Guided Wave Generation and Propagation in Piezoelectric Composite Plates for Establishing Structural Self-awareness

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ABSTRACT

This paper presents a numerical investigation of guided wave generation, propagation, interaction with damage, and reception in piezoelectric composite plates for the purpose of establishing structural self-awareness. This approach employs piezoelectric composite materials as both load bearing structure and sensing elements. To understand the wave propagation characteristics in piezoelectric composite plates, finite element modal analysis of a plate cell with Bloch-Floquet condition is performed. A comparative study is carried out between a standard composite plate and a piezoelectric composite plate to highlight the influence of piezoelectricity on guided wave dispersion relations. Subsequently, a transient dynamic coupled-field finite element model is constructed to simulate the procedure of guided wave generation, propagation, interaction with damage, and reception in a piezoelectric composite plate. Active sensing array is designed to capture the structural response containing the damage information. Three engineering scenarios are considered to demonstrate the ultrasonic sensing capability of the piezoelectric composite system: a pristine case, a one-damage-location case, and a two-damage-location case. Finally, time-reversal method is utilized to locate and image the damage zones. This research shows that piezoelectric composite material possesses great potential to establish structural self-awareness, if it serves both as the load bearing and structural sensing component.

INTRODUCTION

Piezoelectric materials can be made into both actuation and sensing device due to their inverse and direct piezoelectric properties. For example, Piezoelectric Wafer Active Sensors (PWAS) have been widely adopted as enablers for generating and receiving ultrasonic guided waves [1]. On the other hand, composite materials have been increasingly used in mechanical and aerospace structural design, serving as load

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bearing components with their superb strong, light-weight characteristics. Research efforts have been exerted on establishing structural self-awareness by introducing sensing elements into composite materials. Minakuchi and Takeda implemented fiber optic sensors in aerospace composite structures for impact damage detection [2]. Krishnamurthy et al. embedded magnetostrictive particle layers in composite laminates and achieved delamination detection [3]. To foster in-situ ultrasonic inspection of composites, Rosania et al. designed the intelligent composites with embedded piezoelectric sensors to establish the life-cycle health management capability. However, such an embedding practice would inevitably cause stress concentration in the materials and may eventually incubate local cracks. Paget et al. conducted experiments on the performance of embedded piezoceramic transducer in mechanically loaded composites, and the results showed a low survival rate of the sensors [4]. Taking an alternative approach, researchers have also been trying to manipulate material properties by adding functional components. Tallman et al. used carbon nanofiber/polyurethane for the fabrication of nanocomposites and realized enhanced delamination detection and distributed strain sensing [5]. Gallo and Thostenson distributed carbon nanotubes in composites to build structural self-sensing capability and managed to monitor material micro cracks [6]. Recently, Haghishtiani and Greminger utilized polyvinylidene fluoride (PVDF) as the composite matrix for integrated structural load sensing [7]. Such piezoelectric composite material demonstrated promising sensing capability in low frequency mechanical tests.

This study investigates the potential of a polyvinylidene fluoride (PVDF) matrix composite material for integrating both load bearing and structural sensing in ultrasonic range. While sustaining the loads, each location across the piezoelectric composite member can serve as an actuator and a sensor. At one location, a material point under electric excitation can generate ultrasonic mechanical response due to the inverse piezoelectric effect. This mechanical disturbance will propagate along the structure as guided waves, interact with possible damage/fatigue, carry damage information with them, and finally be picked up by the electrodes at the sensing locations due to the direct piezoelectric effect. Such guided wave generation and reception capability enables the piezoelectric composite materials to establish self-awareness through the ultrasonic guided wave interrogations.

GUIDED WAVE CHARACTERISTICS IN PIEZOELECTRIC COMPOSITES

The introduction of piezoelectric effects through the polling procedure may substantially influence the guided wave characteristics in terms of dispersion relations in a composite plate. To obtain the fundamental understanding of guided wave mechanism in piezoelectric composite plates, finite element method (FEM) with Bloch-Floquet boundary condition was adopted. Such FEM technique has been widely used to model dynamic response of periodic structures. Large scale waveguides have been treated as the connection of subsections of periodic components for the solution of dispersion curves and mode shapes [8]. Similarly, the piezoelectric composite plate can be treated as the assembly of unit cells of piezoelectric cubes. The piezoelectric effects enter the solution via the coupled field analysis.

