Flexible Transducers for Guided Wave Structural Health Monitoring of Porous Composite Plates

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Abstract. Most wind turbine blades are composite shell structures made of porous cores sandwiched between fiber-reinforced polymer laminates. Piezoelectric fiber composites (PFC) have been shown to have advantages of excellent actuating abilities and conformability and can be used as surface-mounted sensors on host shell structures in application of active structural health monitoring. Arranging the poling and actuating electric fields in different configurations, the piezoelectric fiber composite sensors can deform in either extension or thickness-shear vibration modes. Therefore, guided structural waves polarized in the sagittal plane or transverse horizontal direction can be generated and sensed. This paper investigates the characteristics of two groups of above-mentioned PFC sensors adhered to the host plates. Both sensors with interdigital electrodes can be functioned under low-voltage and high-frequency operating conditions. One of the advantages is that higher-order harmonic modes can be induced by both groups of PFC transducers.

1. Introduction

Both plate waves polarized in the sagittal planes and transverse horizontal (TH) plate waves have been used in the areas of non-destructive testing and guided-wave structural health monitoring depending on specific applications. Piezoelectric ceramic elements are usually formed in planar shape, and are of difficulty to attach on curve surfaces such as shells, pipes, etc. It results in a need for flexible piezoelectric transducers to actuate and to sense the guided waves in structures. The piezoelectric fiber composites (PFCs) with interdigital electrodes (IDE) on the top and bottom surfaces are one of the best choices in these applications because of their capability in actuation and conformability. The original developments of PFCs [1-2] were designed for generation of extension mode. Later, the PFCs are used to be sagittal guided wave sensors or actuators [3-5]. Arranging the poling and actuating electric fields in different configurations, the PFCs can deform in thickness-shear vibration mode other than extension mode. The TH guided wave transducers made of PFCs were developed and are abbreviated as TH-PFC transducers [6]. The TH modes have less attenuation in guided wave structural health monitoring for the host media comprising porous cores or covered by layered insulation with weak-adhesives.

The flexible guided-wave transducers made of PFCs are formed with unidirectional PZT-5A fibers embedded in epoxy matrix and sandwiched between two flexible polymer sheets printed with interdigital electrodes (IDE). The epoxy resin surrounding the fibers is used to resist tensile stress. For the extension-mode PFC, a periodically inverted poling electric field is induced in the fibers located in the spaces between adjacent electrode fingers,
which are symmetrically aligned across the fibers and epoxy. The PFCs can expand or contract simultaneously when a periodic voltage applies to the electrodes. An alternative design actuates the PFCs to yield guided waves polarized in the sagittal plane using anti-symmetrically aligned IDE, and was abbreviated as AE-PFC transducers as shown in Fig. 1(a). In the schematic, additional zigzag electrodes on opposite surfaces of the PFCs are used to assist the generation of poling electric field. For the TH-PFC transducer depicted in Fig. 1(b), the piezoelectric fibers have been well-poled along themselves prior to fabrication process. The actuating electric fields are through the thickness. The anti-symmetric aligned electrodes on the top and bottom surfaces yield thickness-shear vibration. Either sagittal plate waves or TH plate waves propagate in the direction perpendicular to the electrode fingers.

![Exploded diagrams of the (a) AE-PFC and (b) TH-PFC guided-wave transducers.](image)

Fig. 1. Exploded diagrams of the (a) AE-PFC and (b) TH-PFC guided-wave transducers.

2. Formulation

2.1 Periodic FE Models of AE-PFC and TH-PFC

The cross section diagrams of a unit cell comprising a piezoelectric fiber attached on a host plate for AE-PFC and TH-PFC transducers are schematically shown in Fig. 2. 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 metallic electrodes were made of copper. Average diameter of the piezoelectric fibers is about 250 \( \mu \)m. The wavelength of TH mode is not much longer than the diameter of piezoelectric fiber. Hence, the cell cannot be assumed as a homogeneous material. Every piezoelectric fiber is modeled to have hexagonal symmetry and its axis parallel to the fibers. Other components are assumed to be isotropic materials. The IDE fingers of width \( \lambda/4 \) are separated by an interval \( \lambda/2 \) between axes of two neighbouring fingers of different polarities. For TH-PFC shown in Fig. 2(b), it can be modeled as a combination of a number of unit cells. Each cell comprises of a PZT-5A fiber. Dimensions of each PFC component were measured using a metallurgical microscope and apply to numerical simulation. In evaluation of the natural frequencies and corresponding natural modes, the piecewise interdigital electrodes are assumed to be continuous copper. However, the electrodes are discontinuous in the case of calculating resonant vibration modes and their corresponding frequencies.

