Advancing Measurement of Zero-Group-Velocity Lamb Waves Using PVDF-TrFE Transducers: First Data and Application to In-Situ Health Monitoring of Multilayer Bonded Structures

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Abstract

Driven by the rapid advancement in manufacturing technologies, engineering structures with complex geometries are increasingly applied in various industries, posing challenges to the applicability and adaptability of existing structural health monitoring methods based on guided ultrasonic waves. To fulfill the characterization of defects in complex structures, a novel approach featuring a conjunction of zero-group-velocity (ZGV) Lamb waves and polarized PVDF-TrFE transducers is proposed. In this approach, the PVDF-TrFE solvent is deposited and in-situ polarized on the structure surface to form thin and flexible coatings, with which the ZGV waves can be excited efficiently and measured reliably. On this basis, the defect can be characterized by investigating the defect-induced alteration in ZGV wave features. In experimental validations, disbond defects in multilayer bonded structures are evaluated using the ZGV waves measured with fabricated PVDF-TrFE transducers. For the first time, the ZGV waves are measured in a contact and in-situ manner. Compared with conventional non-contact measurement of ZGV waves, the proposed approach features a remarkably improved reliability, convenience for narrowband excitation, immunity to measurement uncertainty and capability of in-situ monitoring. The proposed approach can advance the ZGV wave-based methods towards the in-situ health monitoring and enable the defect evaluation in emerging complex structures.

Keywords: zero-group-velocity waves; PVDF-TrFE transducers; in-situ health monitoring; multilayer bonded structure; disbond defects

1. Introduction

Driven by the advancements in the manufacturing technologies typified by the additive manufacturing methods, structures with complex geometries built as a whole are emerging recently. These structures have demonstrated advantages in terms of the cost, maintenance convenience and load bearing capability. Replacing conventional structures featuring assembly of simple components, they are playing increasingly important roles in industries including aerospace, automotive, wind energy, pressure vessel, to name a few. Despite the improved properties, these emerging structures are posing challenges to existing structural health monitoring technologies. Thus, it is imminent to develop methods that are capable of fulfilling the structural health monitoring for these complex structures.

Numerous methods exploiting the guided ultrasonic waves (GUWs) have been developed and applied to detect the defects and assess the health conditions of engineering structures, amongst which methods based on specific wave modes have manifested applicability to structures with complex geometries. For example, methods based on diffused ultrasonic waves [1-6], featured-GUWs [7-9], numerical analysis-driven methods[10-15] have been intensively studied and applied. Although these methods have proved their effectiveness for monitoring structures with irregular sections, it is almost a consensus that the interpretation of interactions of GUWs with defect in these methods is fairly challenging. This limit is further stressed by the multimodal and dispersive properties of GUW, modes overlapping and perplexing boundary reflections. In order to circumvent this deficiency, data-driven methods have attracted numerous research efforts in recent years [16-19]. Despite that these methods have proved their applicability, they highly rely on the data used for the model training.

Nevertheless, the collected data are not adequate in many scenarios, and more importantly, the trained model can only be applied to the structures from which the data are collected. In other words, these methods are rarely transferable.

Zero-group-velocity (ZGV) Lamb waves have exhibited potential for the characterization of defects in complex structures. The ZGV modes are a set of specific GUW modes featuring a zero energy velocity, and the energy of these modes is constrained in a local region in the vicinity of the source [20, 21]. Upon the incidence of guided ultrasonic waves, the modes with a non-zero energy velocity propagate away from the source, while the ZGV modes remain in the local region, causing a local resonance. It is such a feature that makes these modes only sensitive to the local material properties and structural conditions, inherently immune to the perplexing wave behaviors related with complex geometrical features. Leveraging the features of ZGV modes, methods have been developed to enable the assessment of material properties and defect identification in local regions in previously challenging structures [22-26], including fairly thin structures, multilayer structures, anisotropic mediums.

Nevertheless, the implementation of existing ZGV mode-based methods only relies on the noncontact measurement technique[22-25] , particularly the noncontact laser ultrasound technique. This is attributed to the fact that the mass addition and wave leakage caused by conventional bulky transducers coupled to the inspected structure disturb the generation and acquisition of ZGV waves significantly, as evidenced elsewhere[27]. The noncontact laser ultrasound technique has demonstrated its effectiveness in investigation of ZGV waves. However, devices for the laser pulse generation, beam control and sensing unit are bulky and wieldy, rendering them inconvenient for the in-situ measurement. To warrant the accuracy of measurement, finely controlled conditions are required, considering that a number of practical factors can impose salient influence on the signal acquisition, for example the surface roughness, the alignment between the laser beam and surface normal, the ambient conditions, the motion of inspected structure, to name a few. In addition, the probing waves induced by the laser pulses are usually weak due to the thermo-elastic regime requirement. These factors lead to a low signal-to-noise ratio and measurement uncertainty which influences the measurement precision of the ZGV wave signals in practical applications. This alludes to the fact that existing measurement methods for the ZGV waves cannot be applied in an in-situ and online manner.

