COVER SHEET

Title: Electro-Mechanical Impedance Spectroscopy Leveraging Zero Group Velocity Modes for Structural Sensing

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ABSTRACT

This paper presents an Electro-Mechanical Impedance Spectroscopy (EMIS) leveraging zero group velocity (ZGV) modes for active structural sensing. EMIS employs a piezoelectric wafer active sensor (PWAS) as both the actuator and the receiver to achieve structural damage evaluation via structural resonances. Distinctive from the conventional EMIS methodology, this research exploits the ZGV modes originated from localized resonance in thickness direction. The ZGV modes possess the unique property of an elapsed group velocity with a finite nonzero wavenumber and can confine the wave energy within the vicinity of the excitation source. To develop an insight into the mechanism behind the ZGV modes, semi-analytical finite element (SAFE) method is implemented to extract and identify the ZGV frequencies and wave modes. Parametric case studies are performed to examine the influence of geometric and material properties change. Subsequently, fully discretized finite element (FDFE) model considering the PWAS is established to conduct coupled-filed harmonic analysis. The obtained EMI spectra verify the capability of PWAS for exciting and identifying the ZGV modes. Ultimately, the experimental validations on aluminum plates bonded with PWAS transducers are carried out to demonstrate the practical feasibility to extract the ZGV modes. The ZGV frequencies are mutually verified in comparison with the SAFE and FDFE results and are in consistency with each other. This study excavates the potential of EMIS method exploiting ZGV resonance modes for the damage characterization.

INTRODUCTION

The fascinating non-propagating wave phenomenon, called zero-group velocity (ZGV) mode, has recently triggered tremendous research curiosity. ZGV modes possess the distinctive property of an elapsed group velocity with a finite nonzero wavenumber [1]. Under such a circumstance, stationary modes can be generated from the constructive interference of two modes propagating in opposite directions with equal phase velocity, indicating the wave package spatially propagates under a

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motionless envelop [2, 3]. This stationary mode yields a localized resonance, trapping the wave energy in the vicinity of its source [4, 5]. Considering the peculiar characteristics of ZGV modes, endeavors have been devoted to the understanding and extraction of ZGV modes. The existence of ZGV lamb modes was observed by Tolstoy and Usdin [2] and was associated with a 'sharp continuous wave resonance and ringing effect'. Researchers also found ZGV lamb modes at the minimum frequency of the S_1 mode in plates [6]. The ZGV mode formed by the S_1 'forward propagating mode' and the S_2 'backward propagating' mode was observed, rendering a localized resonance. The aforementioned researches have demonstrated the existence of ZGV lamb modes and the relevant local resonances and they could be measured and evaluated by contact sensors [7], air-coupled transducers [8], laser interferometers [5], and laser doppler vibrometers [9].

The deep insight into the mechanism behind ZGV modes and successful extraction of the mode paved the way for the SHM and NDT applications. The local resonances induced by ZGV modes in the thickness direction correspond to the minimum frequency points of the branches in dispersion curves. These resonance frequencies are determined by the mechanical and geometrical properties of the structure. Therefore, such resonances possess prominent advantages in localized monitoring of the structural damage and material properties change [10]. The thickness and the Poisson's ratio of the aluminum plate were evaluated through ZGV resonant frequencies [11, 12], obtaining a spatial resolution of 0.5 mm [13]. Previous works also demonstrated the potential application of ZGV modes for material properties evaluation such as interfacial stiffness [13] and bulk sound velocity [14]. The application of ZGV could be extended to cylinder shape structures [15], and multi-layered structures, including adhesively bonded plates[16] and carbon fiber reinforced polymers [17].

The aforementioned applications mostly rely on non-contact measurements through complicated and meticulous procedures. This paper presents an Electro-Mechanical Impedance Spectroscopy (EMIS) to extract the ZGV modes of various aluminum plates. EMIS has been investigated as an effective technique for SHM. It employs piezoelectric wafer active sensor (PWAS), coupling the mechanical impedance of host structures with the electrical impedance measured at PWAS terminals, to evaluate the structural resonances [18-20].

The paper starts with the semi-analytical finite element (SAFE), identifying theoretical ZGV modes and frequencies by the dispersion curves. The fully discretized finite element (FDFE) analysis is then conducted to demonstrate the capability of the PWAS for exciting and capturing the ZGV modes. Ultimately, the experimental investigations are implemented to verify the SAFE and FEA results and demonstrate the feasibility of EMIS leveraging the ZGV modes. The paper finishes with concluding remarks and future work.

