Piezoelectric Wafer Active Sensor Guided Wave Imaging
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ABSTRACT
Active sensing methods use actuators/sensors permanently attached to the structure to generate guided waves and measure the arrival waves propagating through the structures. The damage diagnosis is performed through the examination of the arrival waves carrying structural features. Since direct sensory data in guided wave interrogation are implicit with damage related information, advanced signal processing is necessary to extract damage related features for damage diagnosis. Array signal processing is an approach that can map the structure being interrogated with propagating guided waves, producing a visual indication of damage presence, location, and size for crack damage. The arrays can be configured with sensors closely placed or spatially distributed and used in pitch-catch mode.

In this paper, we first studied guided wave excitation on isotropic plates and the capability of using piezoelectric wafer active sensors to selectively excite a certain mode in the structure. Then several algorithms for imaging with different types of arrays were investigated. The algorithms were applied to isotropic specimens including thin aluminum plates with hole and crack damage, and thick steel plates with hole damage. The resolution (minimal detectable damage size) was also investigated and compared to the resolution of a linear phased array. Image post processing was used to yield an estimation of the damage size.

Keywords: Guided Waves Imaging, Array Imaging, Active Sensing, Piezoelectric Wafer Active Sensors, PWAS

1 INTRODUCTION
Guided waves have opened new opportunities for cost effective detection of damage in structures because they are more global in nature and can provide more measurable features that are related to the interaction between the guided waves and defects and hence contain more information about the defects in the structure (Zhu et al., 1998). Lamb waves are guided waves that travel in thin-wall structures and they can facilitate efficient detection over large areas (Viktorov, 1967). Of particular interest in this subject study is the use of guided waves to detect through-the-thickness damage, hole and crack, in metal structures.

1.1 PIEZOELECTRIC WAFER ACTIVE SENSORS
Piezoelectric wafer active sensors (PWAS) as an active sensing device work on the piezoelectric principles and provide a tensorial relation between mechanical and electrical variables. They can be permanently attached to the structure to interrogate at will and can operate in propagating wave mode. The strains experienced by PWAS are direct strains and can be used to produce in-plane and thickness-wise vibration.

The transmission of actuation and sensing between the PWAS and the host structure is achieved through the bonding adhesive layer. The adhesive layer acts as a shear layer, in which the mechanical effects are transmitted through shear effects. Using 1-D plane-strain analysis (Crawley and deLuis, 1987) for static morphing and the quasi-static low frequency vibrations, it has been found that the shear transfer process is concentrated towards the PWAS ends at large value of shear-lag parameter. The shear lag analysis indicates that at infinite large shear-lag parameter, all the load transfer can be assumed to take place at the PWAS ends. This leads to the concept of ideal bonding, also known as the pin-force model, in...
which all the load transfer takes place over an infinitesimal region at the PWAS ends, and the induced-strain action is assumed to consist of a pair of concentrated forces applied at the ends.

For embedded NDE applications, PWAS can be used as embedded ultrasonic transducers acting as either actuators to excite guided waves or as sensors to receive the structural response in the pitch-catch mode (as illustrated in Figure 1). PWAS couple their in-plane motion with the particle motion of Lamb waves on the material surface while the in-plane motion is excited by the applied oscillatory voltage through the $d_{31}$ coefficient.

![Figure 1] PWAS embedded NDE in pitch-catch mode as actuator and sensor

### 1.2 Tuned PWAS Lamb Waves

For Lamb waves, there are at least two wave modes, A0 and S0, existing simultaneously where the product of the wave frequency and structure thickness falls in the range of 0~1 MHz-mm. The tuning of Lamb wave attempts to modify the excitation parameters such as to excite certain mode for detecting certain damage. With wedge-coupled conventional ultrasonic transducers, guided wave tuning is performed by varying the frequency and the wedge angle until a maximum response is recorded. The change in frequency modifies the wave speed of the dispersive guided wave, while the change of wedge angle modifies the wave conversion relationship in Snell’s law. Certain combinations of wedge-angles and excitation frequencies were able to generate increasing response in certain guided-wave modes. An important characteristic of PWAS, which distinguishes them from the conventional ultrasonic transducers, is their capability of exciting multiple guided wave modes at a single frequency. A comprehensive study of these prediction formulae in comparison with experimental results has been given by Giurgiutiu (2008). By carefully selecting PWAS length at an odd multiple or at an even multiple of the half wavelength, a complex pattern of strain maxima and minima emerges. Since several Lamb modes, each with its own different wavelength, coexist at the same time, a selected Lamb mode can be tuned by choosing the appropriate frequency and PWAS dimensions.

