Piezoelectric Fiber Composite Ultrasonic Transducers for Guided Wave Structural Health Monitoring

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Abstract. This paper presents the characterization of a low-voltage high-frequency piezoelectric fiber composite (PFC) transducer for guided wave structural health monitoring applications. The PFCs with interdigital electrodes have been utilized as smart material sensors and actuators. The structural guided waves exhibit complicated multimodal dispersive behavior. It has resulted in a need that the transducers can launch and sense guided waves of specific frequency or wavelength propagating through the host structure. The devised PFC transducer is poled symmetrically with respect to its mid-plane and thereafter activated by anti-symmetrically aligned interdigital electrodes. Directional Lamb waves can be generated at the frequency, nearly one megahertz, which corresponds to the fundamental extensional resonance of PFC alone. The directivity patterns of free $A_0$ and $S_0$ Lamb modes transmitted by the PFC transducer through the host plate were measured. A point-focus pulsed laser-induced ultrasound was used to emulate an acoustic source in response to crack formation. Experimental results reveal that the PFC transducer can capture multimode fixed-wavelength Lamb waves, which can be discriminated by wavelet transform technique.

Introduction

Taking advantages of excellent actuating abilities and conformability, piezoelectric fiber composites (PFC) have been utilized as smart material actuators in applications of vibration suppression and structural health monitoring (SHM). The conventional PFC are made of either circular \cite{1-3} or rectangular \cite{4-6} cross sectional unidirectional piezoelectric fibers embedded in epoxy matrix and sandwiched between two flexible polymer sheets printed with symmetrically aligned interdigital electrodes (IDE). The electrode fingers are perpendicular to the piezoelectric fibers. A periodically inverted electric field is induced in the spaces between two adjacent electrode fingers during poling and actuation. The PFC can expand or contract simultaneously when a periodic voltage applies to the electrodes. However, the PFC can not be an effective acoustic wave transducer because of its symmetric configuration. Most PFC devices operate in frequency range lower than 100 kHz. It can not satisfy the needs in application of SHM.

The acoustic transducers in SHM applications are usually transmitting guided waves, for example, Lamb waves in plates. The structural guided waves exhibit multimodal dispersive behavior. Large sensitivity, high temporal and spatial discriminations are required for guided wave transducer in defect detection. It has resulted in a need for high frequency and directive transducers. The performance of PFC used as guided wave transducers can be improved by a new electrode layout \cite{7}. The developing PFC transducer is poled symmetrically with respect to its mid-plane and thereafter activated by anti-symmetrically aligned interdigital electrodes. The devised PFC has periodic deformation when it is actuated by anti-symmetric electrodes and therefore, is abbreviated as AE-PFC. The transducers transmit Lamb waves at frequency up to 1 MHz. The operating frequency depends on the properties of AE-PFC and the host plate. In this work, characterization of the PFC transducers is conducted by directivity measurement and detection of broadband signal simulated by point-focus laser-induced ultrasound.
Piezoelectric Fiber Composite with Interdigital Electrodes

A schematic of the PFC under poling process and actuation is illustrated in Fig. 1. Two sheets of polyimide films printed with IDE are placed on the top and bottom surfaces of unidirectional PZT-5A fibers (Advanced Cerametrics Inc., Lambertville, New Jersey) embedded in epoxy resin. The piezoelectric fibers have circular cross section with the average diameter 0.25 mm. The top and bottom surface electrode fingers are anti-symmetrically aligned with center-to-center one-quarter wavelength offset. Besides the IDE, two sets of zigzag electrodes might distribute on both top and bottom sheets to facilitate yielding intensive poling electric field. A piecewise inverted electric field is symmetrically generated. In contrast, an alternating voltage is applied on the IDE alone to yield an anti-symmetric electric field for excitation. The acting electric field would be along or against the polarization alternately. A periodic deformation is therefore induced in the PFC transducer.

When the PFC transducer surface adhered on a host plate, the resonant frequencies of PFC will be altered with amounts depending on the host plate. This effect has been discussed by the authors [7]. The fundamental extensional resonance of the PFC is used to emit Lamb modes in a 1 mm thick aluminum plate, in which the cut-off frequency of $A_0$ mode approximates to 1.6 MHz. Only two fundamental modes, named as $A_0$ and $S_0$ modes, can be actually excited within the frequency range from dc to 1.6 MHz. Fig. 2 shows the calculated displacement contours for $A_0$ and $S_0$ Lamb modes launched by a one wavelength long AE-PFC. The Lamb waves have the same frequency as the excitation. The transmitted Lamb mode near the area adhered to AE-PFC has a different wavelength other than the corresponding free Lamb wave since local stiffness of the host plate has been changed by AE-PFC.