ZGV IDENTIFICATION AND EXPLORATION UTILIZING SAFE

This section aims at identifying the ZGV modes from the single layer and multi-layer adhesive aluminum plate via the SAFE method. Several single-layer aluminum plates and multi-layer aluminum plates with different bonding layers will be discussed as case studies shown in Figure 1. The separate ZGV modes of the 4 mm/6 mm/10 mm single-layer aluminum plates were identified, laying the foundation for the better recognition of the corresponding ZGV modes in the 10.3 mm Al-Epoxy-Al. The frequency group velocity curves were computed using SAFE to predict the ZGV modes as showcased in Figure 2. The corresponding ZGV frequencies were 707.5 kHz, 471 kHz, and 283 kHz for 4 mm, 6 mm, and 10 mm Aluminum plates. There existed four ZGV points in the Al-Epoxy-Al plate, which were 198.5 kHz, 506.5 kHz, 735.5 kHz, and 786 kHz.

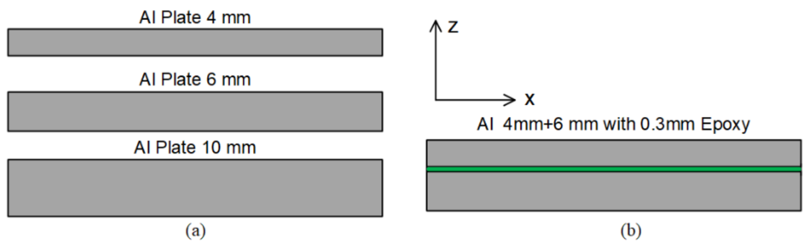

Figure 1: case studies: (a) 4 mm/6 mm/10 mm single-layer Al plates; (b) 4 mm+6 mm multi-layer Al plates with 0.3 mm adhesive layer.

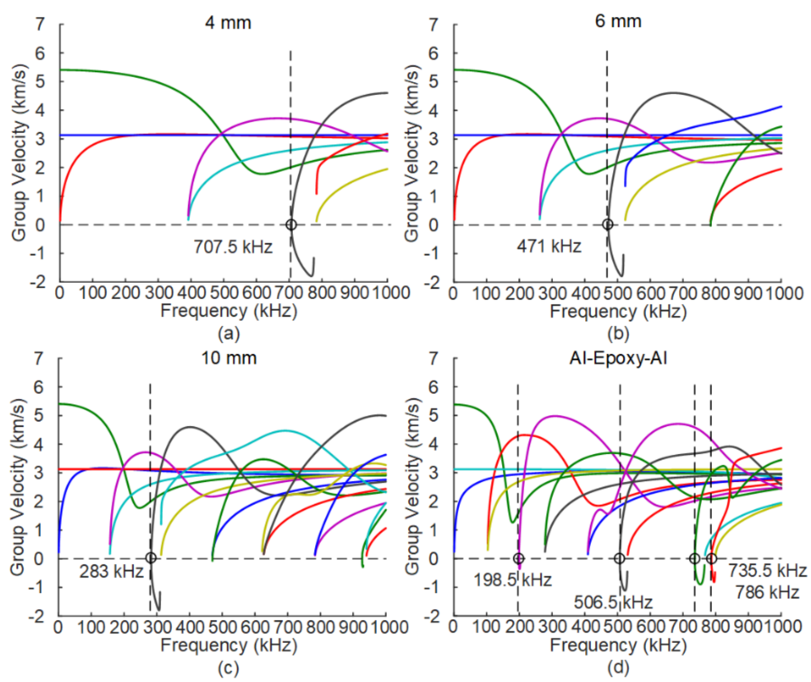

Figure 2: The frequency group velocity curves for the (a) 4 mm (b) 6 mm (c) 10 mm single layer Aluminum plates and (d) 10.3 mm multi-layer Al-Epoxy-Al plate.

