ULTRASONIC GUIDED WAVE ANNULAR ARRAY TRANSDUCERS FOR STRUCTURAL HEALTH MONITORING

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ABSTRACT. The work presented in this paper utilizes the physics of guided wave propagation for structural health monitoring (SHM) transducer designs. Both the theoretical and experimental studies illustrated the importance of guided wave mode selection for SHM applications. Guided wave mode control is realized with an annular array transducer design on a PVDF polymer piezoelectric film. A sample problem on a 1mm thick aluminum plate is presented. Numerical calculations of the wave structures and guided wave power flow distribution inside the plate provide quick guidelines for the wave mode selection in structural health monitoring. Experimental study illustrates the importance of mode control with the comparison of PVDF annular array transducers and PZT ceramic disc transducers. The characteristics of wave mode reflections to defect depth and the defect sizing effect are also discussed in this paper.

Keywords: PVDF sensor, SHM, dispersion curve, power flow distribution
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INTRODUCTION

Ultrasonic guided wave based technologies are commonly used in nondestructive evaluation (NDE). With the merits of long distance monitoring, easy accessibility for in service structural components, and wireless interrogation potential [1], ultrasonic guided waves have attracted much research attention in structural health monitoring (SHM). In addition, a predefined reference state provides an opportunity for the application of many data driven and statistical signal processing technologies in SHM. However, a physically based “theoretically driven” monitoring methodology becomes more and more important for better interpretation of the sensor signal changes. Guided wave mode selection often needs to be considered in the design stage of the monitoring system to achieve specific monitoring requirements. In order to get good correlation between the time domain signal and the spatial domain damage localization information, a single mode guided wave excitation is preferred. This requires that the ultrasonic guided wave transducers have good mode-control capability.

PVDF polymer based piezoelectric transducers are flexible and cost effective [2-3]. The flexibility and the thin film structure of the PVDF transducers make them extremely suitable for surface mounted or embedded SHM. By properly patterning the PVDF

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transducer electrode, comb transducers, interdigital transducers, annular array, and sectioned annular array transducers can be designed to achieve guided wave mode control and mode selection.

The importance of the wave mode selection in ultrasonic guided wave based SHM is the focus of this paper. Power flow distribution of a certain wave mode is utilized as a key parameter to estimate the magnitude of wave-defect interaction. Theoretical study on a 1mm thick aluminum plate provided an example guideline on how to choose appropriate a wave mode for the best sensitivity for surface damage monitoring and easy damage severity assessment. In the experiment, wave mode selection is realized with a group of sectioned annular array transducers with adjustable electrode periods Experimental results clearly illustrated the performance difference of different wave modes in studying defect depth and defect sizing.

THEORY

Guided wave mechanics is the basis for appropriate wave mode selection in structural health monitoring. Guided wave displacement, stress, and power flow distribution along the thickness of the structure are very important issues in selecting a good mode for a particular type of damage. Take a 1 mm thick aluminum plate for example, the guided wave phase velocity and group velocity dispersion curve are shown in Figure 1 and Figure 2 respectively.

Each point of the dispersion curves represents a possible guided wave testing mode with a unique frequency and wavelength combination. Since each wave modes has its unique characteristics, appropriate mode selection is very important for a successful structural health monitoring sensor network design [4]. The displacement and power flow distribution of a certain wave mode can be calculated as follows.

Displacement field distribution can be obtained from wave structure analysis.

$$u_1 = f_{u_1}(x_3)e^{i\xi(x_1 - vt)}. \tag{1}$$

$$u_3 = f_{u_3}(x_3)e^{i\xi(x_1 - vt)}. \tag{2}$$

Here f_{u_1} and f_{u_3} are the distribution of the x_1 and x_3 direction displacement along the thickness of the structure. Using the strain-displacement relation, constitutive relation, and displacement-particle velocity relation of the material, strain field, stress filed, and the particle velocity field can be derived.