Figure 1 presents the unit finite element cell with Bloch-Floquet boundary condition for a piezoelectric composite plate. The Bloch-Floquet boundary condition imposes constrains on the degrees of freedom (DOFs), implying phase delays between the unit cell boundaries. ξ_x and ξ_y represents the wavenumber in x and y direction, defining a corresponding wavelength at the angular frequency ω. a_x and a_y are the unit cell dimensions. They usually take very small values, 0.1 mm for the current analysis, to accurately capture short wavelength ultrasonics waves. The solving scheme sweeps through the wavenumber domain. At each wavenumber, corresponding to a certain wavelength, the only unknown terms in the dynamic equation system are the frequencies. Thus, the target problem retrieves to the conventional modal analysis, where the eigenvalues are the frequencies of the wave modes possessing the same defined wavelength and the eigenvectors represent their mode shapes. The physical interpretation of the solution mechanism can be perceived from the nature of guided waves: cross-sectional mechanical resonance propagating in the normal direction. It should be noted that the Bloch-Floquet boundary condition is applied on all the vertical boundary nodes. In addition to the corner nodes, if intermediate boundary nodes exist, they need to be compatible with the corresponding counter facing nodes, i.e., the counter facing nodes at $X = 0$ and $X = a_x$ should possess a $e^{i\xi_x a_x}$ phase difference. It should also be noted that, for the modeling of piezoelectric effects with coupled field analysis, the Bloch-Floquet condition not only applies to displacement DOFs but also voltage DOFs.

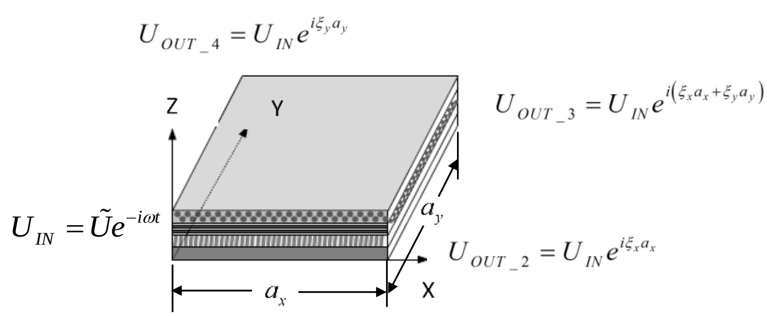

Figure 1: Unit finite element cell with Bloch-Floquet boundary condition for the computation of guided wave dispersion and mode shapes in a piezoelectric composite plate.

To better appreciate the influence of piezoelectricity on the dispersion relations of plate guided waves, numerical investigation on a glass fiber PVDF matrix composite plate was performed before and after the polling procedure. Before polling, the piezoelectric constants of the material are set to zero, while they would take non-zero values after polling. It should be noted that the detailed material stiffness matrix and piezoelectric constants need to be obtained from experimental measurements. However, this study focuses more on the phenomenological aspect of the active sensing procedure. Systematic experimental efforts will be performed in a future study. For current stage, a quasi-isotropic composite material property was assumed. Figure 2 shows the dispersion relations obtained from the Bloch-Floquet FEM. The multimodal, dispersive nature of guided wave is quite obviously illustrated. Figure 2a presents the frequency-phase velocity dispersion relations of a 2-mm thick composite plate before polling, while Figure 2b plots the dispersion curves after the introduction of piezoelectric effects. It is apparent that all the Lamb modes travel much faster with the coupling of mechanical and electrical quantities, and the cut-off frequencies shifts to higher values. However, the shear horizontal modes are not influenced since the shear piezoelectric coupling coefficients are zero. The influence is especially obvious for the fundamental symmetric Lamb mode (S0). Before polling, the phase velocity is merely 2748 m/s at the low frequency range, while it reached 4140 m/s with the piezoelectric effects. S0 also became much more dispersive. All the Lamb modes finally converged towards the surface guided Rayleigh waves, which showed a much higher wave speed in the piezoelectric composite plate. These distinctive dispersion variations are, after all, related to the piezoelectric constant values. The degree of influence need to be further determined from experimental validations in a future work.