A tuning example is given here. On a 1-mm thick aluminum plate installed with 7-mm round PWAS, within an operation frequency range of 0-500 kHz, two Lamb wave modes (A0 and S0) exist simultaneously (Figure 2). However, as shown in the strain plot (Figure 2a), there are frequency values where one of the two modes is nearly suppressed. At 300 kHz, A0 mode vibration is very small leaving the S0 mode dominates. Group velocity vs. frequency plots of S0 and A0 modes are shown in figure 5b. We can see that within the 0~500 kHz range, the S0 mode velocity is almost constant, i.e., the S0 mode is much less dispersive compared to the A0 mode.
2 PWAS LAMB WAVE PHASED ARRAY IMAGING

The PWAS phased array application allows large structural areas to be monitored from a single location. The phased array application utilizes the beam steering concepts differentially firing various elements of the phased array such that constructive/destructive interference of all the transducers forms a wave beam in a certain direction (Giurgiuțiu, 2008). Our previous work also showed that the minimum detectable size on 1-mm aluminum plate using a linear 8-PWAS (7-mm in diameter) phased array is 1.57 mm.

An example of using a linear 8-PWAS phased array to detect and locate a 20-mm simulated crack on a 1-mm aluminum plate is given in Figure 3a. The phased array was installed in the middle of the plate and used to scan the upper side from 0° to 180°. In the array, sensors were put side by side with 1-mm gap. To interrogate, each PWAS takes turn to serve as the actuator sending out a 3-count toneburst signal while others are used as sensors to receive the structural responses in a round-robin pattern. After the data are collected, they are post-processed by the embedded ultrasonic structural radar (EUSR) algorithm (Giurgiuțiu et al., 2006) to generate the virtual beam and the scanning 2-D image (Yu and Giurgiuțiu, 2007). The result is shown in Figure 3b. A highlighted shade about 305 mm in front of the array at 90° clearly indicates the presence of the broadside crack in the plate. However, to measure the size of the crack, additional image processing need to be developed.
3 PWAS LAMB WAVE SPARSE ARRAY IMAGING

3.1 Sparse Array Damage Detection

Unlike phased arrays where sensors are physically close to each other, sparse arrays consist of a network of PWAS transducers spatially distributed and are used to scan the area in and outside the array. In the network, one PWAS sends out interrogating guided wave. When the wave encounters damage, the wave gets scattered (Figure 4a). By the comparison of the pristine and damaged wave signals, a scatter signal can be extracted. One advantage of using scatter signals is to minimize the influence caused by boundaries or other structural feature which would otherwise complicate the Lamb wave analysis. Analysis of the scattered signals between each pitch-catch pairs permits the correlation of the wave propagation in the structure with the damage progression.

The image construction of the sparse array is based on a synthetic time reversal concept (Wang et al., 2004) by shifting back the scatter signals at time quantities defined by the transmitter-receiver locations used in the pitch-catch mode. Figure 4b and Figure 4c illustrates the imaging approach. Assuming a single damage scatter is located at point \( Z(x, y) \) in the structure, the scatter signal from transmitter \( T_i \) to receiver \( R_j \) contains a single wave packet caused by the damage (Figure 4c). The total time of traveling \( \tau_Z \) is determined by the locations of the transmitter \( T_i \) at \( (x_i, y_i) \), the receiver \( R_j \) at \( (x_j, y_j) \), and \( Z(x, y) \), as

\[
\tau_Z = \frac{\sqrt{(x_i - x)^2 + (y_i - y)^2} + \sqrt{(x - x_j)^2 + (y - y_j)^2}}{c_g}
\]  

(1)

where \( c_g \) is the group velocity of the traveling Lamb wave, assuming constant. Using the time-reversal concept in Wang et al., 2004, when a wave packet is shifted back by the quantity defined by the transducers and the exact position of the damage, i.e., \( \tau_Z \), ideally the peak will be shifted right back to the time origin. If the wave packet is shifted by a quantity defined with otherwise cases (such as \( \tau_i \) and \( \tau_o \)), the peak will not be shifted right at the time origin (Figure 4c).