Experimental Characterization of AE-PFC

The PFC transducer has been characterized by a series of experimental measurements. A PFC transducer was surface adhered to a 1 mm thick aluminum square plate of side length 1 m. The distance from the front edge of PFC to the plate periphery is two-third of the side length. The first experiment was conducted to measure the directivity of the PFC transducer. A conventional broadband 1 MHz ultrasonic transducer (ABT0104-R, Staveley Sensors Inc.) was used to capture the waveforms transmitted from the PFC transducer. The ultrasonic transducer was placed normal to plate or inclined to the plate in combination with a 39° wedge (Fig. 3).

![Fig. 1](image1.png) Schematic diagrams of the presented piezoelectric fiber composite which is (a) polarized by symmetric electric field, and (b) actuated by anti-symmetric electric field about its mid-plane. The arrow with P indicates polarization direction.

![Fig. 2](image2.png) Contours of the axial displacements for the (a) $A_0$ and (b) $S_0$ Lamb modes excited by AE-PFC adhered on the top surface of a 1 mm thick aluminum plate using a 1.03 MHz sinusoidal signal.
The PFC transducer was excited by 10 periods of low voltage 950 kHz sinusoidal wave at 10 V_{p-p}. Signal-to-noise ratio (SNR) can be increased by waveform averaging. Fig. 4 shows the waveforms measured by the broadband transducer which directly contacted with the plate and was located at distances of 200 and 300 mm from the PFC. The S\textsubscript{0} waveform is relatively small in comparison with the A\textsubscript{0} waveform. It was difficult to measure directivity of such a S\textsubscript{0} mode. A 39\textdegree wedge was then used to magnify amplitude of the S\textsubscript{0} mode. The A\textsubscript{0} mode was simultaneously reduced to almost the same intensity as S\textsubscript{0} mode. The group velocities of the A\textsubscript{0} and S\textsubscript{0} Lamb modes were measured as 3.19 and 5.18 mm/μs. Compared with theoretical group velocities of Lamb waves propagating in an aluminum plate (Fig. 5), the measured results confirm both wave packets are A\textsubscript{0} and S\textsubscript{0} modes, respectively.
The experiment for measuring beam patterns of $A_0$ and $S_0$ Lamb modes were conducted using bursts launched by the PFC operated at 950 kHz. The intensity of the waveform was measured every $5^\circ$ interval from $0^\circ$ to $180^\circ$ along a circle of radius 200 mm with the center located at the middle of front edge of the PFC. The directivity of $A_0$ mode is much stronger than $S_0$ mode. In addition, the $S_0$ mode has a skewed pattern inclined at an angle of 10 degrees. It is probably caused by the leakage of electric field lines at the edge of the electrode finger.

![Fig. 6](image1)

**Fig. 6** Radiation patterns of (a) $A_0$ and (b) $S_0$ Lamb modes emitted by a PFC transducer surface adhered on a 1 mm thick aluminum plate.

Sudden crack formation in plates or shells made of brittle materials usually emits structural guided waves. A point-focus pulsed laser-induced ultrasound was used to emulate an acoustic source in response to crack formation. The acoustic source was located at 200 mm from the PFC transducer, which is a fixed-wavelength transducer. Fig. 7 depicts the multimode waveforms captured by the PFC transducer. Both $S_0$ and $A_0$ modes occurring in time domains, from 40 to 50 sec. and from 60 to 75 sec., exhibit a bit dispersive. The time-of-flights are the same as what are shown in Fig. 4(a), in which the $S_0$ and $A_0$ bursts traveling the same distance. Besides the fundamental modes, a 2.5 MHz signal and its echoes reflected from the edges of plate arrived twice in this time window. The multimode dispersive Lamb waves can be discriminated by wavelet transform or other time-frequency representation techniques. In practice, the high-frequency modes can be removed by low-pass filters and would not be confused with the fundamental modes.

![Fig. 7](image2)

**Fig. 7** A 40 mJ pulse laser induced transient waveform captured by AE-PFC at a distance of 200 mm.

![Fig. 8](image3)

**Fig. 8** Spectrogram corresponding to the multimode Lamb wave signal shown in Fig. 7.
Conclusions

The presented low-voltage high-frequency PFC transducer is poled symmetrically and activated by anti-symmetrically aligned interdigital electrodes about its mid-plane. The radiation patterns of free A₀ and S₀ Lamb modes transmitted by the PFC transducer through the host plate were measured. The A₀ mode has stronger directivity than the S₀ mode. A leakage of electric field lines at the edge of front electrode fingers might yield skewed beam pattern of the S₀ mode. But, A₀ mode is free from such influence. A point-focus pulsed laser-induced ultrasound was used to emulate a broadband acoustic source in response to sudden crack formation. Experimental results reveal that the PFC transducer is a fixed-wavelength acoustic sensor which can capture multimode dispersive guided waves. Unexpected high frequency Lamb modes can be discriminated by time-frequency representation techniques. The high-frequency PFC transducer has a great potential in applications of guided wave structural health monitoring with the advantages of low voltage drive and fixed-wavelength sensing capability.

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References