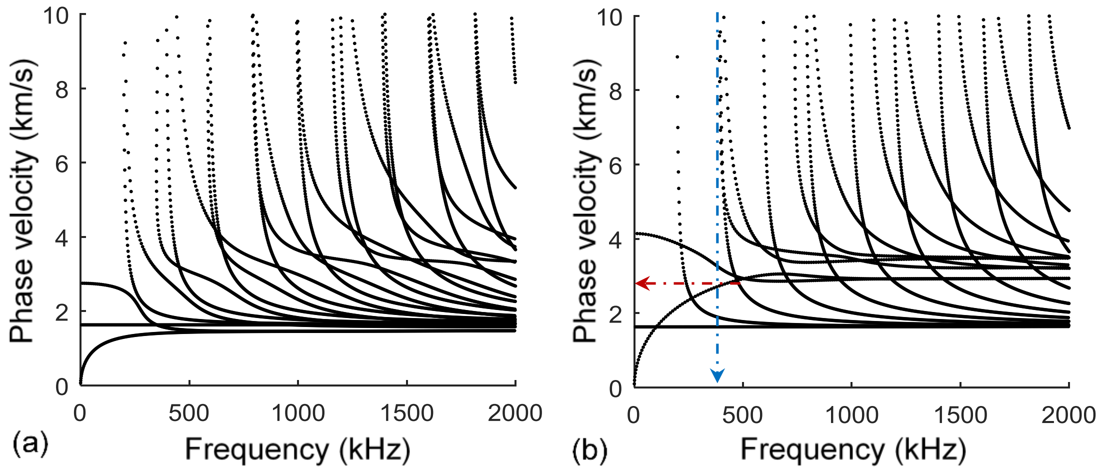

Figure 2: Guided wave dispersion curve results for a 2-mm thick composite plate: before polling (left); after polling and exhibiting piezoelectric effects (right).

FINITE ELEMENT MODELING OF STRUCTURAL SENSING

Built upon the comprehensive understanding of the guided wave features in the piezoelectric composite plate, the guided wave generation, propagation, interaction with damage, and reception will be further studied by a transient dynamic coupled field finite element model.

Finite Element Model and Sensing Array Design

Figure 3 shows the finite element model adopted for the simulation of guided wave active sensing in a 500-mm long, 500-mm wide, and 2-mm thick piezoelectric composite plate. Commercial finite element package ANSYS was used to conduct the simulation task. SOLID5 coupled field element was deployed to discretize the simulation domain. Extended region of absorbing layers with increasing damping (ALID) was implemented surrounding the plate to eliminate the boundary reflections as well as to minimize the model size. Thus, the computation of wave propagation in infinitely large plates can be achieved with a finite size model. The piezoelectric composite material is used as both the structural and sensing components. Consequently, only surface bonded electrodes are needed at the designated actuation and sensing locations. In this study, a total number of eight sensing pairs were used in the sensing array design. Each sensing pair was comprised of one actuation electrode and one sensing electrode. The electrodes took the circular shape with a diameter of 10 mm. The actuation and sensing electrode were placed 20 mm apart, forming the pulse-echo active sensing mode. The rational for such an array design aims to better identify the wave packets scattered from the damage. Guided waves generated by the actuation electrode would reach the sensing location right after their emission as a direct incident wave packet. Then, they will propagate along the plate structure, be scattered at the damage sites, and finally arrive at the sensing electrode as echo wave signals. Thus, ideally, after the direct incident wave packet, the rest of the waves are all from damage reflections. For case study, three engineering scenarios were considered: a pristine case, a one-damage-location case, and a two-damage-location case. Without losing generosity, the damage coordinates for one-damage-location case was (290 mm, 290 mm), and another damage at (170 mm, 210 mm) was additionally introduced for the two-damage-location case. These 2 cm by 2 cm through-thickness square damage zones are modeled by reducing the material stiffness by 90% within the damage areas.

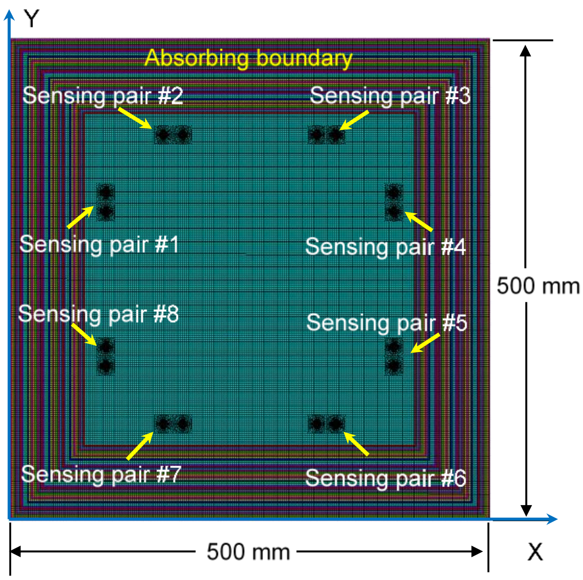

Figure 3: Full-scale finite element model with eight sensing pairs.

