Piezoelectric-wafer active sensors (PWAS) are small, inexpensive, non-invasive, elastic wave generators/detectors that can be easily affixed to a structure. Piezoelectric-wafer active sensors are broadband non-resonant devices. They can be deployed into sensor arrays and sensor networks. They can be connected to data concentrators and wireless communicators. However, the PWAS development is not yet complete, and a number of issues have still to be resolved. This paper will present recent advancements obtained by the authors in using the PWAS for structural health monitoring. Several directions are explored. The tuned selective excitation of $A_0$ and $S_0$ Lamb wave modes is theoretically predicted using a space-domain closed form solution and experimentally verified using the pitch-catch approach. For crack detection, tuned $S_0$ Lamb waves were used, since this wave type seems to be more sensitive to through-the-thickness cracks. The low-dispersion $S_0$ mode was generated in a PWAS phased array in order to create a virtual sweeping interrogative beam that is able to detect the presence of cracks in a large metallic plate. The embedded ultrasonic structural radar (EUSR) algorithm is used to process the data. The crack detection was performed with the pulse-echo method. Both flat and curved plates are explored. As expected from the theoretical analysis, it is shown that the application of shallow curvature ($2m < R < 4 m$) does not noticeably modify the crack detection capabilities of the EUSR method. For corrosion detection, tuned $A_0$ Lamb waves were used, since these type of waves seems to be more sensitive to thickness changes experienced during corrosion progression. The high-dispersion $A_0$ modes, which are strongly influenced by the plate thickness changes, are used to detect the presence of corrosion. A 15-mm diameter corrosion pit is generated in a 1-mm aluminum plate with incremental depth ranging from 0.04 to 0.36 mm. The paper ends with conclusions and proposal for further work.

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PIEZOELECTRIC WAVER ACTIVE SENSORS (PWAS)

In recent years, several investigators[1][2][3] have explored the generation of Lamb waves with piezoelectric wafer active sensors (PWAS)[4]. PWAS are inexpensive, non-intrusive, un-obtrusive, and minimally invasive devices that can be surface-mounted on existing structures, or inserted between the layers of lap joints or inside composite materials. Typical PWAS weigh around 68 mg, are 0.2 mm thick, and cost $15. PWAS operated on the piezoelectric principle that couples the electrical and mechanical variables in the material (mechanical strain, $S_{ij}$, mechanical stress, $T_{kl}$, electrical field, $E_{ks}$, and electrical displacement $D_j$) in the form

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

where $s_{ijkl}^E$ is the mechanical compliance of the material measured at zero electric field ($E = 0$), $e_{jk}^T$ is the dielectric permittivity measured at zero mechanical stress ($T = 0$), and $d_{ij}$ represents the piezoelectric coupling effect. For embedded NDE applications, PWAS couple their in-plane motion (which is excited through the piezoelectric effect by an oscillatory applied voltage) with the Lamb-waves particle motion on the material surface. Lamb wave modes can be either symmetric ($S_0$, $S_1$, $S_2$, …), or antisymmetric ($A_0$, $A_1$, $A_2$, …). PWAS transducers can act as both exciters and detectors of the elastic Lamb waves traveling in the material. For NDE, PWAS can be used as both active and passive probes. Laser scanning interferometer visualization [5] of the Lamb wave field around a PWAS bonded to a thin aluminum plate (Figure 1) reveals the typical omnidirectional circular-crested wave propagation pattern expected from a point source.