For an unknown damage, for certain scatter signal with \( \tau_Z \), the possible locations of the damage is an orbit of ellipse with the transmitter and receiver as the foci (Figure 4b). To locate the damage, ellipses from other scatters (or transmitter-receiver pairs in the network) are needed. For a given network of \( M \) transducers, a total of \( M^2 \) scatter signals will be used if reciprocity is not considered. In our study, two algorithms, one based on summation process and the other based on the correlation process, have been employed for the imaging. Using the summation processing (Michaels and Michaels 2007), the pixel value at an arbitrary location \( Z(x, y) \) in the scanned plane is defined as

\[
P_Z(t_0) = \sum_{i=1}^{M} \sum_{j=1, j \neq i}^{M} s_{ij}(\tau_Z), \quad i \neq j
\]  

(2)

where \( s_{ij} \) is the scatter signal obtained from the \( j^{th} \) receiver when the \( i^{th} \) transmitter sends. Using the multiplication processing (Ihn and Chang 2008), the pixel value is defined as

\[
P_Z(t_0) = \prod_{i=1}^{M} \prod_{j=1, j \neq i}^{M} s_{ij}(\tau_Z), \quad i \neq j
\]  

(3)
A simple sparse array configuration consisting of four sensors is shown in Figure 5a. It can be used to detect a damage within or outside the array network. Figure 5b illustrates the triangulation principle used to locate the damage. Details of principles and applications of triangulation in damage detection can be found in many references and will not be described in this paper. In triangulation approach, a minimum of three sensors are required in order to locate the damage. However, when the damage accidentally falls into the line between two sensors, triangulation will be invalid and fail in locating the damage. Therefore, in sparse array application, usually a minimum of four sensors is required to correctly identify and localize the presence of damage.

![Figure 4 PWAS sparse array imaging principle: (a) wave scattering; (b) damage orbit; (c) signal shifting]

Figure 4  PWAS sparse array imaging principle: (a) wave scattering; (b) damage orbit; (c) signal shifting

3.2 SPARSE ARRAY HOLE DETECTION

The sparse array imaging test was conducted on a 1-mm aluminum plate to detect the development of a through-hole located at (328 mm, 326 mm). Four PWAS were installed on the plate at random locations (Figure 6a). Scanning frequency was selected at 300 kHz to excite S0 Lamb wave mode with a traveling speed at 5500 m/s. Baseline signals were recorded when the hole had a diameter of 2 mm; then the hole was enlarged to 6 mm and measurements were taken (Figure 6b). Imaging results using the two aforementioned algorithms are presented in Figure 7. The initial investigation for minimum detectable size on 1-mm aluminum plate using a 4-PWAS sparse array is initially concluded at 4 mm.

![Figure 5 Sparse array imaging: (a) a simple sparse array configuration; (b) triangulation principle](image)
3.3 Sparse Array Crack Detection

The test specimen is shown in Figure 8. A total of 7 PWAS were installed randomly with locations indicated in the plot on the right. After the baseline (pristine) data was recorded, a crack centered at (315, 249) were introduced, oriented as indicated (along the line of PWAS #2 and #3, perpendicular to PWAS #0 and #5). The crack was increased in length from 10 mm to 18 mm, 23 mm.
3.3.1 Inside Crack Detection