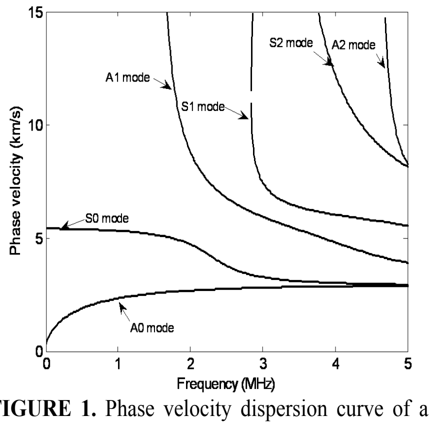


FIGURE 1. Phase velocity dispersion curve of a 1mm Al plate.

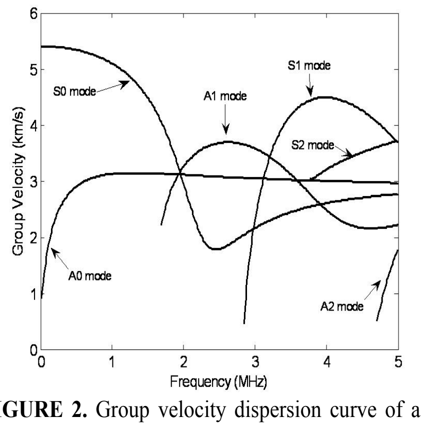


FIGURE 2. Group velocity dispersion curve of a 1mm Al plate.

Poynting's vector of the wave propagation at a certain point can be expressed as Equation 3 [5].

$$\mathbf{P} = \frac{-\mathbf{v}^* \bullet \boldsymbol{\sigma}}{2}. \qquad (3)$$

The entire power flow along a cross section can be expressed as the integration of Poynting's vector.

$$\int_S \mathbf{P} \bullet \hat{n} \;\; ds = P_S + i\omega[(U_S)_{peak} - (U_v)_{peak}]. \qquad (4)$$

For guided Lamb waves in an aluminum plate, power flow along the x_1 and x_3 directions are real and imaginary respectively. This means when a wave propagates in a structure, energy flow occurs in both the x_1 and x_3 direction. In the x_1 direction, there is net power transmission. While in the x_3 direction, there is flow of reactive peak kinetic energy and elastic energy. Reactive power flow is zero at both surfaces. This means there is no energy flow out of the system from the surface. Reactive power flow is zero at symmetric plane of the system. The power flow distributions of 4 typical wave modes are shown in Figure 3. Figure 3 (a), (b), (c), and (d) represents the A_0 mode at 1.15MHz, S_0 mode at 1.39 MHz, S_0 mode at 2.1 MHz, and the A_1 mode at 2.1 MHz respectively. It is shown in these figures that the first two modes have comparably flat x_1 direction power flow distribution along the entire thickness. However, the power flow of the third and fourth mode concentrates at the center region and surface region respectively. These information implies that the first two mode will produce quasi-linear signal to defect relation, while the third and fourth mode will be particularly sensitive to center and surface defects respectively.