Finite Element Simulation Results for Guided Wave Active Sensing

Figure 4 shows the snapshots of the stress wavefield as well as the representative sensing signals from sensing pair #3. Only single S0 wave mode was excited, which is quite different from conventional PWAS generated multimodal guided waves containing both S0 and A0 components. Thus, the benefit of using piezoelectric composite plate as both structural and sensing member is that the complexity of sensing signals may be substantially reduced. Effective wave absorption at the ALID boundary can be noticed. Between the actuation and sensing electrodes, electromechanical resonances were observed causing subtle sequential waves. In the two-damage-location case, scattered waves from the damage can be clearly identified. Subtle wave packets were also found due to the multiple reflections within the damage zone. In the active sensing signals, for pristine case, only direct incident wave packet and electrode resonant waves were present in the beginning and silent signal followed. On the other hand, in the two-damage-location case, in addition to the incident wave and electrode resonant waves, two obvious echo wave packets appeared from the reflections at the two damage locations. Signals from other sensing pairs resemble such situation and will not be shown in details in this paper.

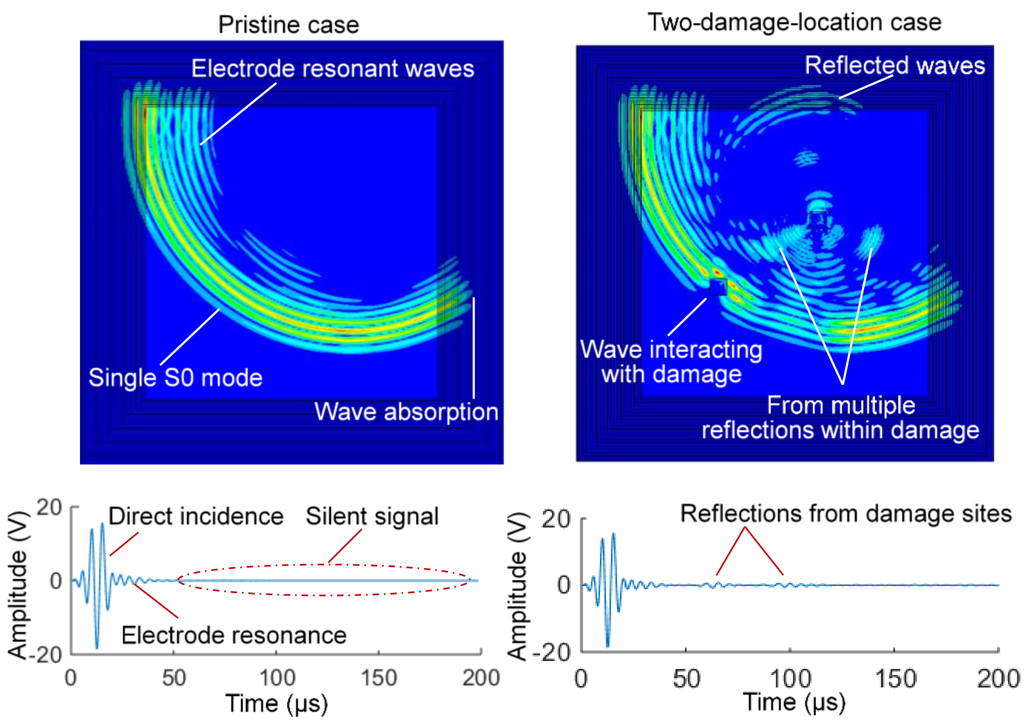

Figure 4: Wave propagation snapshot and sensing pair #3 signal of in the piezoelectric composite plate: pristine case (left); two-damage-location case (right).

TIME REVERSAL METHOD FOR DAMAGE IMAGING

In order to achieve high quality structural sensing, damage localization and imaging techniques were employed, among which time reversal method has been extensively investigated and developing towards its mature stage [9-11]. Thus, the time reversal imaging algorithm was used to construct active sensing images.

The time reversal method virtually back propagate the time reversed wave signal into the medium. Due to the reciprocity of the linear ultrasonic system, guided waves will trace back and focus on the wave sources. Damage, scattering waves, is considered as a secondary wave source. The raw sensing signals were processed with window function to eliminate the influence from the direct incident wave packet. Then, the signals were further enveloped to represent wave packet energy propagation and focusing phenomena. This signal processing procedure is presented in Figure 5.