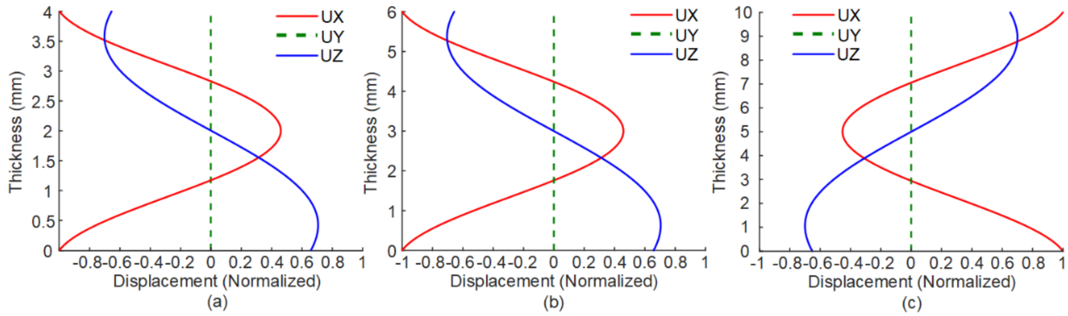

Figure 3: The mode shapes of the single-layer plate: (a) 4 mm case; (b) 6 mm case; 10 mm case.

The corresponding mode shapes along the thickness direction were presented to visualize the ZGV modes as shown in Figure 3 and Figure 4. The extracted ZGV points in the three single-layer plate were basically the extrema of S_1 mode. Regarding the multi-layer plate, the first ZGV mode (198.5 kHz) corresponded to the S_1 mode of the 10 mm plate according to the mode shape in Figure 4(a). Similarly, the second and the third ZGV resonances were relevant to the ZGV modes of 6 mm plate and 4 mm plate respectively. It is worth noting that the generation of the fourth ZGV mode may arise from the adhesive layer. The mode shape of the fourth ZGV resonance revealed that it could be the anti-symmetric mode of the 6 mm plate. Meanwhile, the frequency deviations of the first three ZGV modes from the stand-along plate ZGV modes were also induced by the relatively soft epoxy layer.

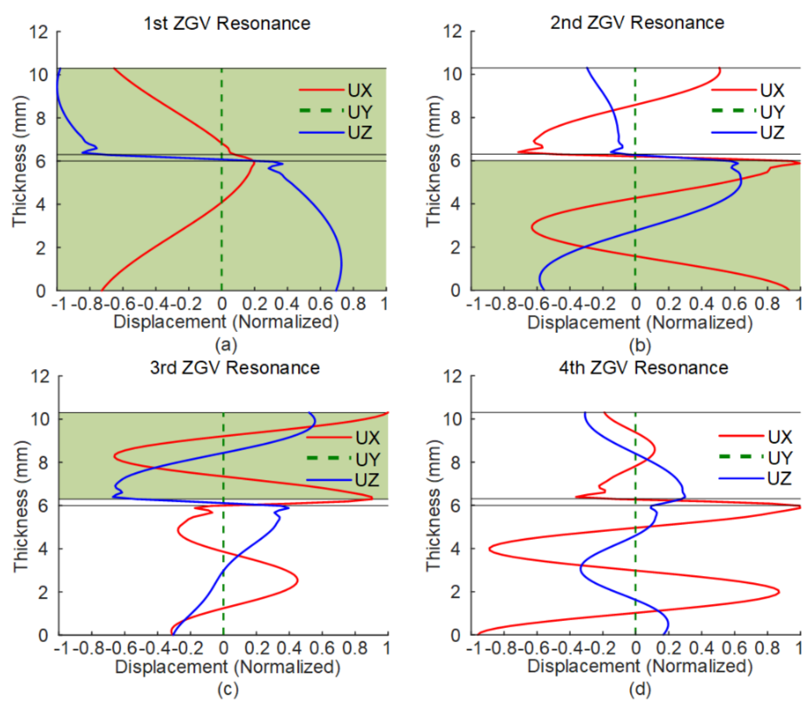

Figure 4: The ZGV mode shapes of the Al-Epoxy-Al plate.

FULLY DISCRETIZED FINITE ELEMENT ANALYSIS

The FDFE analysis was conducted to verify the capability of the PWAS transducers for exciting and capturing the ZGV modes in aluminum plates. A typical multi-layer Al-Epoxy-Al model was illustrated in Figure 5. The quarter model consisted of a 4-mm plate adhesively joint by a 0.3 mm epoxy layer to a 6-mm plate, with a PWAS bonded on the top center of the plate. The harmonic analysis was conducted sweeping from 1 kHz to 1 MHz to obtain the EMI spectra.