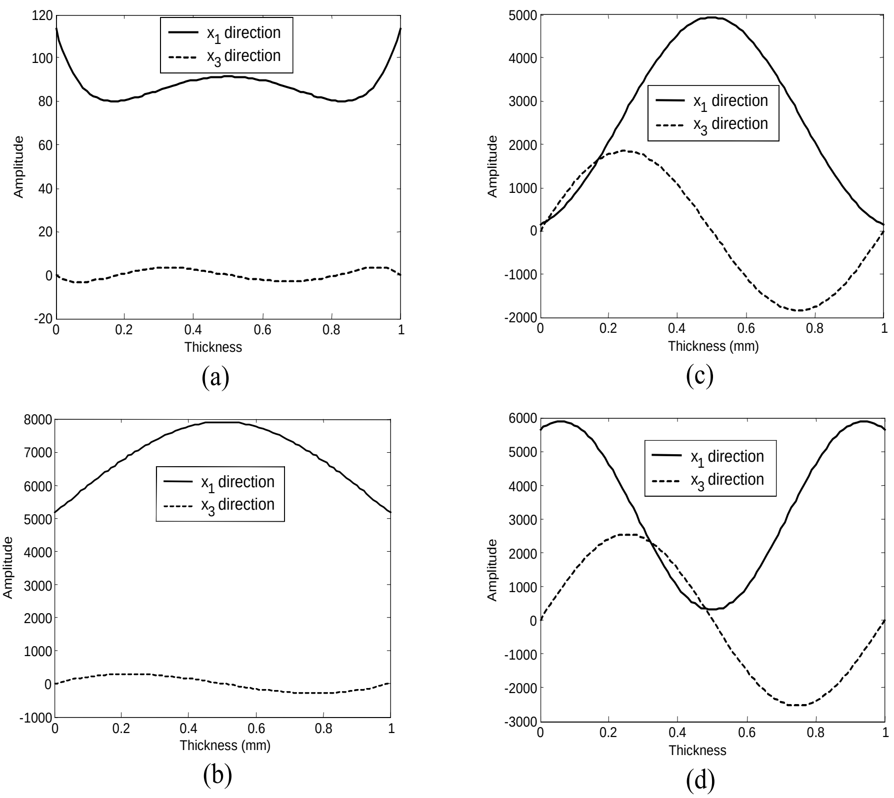


FIGURE 3. Power flow distribution of guided wave modes along the thickness of a 1mm aluminum plate structure. (a) A_0 mode at 1.15MHz, (b) S_0 mode at 1.39 MHz, (c) S_0 mode at 2.1 MHz, and (d) A_1 mode at 2.1 MHz.

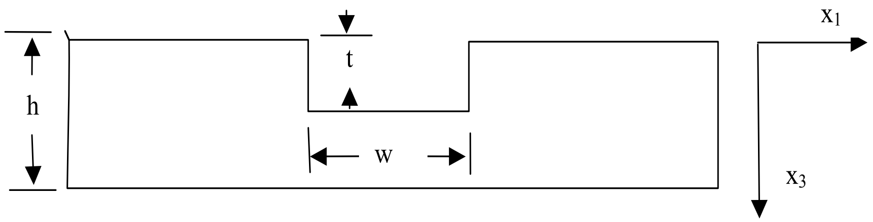


FIGURE 4. A model of defect in a plate structure.

A first order hypothesis for a quick estimation of wave defect interaction is expressed as follows. Defect influence on a particular guided wave mode is strongly related to the power flow distribution. A planar defect is a strong reflector of x1 direction power flow; x3 direction power flow will also be affected by volumetric defect. The interference of these two factors affects the final pulse echo and through transmission signal. A simple model of square notch defect is shown in Figure 4.
The total power flow through the entire thickness along x_1 direction is

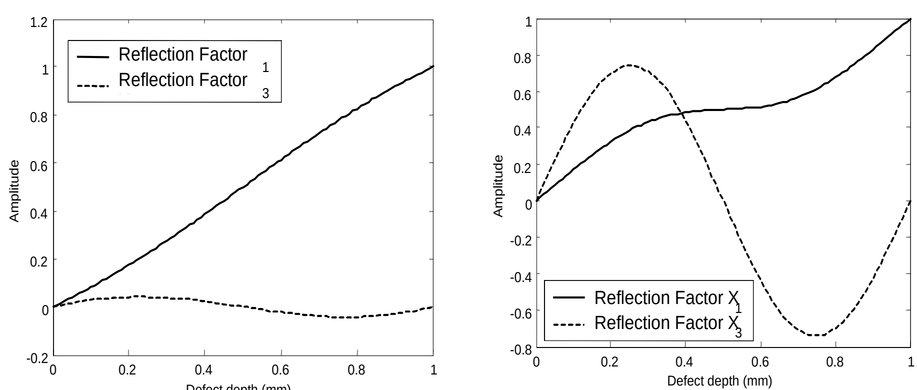
$$P_{total} = \int_0^h P_{x1}(dx_3) \ . \tag{5}$$