PWAS operation is different from that of conventional ultrasonic probes:

1) PWAS are coupled to the Lamb waves through in-plane surface strains; conventional ultrasonic transducers are coupled through out-of-plane stresses that acts normal to the material surface
2) PWAS are strongly coupled with the structure and follow the structural dynamics; conventional ultrasonic probes are relatively free from the structure and follow their own dynamics
3) PWAS are non-resonant wide-band devices, while conventional ultrasonic probes are narrow-band resonant devices

The main advantage of PWAS over conventional ultrasonic probes lies in their small size, lightweight, low profile, and small cost. In spite of their small size, these novel devices are able to replicate many of the functions performed by conventional
TUNED LAMB-MODE EXCITATION WITH PWAS TRANSDUCERS

The excitation of Lamb waves with PWAS transducers can be studied by considering the excitation applied by the PWAS through a surface shear stress $\tau = \tau_0(x)e^{i\omega t}$. Using the space-domain Fourier transform analysis of the basic Lamb wave equations yields the strain and displacement solutions in the form[6][7]

$$\varepsilon_s(x,t) = \frac{1}{2\pi \mu} \left[ \frac{\hat{\tau}N_S}{D_S} + \frac{\hat{\tau}N_A}{D_A} \right] e^{i(\xi_x - \omega t)} d\xi$$

where $\hat{\tau}$ is the Fourier transform of $\tau_0(x)$, $p^2 = (\omega^2 / c_t^2) - \xi^2$, $q^2 = (\omega^2 / c_t^2) - \xi^2$, while $c_t^2 = (\lambda + 2\mu) / \rho$ and $c_t^2 = \mu / \rho$ are the longitudinal and transverse wave speeds, $\lambda$ and $\mu$ are Lamb constants, $\rho$ is the mass density, and

$$N_S = \xi q(\xi^2 + q^2) \cos \phi \cos qh, \quad D_S = (\xi^2 - q^2)^2 \cos \phi \sin qh + 4\xi^2 p q \sin \phi \cos qh$$

$$N_A = \xi q(\xi^2 + q^2) \sin \phi \sin qh, \quad D_A = (\xi^2 - q^2)^2 \sin \phi \cos qh + 4\xi^2 p q \cos \phi \sin qh$$

Note that $p$ and $q$ depend on $\xi$, thus increasing the problem complexity. The integral in Equation (2) is singular at the roots of $D_S$ and $D_A$. The equations $D_S = 0$ and $D_A = 0$ are exactly the Rayleigh-Lamb characteristic equations for symmetric and anti-symmetric motions. These equations accept the simple roots:

$$\xi_{00}, \xi_{01}, \xi_{02}, ... \quad \xi_{00}, \xi_{01}, \xi_{02}, ...$$

(4)

corresponding to the symmetric (S) and anti-symmetric (A) Lamb wave modes. The evaluation of the integral in Equation (2) is done by the residue theorem, using a contour consisting of a semicircle in the upper half of the complex $\xi$ plane and the real axis. For ideal bonding between the PWAS and the plate, the shear stress in the bonding layer and the corresponding space-domain Fourier transform are

$$\tau(x) = a\tau_0 [\delta(x-a) - \delta(x+a)], \quad \hat{\tau} = a\tau_0 [-2i\sin \xi a]$$

(5)

Hence, the strain-wave solution becomes

$$\varepsilon_s(x,t) = -i\frac{\alpha \tau_0}{\mu} \sum_{\xi} \sin \xi s a \frac{N_S(\xi s)}{D_s(\xi s)} e^{i(\xi_x - \omega t)} - i\frac{\alpha \tau_0}{\mu} \sum_{\xi} \sin \xi a \frac{N_A(\xi a)}{D_A(\xi a)} e^{i(\xi_x - \omega t)}$$

(6)

Similarly, the displacement wave solution is obtained as

$$u_s(x,t) = -i\frac{\alpha \tau_0}{\mu} \sum_{\xi} \sin \xi s a \frac{N_S(\xi s)}{D_s(\xi s)} e^{i(\xi_x - \omega t)} - i\frac{\alpha \tau_0}{\mu} \sum_{\xi} \sin \xi a \frac{N_A(\xi a)}{D_A(\xi a)} e^{i(\xi_x - \omega t)}$$

(7)

A plot of these equations up to 1000 kHz is presented in Figure 2. Equations (6) and (7) contains the $\sin \xi a$ behavior that displays maxima when the PWAS length $l_a = 2a$ equals an odd multiple of the half wavelength, and minima when it equals an even multiple of the half wavelength. A complex pattern of such maxima and minima emerges, since several Lamb modes, each with its own different wavelength, coexist
at the same time. Figure 2a shows that, at 300 kHz, the amplitude of the \( A_0 \) mode goes through zero, while that of the \( S_0 \) is close to its peak. This represents an excitation “sweet spot” for \( S_0 \) Lamb waves. Experimental results confirming this prediction are presented in Figure 2b.