The EMI spectra of the single-layer aluminum plate of 4 mm, 6 mm, and 10 mm and the EMI for the Al-Epoxy-Al plate were illustrated in Figure 6. The ZGV frequencies in FDFE results were in good agreement with those from SAFE analyses. It should be noted that the resonance peaks below 100 kHz originated from the structural vibration modes of the plate. The resonance of the ZGV mode can be distinguished by the trembling disturbances following a spectral peak as denoted in Figure 6(a). The four resonance peaks in EMI spectrum of the Al-epoxy-Al multi-layer plate were also in consistency with the SAFE results as signified in Figure 6(b). The new peak located around 700 kHz was generated by the PWAS.

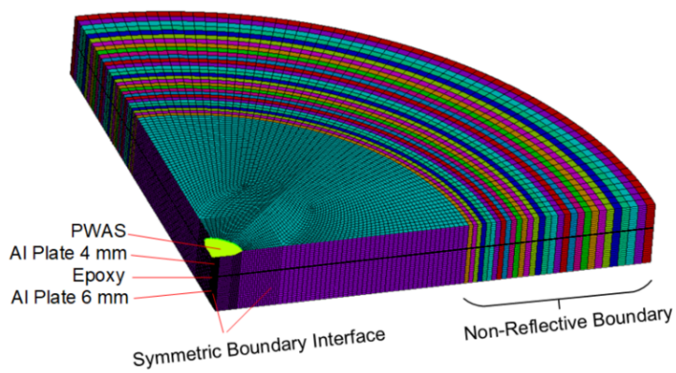

Figure 5: Finite element model for EMIS active sensing of the multi-layer aluminum plate.

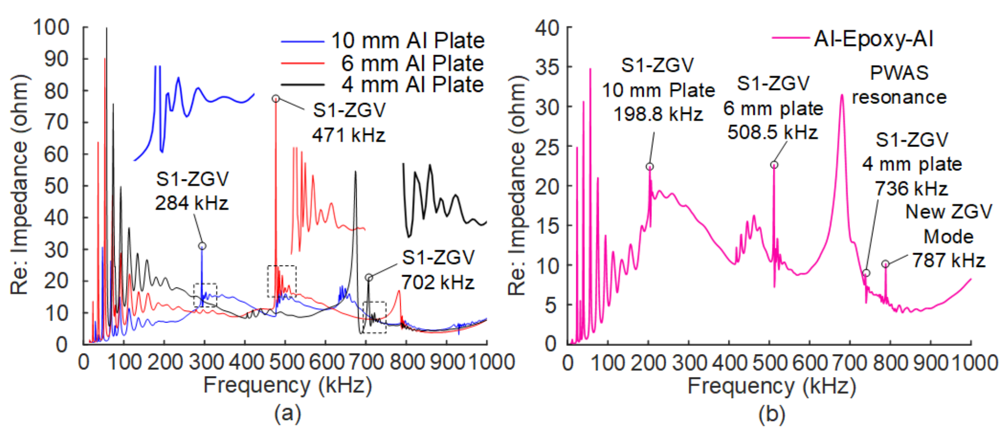

Figure 6: (a) EMI spectra of single-layer Al plates; (b) EMI spectrum of the Al-Epoxy-Al plate

EXPERIMENTAL INVESTIGATION OF ZGV MODES EMIS

The experimental validations of the ZGV modes EMIS were conducted on the corresponding aluminum plates. The overall experimental setting was displayed in Figure 7. A 7 mm*0.2 mm circular PWAS was bonded on the 500 mm*500 mm single-layer and multi-layer plates with the aforementioned thicknesses and adhesive condition. The Omicron BODE 100 impedance analyzer was employed to measure the EMI spectra of the plates.