Using PWAS 0, 2, 3, 6 given in Figure 8 to form a sparse array, we are going to detect the presence of crack (at 10 mm) and its growth to 18 mm and 23 mm, as well as giving a crack size estimation with the yielded image results. The Lamb wave mode used here is S0 mode at 310 kHz with a wavelength around 17 mm. The image result of crack of 10 mm is given in Figure 9a. Since the wave used for interrogation has a wavelength smaller than the damage size, the damage shows up as an intensified spot in the resulting image, clearly and correctly representing the presence and location of the crack. When crack increases to a size comparable to or larger than the interrogation wavelength, the two tips of the crack forms two strong scatters of the Lamb wave and generated two strong intensified spots on the images, representing the crack’s tips, as shown in Figure 9b and Figure 9c. With the indication of crack tips, we can easily estimate the size of the crack. For example, for the 23 mm crack, the zoomed in damage image yielded out the locations of the two crack tips at (309, 255) and (328, 243), giving an estimation of crack size at 22.47 mm with an error of 2.3%. With the sparse array imaging, crack tips can be mapped; and therefore crack size can be measured immediately.
3.3.2 Outside Crack Detection

When PWAS 2, 4, 5, 6 are used to form the sparse array, the crack lies outside the network. Imaging results are given in Figure 11. Although the detection of 10-mm crack failed, we have obtained clear and correct images for 18-mm and 23-mm crack when they are outside the sparse array network.
ARRAY IMAGING ON THICK STEEL PLATE

Recently, PWAS has been tried on thick steel bridge structures to detect crack growth in both passive and active modes (Yu et al., 2009). In active mode, PWAS network was intended to scan the entire specimen and present the detection result as a 2-D image. To initiate such a study, we tested a five PWAS sparse array network on a 24x24x½ (unit: inch) square steel plate (Figure 12a).

To obtain appropriate guided waves for damage analysis, frequency tuning was conducted first. Figure 13 shows the strain curves and dispersion curves obtained from wavescope software within 0-425 kHz range (Giurgiutiu 2008). It can be seen the wave excitation is very complicated on the thick plate. A single mode nondispersive signal is very difficult to obtain in this situation and the sparse array imaging failed. A statistics based imaging algorithm called RAPID (reconstruction algorithm for probabilistic inspection of defects) was then used (Zhao et al., 2007) to identify the possibility of the damage present at a certain point in the structure without requiring prior knowledge of the wave propagation such as wave modes and velocity. The imaging result is shown in Figure 12b. The highlighted area shows the highest possibility of damage presence which is a zone centered around (318, 356). Though with deviation, such an image gave a correct indication of the damage presence and a close estimation of location.

Figure 12 Thick steel hole detection. (a) ½” steel plate with 5 PWAS installed, a 7.9 mm hole was introduced later; (b) image result of the hole detection at 138 kHz

Figure 13 Lamb wave tuning curves on ½” steel specimen. (a) group velocity; (b) strain curve.
5 CONCLUSIONS

In this paper, several ultrasonic guided wave imaging approaches using piezoelectric wafer active sensor arrays were presented. The imaging approaches were applied to thin aluminum plate and thick steel plate specimens to detect through-the-thickness damage and have obtained good results.

The linear PWAS phased array algorithm uses a group of sensors physically close to each other and excited at certain time interval. The beamforming and damage detection do not require the usage of baseline data and can provide a resolution as small as 1.7 mm on 1-mm aluminum plate when eight PWAS were used. Limitations include that the linear array can only scan half part of the specimen and needs additional imaging processing to estimate the crack size.

The sparse array uses the scattering signals, requiring the access to baseline data. However, it has the advantages of using a minimum of four sensors and being able to image the entire specimen. Currently, the detection resolution is 4 mm on 1-mm aluminum plate, but this can be improved with use of more sensors. In crack detection, sparse array has the feature that it images the tips of a crack; therefore it provides a good means of crack size estimation.

On thick plate, due to the complexity of guided wave excitation, statistics based RAPID algorithm was used which does not require the prior knowledge of wave propagation such as modes and propagation speeds. This approach can provide a simple indication of the presence of the damage and a rough estimation of the damage location. To provide high confidence of damage detection, further study will be conducted.

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REFERENCES