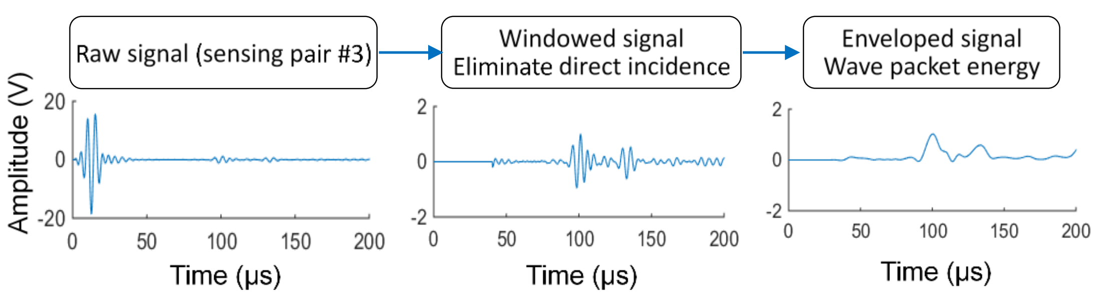

Figure 5: Signal processing using window function and envelop curves.

The “addition” imaging algorithm of time reversal method to compute pixel value $S(i, j)$ at location (i, j) is given by

$$S(i, j) = \sum_{m=1}^{N} A_m V_m (t_{mij}), \quad m = 1, 2, ..., N$$
$$A_m = 10/\max(V_m); \quad t_{mij} = (R_m^a + R_m^s)/c_g \tag{1}$$

where A_m is the unifying weighting function of sensing pair m; $V_m(t_{mij})$ represents the time domain sensing signal after the windowing and enveloping procedure; t_{mij} stand for the time elapse of wave propagation from actuator to pixel location (i, j) and back to the sensor. R_m^a and R_m^s are the distances from the actuator to the pixel location and from the pixel location to the sensor. $c_g = 3439 m/s$ is the group velocity of S0 mode at 200 kHz obtained from the dispersion relations. Similarly, the “multiplication” algorithm can be written as

$$S(i, j) = \prod_{m=1}^{N} A_m V_m (t_{mij}), \quad m = 1, 2, ..., N \tag{2}$$

Figure 6 presents the time reversal imaging results for three situations: pristine case, one-damage-location case, and two-damage-location case. Remarkable accuracy was found for damage localization and imaging.

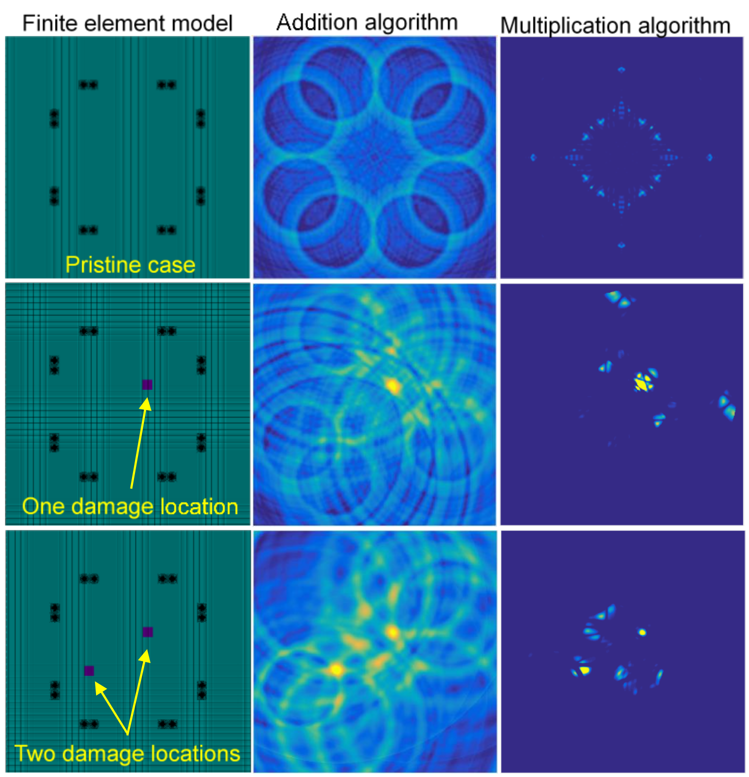

Figure 6: Time reversal results for damage localization and imaging.

CONCLUDING REMARKS

This paper presented a numerical investigation of piezoelectric composites for establishing structural self-sensing capability. A Bloch-Floquet FEM procedure was deployed to obtain the dispersion relations and to demonstrate the influence from piezoelectricity on guided wave propagation. Transient dynamic coupled field finite element modeling was performed to simulate guided wave generation, propagation, interaction with damage, and reception. It was found that signal S0 mode was generated, which may substantially reduce the signal complexity. A time reversal method was utilized to locate the damage. The imaging results showed remarkable agreement with the physical damage locations. This research shows that piezoelectric composite material possesses great potential to establish structural self-awareness.

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