The EMI spectra for 4 mm, 6 mm, and 10 mm single-layer aluminum plates, and the multi-layer Al-Epoxy-Al plate were obtained to verify the practical capability of EMIS for extracting the ZGV modes and mutually validate the accuracy of SAFE and FDFE results, as displayed in Figure 8. It can be observed that the ZGV modes of 4 mm and 6 mm plates could be observed respectively in the Al-Epoxy-Al plate. The two spectra in Figure 8(b) were measured by two separate PWAS transducers bonded on the 4 mm plate side and 6 mm plate side. However, the ZGV mode for the 10 mm plate was missing, which may result from the bonding quality and damping effect of the adhesive layer. Therefore, only the ZGV modes of the corresponding bonded side of PWAS could be measured. Regarding the accuracy of the ZGV frequency, the experimentally obtained ZGV frequency for 4 mm aluminum plate (707 kHz) was in consistency with SAFE (707.5 kHz) and FDFE (702 kHz) ZGV frequency, with tiny difference resulting from material properties error, and so were the ZGV frequencies for the 6 mm plate and the 10 mm plate. Similar to the EMI spectra in the FEM analysis, the resonance peaks of the ZGV modes were featured by the tremblings accompanying the peaks, which were different from the conventional resonance peaks of the plate vibration modes and the PWAS vibration modes. Such a feature can serve as guideline for identifying the ZGV resonances.

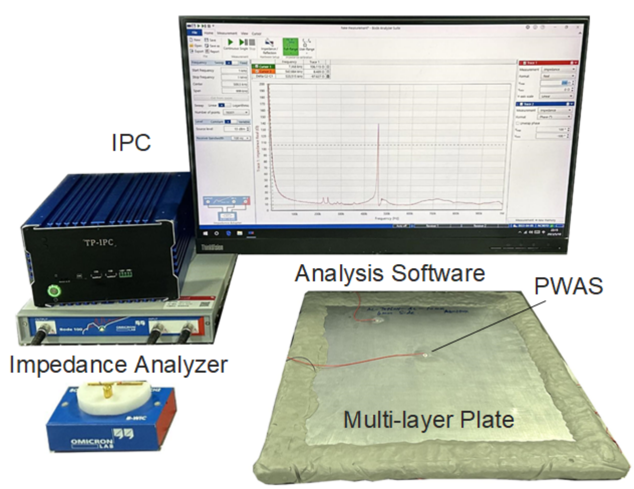

Figure 7: The experimental setting of ZGV mode EMIS.

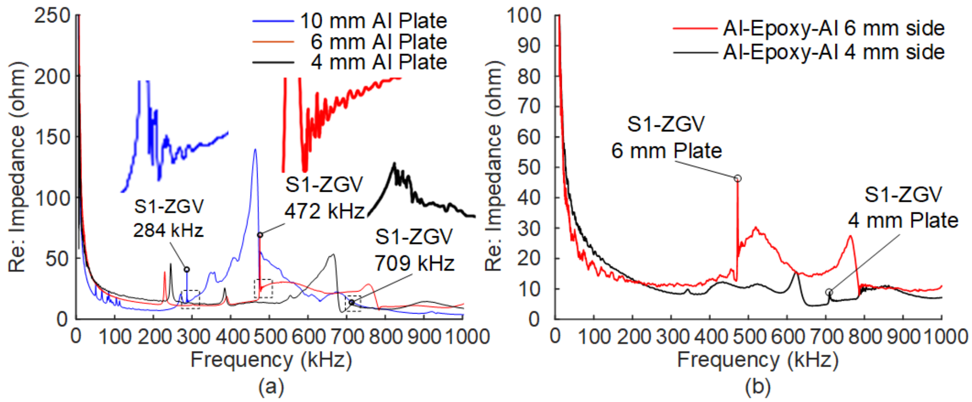

Figure 8: (a) EMI spectra of single-layer Al plates; (b) EMI spectrum of the Al-Epoxy-Al plate.

CONCLUDING REMARKS AND FUTURE WORK

This paper proposed a EMIS methodology leveraging the ZGV modes for active structural sensing. The SAFE analysis laid the theoretical foundation of the ZGV modes, identifying the frequencies and mode shapes. The capability of the PWAS for exciting and capturing the ZGV modes was demonstrated utilizing the coupled-field FDFE analysis and the experimental validations. It was found that the theoretical, numerical, and experimental findings agreed well one another. It was also noticed that the ZGV modes in the EMI spectra could be distinguished from their special trembling signature, showing distinctive difference compared with non-ZGV resonances.

For the future work, the EMIS method leveraging the ZGV modes would be applied on other complicated structures such as carbon fiber composites. The monitoring of damage types like disbond, delamination, voids, etc. should be performed and demonstrated.

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