The electric fields in PFC and the mechanical response were determined using the ANSYS finite-element code. For plate waves polarized in the sagittal plane, length of the simulation model is twice of the wavelengths. For TH modes, the number of cells is selected such that the model has the same length as one wavelength. The corresponding degrees of freedom (dofs) on the front and rear faces are assumed to be identical. On both ends, the nodal dofs correspond to each other must be the same value in accordance with the definition of wavelength. Dimensions in thickness direction of the finite-element meshes have to be as small as possible to get rid of introducing extra vibration modes in thickness direction.
2.2 Frequency Spectra and Resonant Modes

In determining the natural frequencies for either AE-PFC or TH-PFC attached to a host plate, the structure is assigned to be of length equal to a specific wavelength \( \lambda \). According to the deformations about the mid-plane of the host plate, the natural modes are classified into symmetric and anti-symmetric modes. Frequency spectra of sagittal plate waves (Fig. 3) or TH plate waves (Fig. 4) can be established by discrete coordinates of the spatial frequencies \( (1/\lambda) \) and their corresponding natural frequencies. The frequency spectra of guided waves can be classified into two categories. The deformation dominated by the PFC is called the PFC mode; otherwise, it is called the plate mode. The frequency spectra split into the PFC modes asymptotically from the curves of plate modes travelling in a bare host plate.

Fig. 3. Comparison of frequency spectra of the sagittal plate waves in a PFC adhered on a 1 mm thick aluminum plate with those in a bare host plate.
Fig. 4. Comparison of frequency spectra of the TH plate waves in a PFC adhered on a 1 mm thick aluminum plate with those in a bare host plate.

Fig. 5 shows deformation shapes of the resonant modes for an AE-PFC attached to a host plate with length equal to twice the 3.2 mm wavelength. No matter what deformation of the AE-PFC, the host plate deforms anti-symmetrically with respect to the mid-plane. Compared with the frequency spectra shown in Fig. 3, the plate mode is the $A_0$ mode. It is found that two additional resonant modes occur at 2.59 and 2.73 MHz. Their wavelengths are one-third of the fundamental wavelength, and they behave as the third harmonics. The plate deformations are still similar to the $A_0$ mode in these two cases.

Similar phenomenon can be observed in the case of TH-PFC with wavelength equal to 4.48 mm attached to the host plate. There are 16 piezoelectric fibers per wavelength. The out-of-plane displacements for every mode of TH plate wave are plotted by contours in Fig. 6. A region with denser contour lines indicates the presence of larger displacements. Two third harmonic modes appear at 2.121 and 2.620 MHz. The host plate deforms like a $TH_0$ mode at 2.121 MHz, but a $TH_1$ mode at 2.620 MHz.

Fig. 5. Resonant modes of the two-wavelength model AE-PFC with $\lambda$ equal to 3.2 mm. The abbreviation THG indicates the third harmonic mode having one-third wavelength of the model.
3. Experiments