This proves that frequencies can be found for which the response is dominated by certain modes. This is **wavelength-based mode tuning**. Another factor that must be considered in Lamb wave tuning under PWAS excitation is the mode amplitude at the plate surface where the PWAS is located. This factor is contained in the values taken for each mode by the function \( N / D' \). It is conceivable that, at a given frequency, some higher modes may have less surface amplitudes, while other may have larger surface amplitudes. Thus, two important factors for the design of PWAS-based Lamb-wave embedded NDE for structural health monitoring have been identified:

a) The variation of \( |\sin \xi a| \) with frequency for each Lamb wave mode

b) The variation of the surface strain with frequency for each Lamb wave mode

### PWAS PHASED ARRAYS ON FLAT AND CURVED PANELS

An important application of the PWAS based ultrasonics is that based on phased array principles. Giurgiutiu and Bao[8] developed a PWAS phased array application and named it embedded ultrasonics structural radar (EUSR). Lamb waves can exist in a number of dispersive modes. However, through smoothed tone-burst excitation and frequency tuning, it is possible to confine the excitation to a particular Lamb wave mode, of carrier frequency \( f_c \), wave speed \( c \), and wave length \( \lambda = c / f_c \). The principles of conventional phased-array radar[9] are applied to the PWAS array, assuming a uniform linear array of \( M \) PWAS, with each PWAS acting as a point-wise omni-directional transmitter and receiver.

In conventional phased array transducers, the ultrasonic wave front can be focused or steered in a specific direction by sequentially firing the individual elements of an array transducer at slightly different times. This approach requires a large number of excitation channels working in parallel (one for each element of the phased array). This would impose a large hardware burden on the SHM system. To reduce the hardware burden, we took a novel approach. We applied a technique in which only one PWAS in the array is excited at a given time, while data is being collected on all
the PWAS in the array. Thus the hardware requirements were reduced to just one excitation channel. The excitation was then switched among all the PWAS in the array in a round-robin manner. Eventually, an array of $N^2$ elemental signals was generated and collected (here, $N = 9$). An algorithm for creating a virtual beam-steering/focusing effect (called the EUSR algorithm) was applied to the array of $N^2$ elemental signals. Once the beam steering and focusing were established, the crack detection was done with the pulse-echo method.

Figure 3. Crack detection at high curvature ($R = 1.95\text{ m}$) in direction 2: (a) photo of specimen while being bend; (b) crack imaging and crack echo in the EUSR algorithm

To verify the theoretical results, experiments were conducted in the Laboratory for Adaptive Materials and Smart Structures (LAMSS) at the University of South Carolina[10]. The experiments were conducted on both flat and curved panels. Curvature radii between 2 m and 4 m were tested. These curvatures were applied in two directions. One direction was with the chord parallel to the PWAS array (direction 1), while the other was with the chord perpendicular to the PWAS array (direction 2). Good crack detection was obtained for all curvatures and all directions. No significant difference due to curvature could be observed. These results agree with
the theoretical predictions which indicate that, for shallow cylindrical shells \((h/r \text{ and } h/\lambda << 1)\), the longitudinal modes approach the Lamb wave modes[11].