$$P_{echo} = \int_0^t P_{x1}(dx_3) + \alpha P_{x3} w \ . \tag{6}$$

$$RCoeff = P_{echo} \big/ P_{total} \ . \tag{7}$$

Here, h is the thickness of the plate. The width and depth of the defect is w and t. α is a coefficient representing the conversion from x_3 direction power flow to x_1 direction reflected guided wave strength. When the influence from the x_3 direction is negligible, a sensitivity factor of the wave modes to a certain depth defect can be estimated from only the integration term.

Take the S_0 mode 1390kHz and A_1 mode 2100 kHz for example. The relation between defect depth and echo strength is shown in Figure 5. The figure shows that the S_0 mode at 1390kHz generally has good linear correlation between defect depth and reflection signal. However, the A_1 mode at 2100kHz has strong nonlinearity. The energy flow along the x_3 direction is also large. There exist possibilities that the reflection from a certain depth defect could be larger than a through hole defect.



(a) (b)

FIGURE 5. Relation between reflection factor and defect depth when the width of the defect is 1mm. (a) S_0 mode at 1.39 MHz, (b) A_1 mode at 2.1 MHz.

EXPERIMENTAL STUDY

The PVDF transducers used include two functional components, one is a PVDF piezoelectric thin film, and the other is an electrode pattern fabricated on a polyimide substrate. The lay-up of the PVDF transducer is shown in Figure 6, in which the functional layers are bonded with conductive and normal adhesives.

Guided wave mode excitation and receiving are controlled by the joint influence of electrode pattern and wave propagation characteristics of the structure under monitoring. For a PVDF annular array, the electrode trace is circular, such that the waves excited from the transducer is omni directional. In order to control the wave excitation angular profile, sectioned circular arrays are studied in this work. A sample electrode patterns of a sectioned annular array is shown in Figure 7. For the 90 degree span sectioned annular array, the line width and the spacing between lines are both 1mm. When only one set of electrode is connected to excitation signal, the period of the electrode pattern is 4mm. When both sets of electrodes are connected to the excitation signal, the period is 2mm. Therefore, wave modes with two wave lengths can be achieved with this electrode pattern. The theoretical excitation lines are shown in Figure 8.

Comparison of mode selection performance of the PVDF transducer and a PZT disc transducer is shown in Figure 9. The seven finger PVDF sectioned annular array transducer has good mode selection performance. However, the PZT disc transducer excites both A_0 and S_0 mode with comparable amplitude at 1.39 MHz.

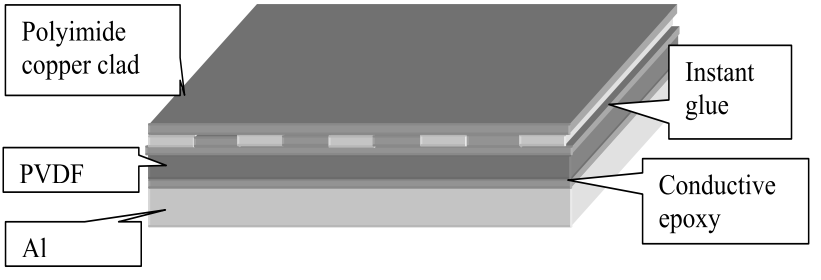


FIGURE 6. PVDF transducer element lay-up.

FIGURE 7. Annular array and section annular array with 90^o span.