The measurements of frequency response functions for AE-PFC and TH-PFC transducers were carried out by the experiment setup shown in Fig. 8. The AE-PFC and TH-PFC had electrode finger width 0.4 mm and 1.12 mm; the pitch between axes of two neighbouring fingers of different polarities was 0.8 mm and 2.24 mm, respectively. The overlap length of two electrode fingers was 25 mm for both transducers. Two PFC transducers were adhered to a host plate apart from a distance 400 mm in the experiments. The transmitter was actuated by a 10-cycle, 10 Vpp amplitude tone-burst generated by a function generator (Tektronics AFG3102). The guided wave signal detected by the receiver was magnified by a built-in amplifier of Panametrics 5800PR with 40 dB gain. The receiver was surrounded by an aluminum shield case against electromagnetic interference.
The host structures considered in experiments were aluminum plates and composite laminates formed by a 3.69 mm thick porous balsa wood sandwiched between two sheets of woven glass/epoxy of thickness 0.32 mm. The composite specimens were manufactured by resin transfer molding process, in which the epoxy resin ML 3564 was mixed with ML 3500B hardener. The balsa wood has cellular microstructures and is often used as sandwich core materials in application of impact energy dissipation. The presence of porosity usually causes sound attenuation. Fig. 8 shows a comparison of the attenuations of TH plate waves and the plate wave polarized in the sagittal plane travelling through a glass/epoxy balsa core sandwich plate. Attenuation is 0.0178 Np/mm for the sagittal plate waves and 0.0167 Np/mm for the TH plate waves. It reveals that TH plate waves have an advantage in application of guided-wave structural health monitoring for porous sandwich composites.

![Fig. 8. Attenuations of TH plate waves and sagittal plate waves propagating in a sandwich plate with glass/epoxy face sheets and balsa wood core.](image)

4. Results and Discussion

The frequency of tone-burst signal is linearly swept from 20 kHz to 5 MHz in experiments. The specific PFC mode yields when the excitation frequency approaches the corresponding dispersion conditions of guided waves, in which the wavelength is equal to twice the electrode pitch. Large-amplitude plate wave yields if the frequency spectrum of PFC mode is close to that of plate mode in a bare host plate. Fig. 9 shows the tone-burst waveforms received by above-mentioned PFC transducers adhered to a 1 mm thick aluminum plate. As shown in Fig. 9(a), the first arriving signal captured by AE-PFC at 1.1 MHz is the $S_0$ mode. The later arrival having larger amplitude is $A_0$ mode. The TH-PFC usually transmits a single TH plate wave at each frequency. As depicted in Fig. 9(b), the signal detected at 750 kHz is the $TH_0$ mode, whose deformation is out of the sagittal plane and symmetric about the mid-plane.

![Fig. 9. Tone-burst waveforms captured by (a) AE-PFC (1.1 MHz) and (b) TH-PFC (750 kHz).](image)
The measurements of frequency response functions (FRF) of both PFC transducers were carried out using the same swept frequency, tone-burst signals. One PFC transducer launched a tone-burst waveform; the travelling plate waves were captured by the other PFC transducer. Fig. 10 shows the experimental results. The spikes in the spectra correspond to the PFC modes whose frequency and wavelength are close to the dispersion conditions of plate modes shown in Fig. 3. As shown in Fig. 10(a), the largest spike appearing at 2.62 MHz corresponds to the third harmonic mode generated by the AE-PFC in comparison with the resonant modes shown in Fig. 4. Similar phenomenon can be found in the FRF of the TH-PFC transducers at 2.12 MHz. Odd-order harmonics can be generated by AE-PFC or TH-PFC transducer since the direction of electric field induced mechanical response reverses at each interdigital interval or coverage of electrodes.

![Fig. 10. Frequency response functions of above-mentioned (a) AE-PFC and (b) TH-PFC transducers adhered to the host plates.](image)

5. Conclusion

The characteristics of flexible transducers for generating plate waves polarized in either sagittal or transverse horizontal plane have been successfully investigated. Both AE-PFC and TH-PFC equipped with interdigital electrodes are multi-mode transducers. They can be actuated under low-voltage and high-frequency operating conditions. Frequency responses of the flexible transducers depend on material properties of the host plate and electrode pitch, which is equal to one-half of the wavelength in this study. Clear guided wave signal can be achieved if the frequency spectra of selected guided modes are close to the plate modes of the bare host plate. Both PFC transducers can generate higher-order harmonics, which are not caused by micro defects embedded in the transducers. Instead, they are due to the reverse direction of electric field induced mechanical response at neighbouring interdigital interval or coverage of electrodes. The TH plate waves have less attenuation than sagittal plate wave in sandwich structures with cellular or porous cores. The TH-PFC transducers have potential to be used in guided wave structural health monitoring application for porous sandwich structures.
Acknowledgment

This work was supported by the Ministry of Science and Technology of the Republic of China through the grant MOST 104-2221-E-009-038.

References