CORROSION DETECTION WITH PWAS

Lamb waves are a good candidate method for efficient corrosion detection in large thin-wall structures using conventional ultrasonic transducers. Chahbaz et al.[12] used Lamb waves in pitch-catch mode to detect corrosion in aluminum specimens. They showed that material thinning (either visible or hidden under patches and lap joints) can be detected. A\(_1\) mode of guided Lamb waves transmitted through the corroded area resulted in a received signal of lower amplitude and longer time of flight than when passing through a pristine area. Corrosion around rivets and other fasteners was also detected. Alleyne et al.[13] used guided tube waves to detect corrosion in steel pipes through mode conversion. Jenot et al.[14] used S\(_0\) Lamb waves and copper plate specimens. They detected changes in the group velocity that was attributed to material thinning. The technique was also applied to the back of the plate simulating the detection of hidden corrosion. Sicard et al.[15] applied this method to corrosion detection in airframe structures.

Corrosion detection with embedded PWAS transducers was studied by Thomas et al.[16]. They have successfully detected simulated corrosion in metallic plates using the antisymmetric A\(_0\) Lamb waves. The experiments consisted of transmitting A\(_0\) Lamb waves in a 1-mm aluminum plate across a 15-mm diameter corrosion pit (Figure 4b). The pit depth was gradually increased from 0.04 mm to 0.36 mm. It was observed that the received signal dispersion changed only slightly with corrosion depth since the corroded area was only a small percentage of the total travel. However, the phase change with corrosion depth was more noticeable. The amplitude of the received signal changed with corrosion depth in a bi-modal way: for small corrosion depth, the amplitude actually increased, since the corrosion pit acted as a diffraction lens to the 2-D wave propagation. As the depth of the corrosion pit increased, the amplitude of the received signal decreased, as the pit started to act as a reflector/deflector to the 2-D wave propagation. To capture the phase and amplitude changes, cross plots between the original signal and the “corroded” signal were used to capture the phase and amplitude changes (Figure 4b).

Figure 4. (a) 15-mm diameter corrosion pit; (b) cross plot of A\(_0\) signals
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. Piezoelectric-wafer active sensors are wide-band non-resonant devices. They can be deployed into sensor arrays and sensor networks. They can be connected to data concentrators and wireless communicators. However, the PWAS development is not yet complete, and a number of issues have still to be resolved. This paper has presented recent advancements obtained by the authors in using the PWAS for structural health monitoring. Several directions were explored.

The tuned selective excitation of $A_0$ and $S_0$ Lamb wave modes were theoretically predicted using a space-domain closed form solution. These predictions were experimentally verified using the pitch-catch approach. For crack detection, tuned $S_0$ Lamb waves were used, since this wave type seems to be more sensitive to through-the-thickness cracks. The low-dispersion $S_0$ mode was generated in a PWAS phased array in order to create a virtual sweeping interrogative beam that was able to detect the presence of cracks in a large metallic plate. The embedded ultrasonic structural radar (EUSR) algorithm was used to process the data. The crack detection was performed with the pulse-echo method. Both flat and curved plates were analyzed. As expected from the theoretical analysis, it was shown that the application of shallow curvature ($2 \text{ m} < R < 4 \text{ m}$) does not noticeably modify the crack detection capabilities of the EUSR method.

For corrosion detection, tuned $A_0$ Lamb waves were used, since this type of waves seems to be more sensitive to thickness changes experienced during corrosion progression. The high-dispersion $A_0$ modes, which are strongly influenced by the plate thickness changes, were used to detect the presence of corrosion. A 15-mm diameter corrosion pit with incremental depth ranging from 0.04 to 0.36 mm was generated in a 1-mm aluminum plate. In a pitch-catch setup, the corrosion depth could be correlated with the received signal amplitude and phase. A cross plot of the pristine vs. “corroded” signals was used to identify the presence of incipient corrosion.

Further work needs to be done to understand in more detail the coupling between the PWAS and the structure. It is essential to find frequency/size values that optimally permit the use of PWAS for tuned Lamb-wave excitation/detection with minimum power consumption. Another research direction is the improvement of the EUSR algorithm through the application of advanced signal processing methods for detection of multiple targets and rejection of spurious noise. The corrosion detection studies should be continued to fully understand the different wave propagation effects at low and high corrosion values. It should also be extended from concentrated corrosion to diffused corrosion, and tried on realistic corrosion specimens.

REFERENCES