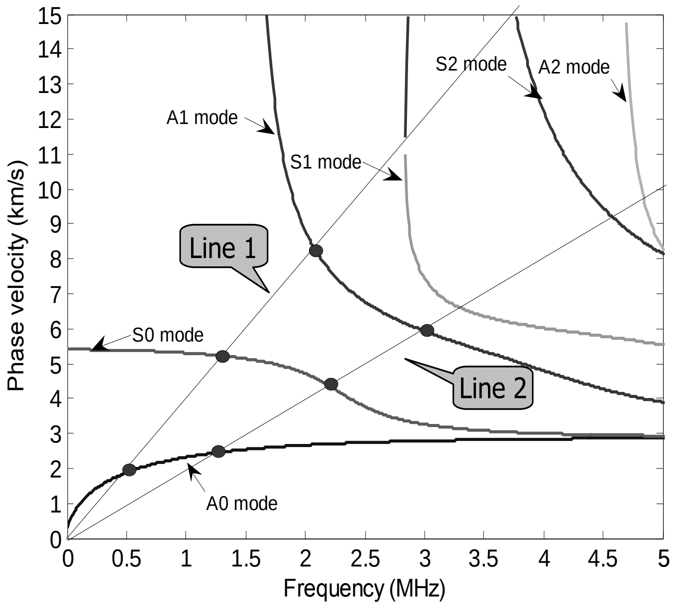


FIGURE 8. Mode selection line of annular array transducers.

Ultrasonic pulse echo tests at different defect depth were studied with the four different wave modes shown in Figure 3. Three structural states were monitored, the first was a reference state, the second was a state with a approximately a 1/3mm depth, 5mm diameter simulated corrosion defect on one side of the plate, the third was a through hole defect with 5mm diameter. The results show that the fourth wave modes used in the experiment had much different responses to these defect states. As was estimated form the power flow theory of the wave modes, A_0 at 1.15 MHz, and S_0 at 1.39 MHz have increasing echo amplitudes from the surface defect to through-hole. S_0 mode at 2.1 MHz are very dispersive, in addition the wave excitability is low, no significant echo from the defects are detected. For A_1 mode at 2.1 MHz, the echo from the surface defect is very strong because the power flow concentrates at the surface region of the structure. When the defect increased from the surface to a through whole, the influence from x_3 direction power flow reflection reduced. Therefore, smaller echo in the signal is detected. Quantitative explanation of this abnormal phenomenon can be obtained from specific finite element modeling of the wave-defect interaction.

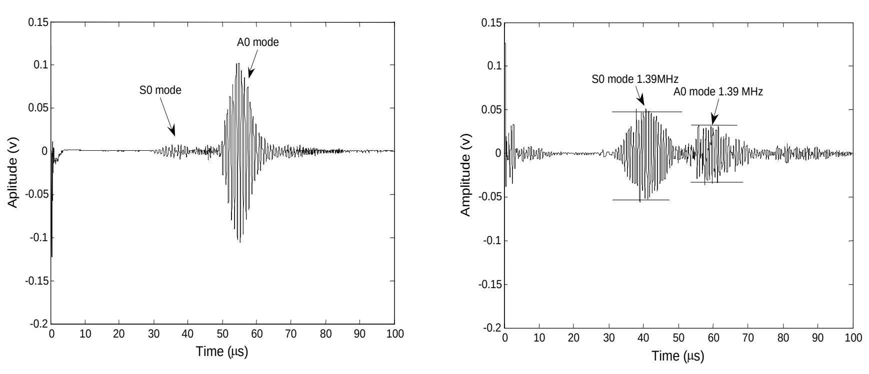


FIGURE 9. Through transmission ultrasound signal from (a) PVDF sectioned annular array transducer, (b) PZT disc transducer.

CONCLUSIONS

Theoretical predictions and experimental validation of the importance of mode selection in guided wave based SHM are clearly illustrated in this study. Much purer mode excitation and receiving can be achieved for example with a PVDF sectioned circular array than single PZT disc transducer. Correlation between wave mode reflection and defect depth and size are studied, which gives a guideline for real monitoring system design. For the four modes used in the experiment, A_0 (1.15MHz) and S_0 (1.39 MHz) has good echo-depth-size linear correlation. However, A_1 (2.1 MHz) is more sensitive to surface defects. S_0 mode at 2.1MHz is very dispersive, the wave package is elongated and the amplitude comparably small.

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