To tackle this deficiency, the sensors permanently mounted on the structures, which allow the in-situ and online excitation and sensing of ZGV waves, are entailed. In order to accurately measure ZGV waves, following requirements on the actuators/sensors must be satisfied: 1) the actuators/sensors are sufficiently light so that their effects on the wave propagation are negligible; 2) the actuators/sensors are flexible enough to conform with inspected structures; 3) the actuators/sensors are capable of exciting and sensing elastic waves at frequencies of ZGV modes. Recent advancements in the piezoelectric film sensors and coatings based on PVDF-TrFE [28-33], which can accommodate above requirements, have opened a novel avenue for the in-situ measurement of ZGV waves. With specific fabrication and processing technologies, coatings made of PVDF-TrFE polymers can be polarized and demonstrate a piezoelectric effect which enables its service as actuators and sensors. Flexible and light, the polarized PVDF-TrFE transducers can be used to fulfill the incidence and sensing of ultrasonic waves without causing excessive cost of mass addition and disturbance of wave propagation. Compared with the laser pulse-based approach, the polarized PVDF-TrFE transducers demonstrate several remarkable advantages: 1. higher efficiency in excitation of narrowband waves owning to the capability of multiple-cycle excitations; 2 improved sensing robustness endowed by high immunity to environment noise. With the PVDF-TrFE transducers, the damage detection methods base on ZGV waves can be advanced towards the in-situ health monitoring of structures. However, relevant research has not been reported.

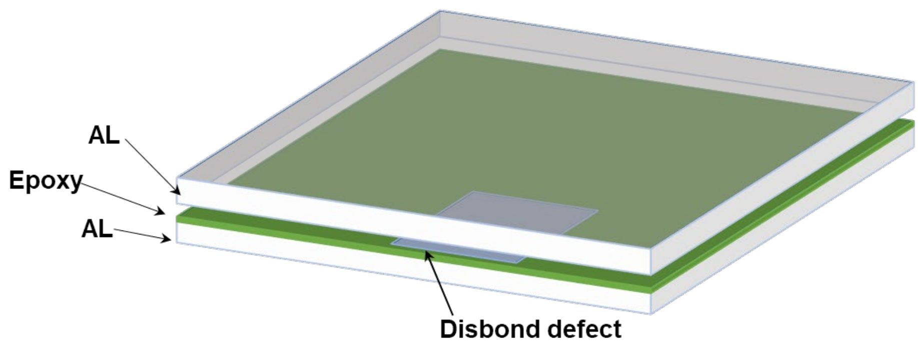
In this investigation, a method based on PVDF-TrFE transducers is proposed to fulfill the in-situ measurement of ZGV waves and health monitoring of complex structures. The piezoelectric PVDF-TrFE coatings are fabricated on the surface of multilayer bonded structure which can act as both actuators and sensors for the ZGV waves. On this basis, the defect can be characterized by analyzing the obtained ZGV waves. The effectiveness of the proposed approach for the defect detection is validated experimentally, in which the ZGV waves in a multilayer structure are obtained and the disbond defects are detected in an in-situ manner.

2. Experimental Set-up

2.1 Representative Sample Preparation

As a representation, an adhesively bonded multilayer structure is investigated in this study to validate the effectiveness of the proposed method. Enabling the construction of stronger and lighter structures, the adhesive bonding is a prevalently applied connection technique for engineering structures in vaiours industries including aerospace, maritime, pressure vessel, etc. Considering that the multilayer bonded structure consists of several layers made of at least two types of materials, the interpretation of wave propagation in the structure is fairly challenging, particularly in the presence of complex structural features, and therefore, it is a typical engineering structure to which the real-world application of conventional GUW-based SHM methods is hindered. During the manufacturing and service of the multilayer bonded structures, bonding degradation and disbond defect can be induced by a variaty of factors, for example inappropriate surface preparation, impact, cyclic loading and thermal fatigue. Thus the health monitoring of multilayer bonded structures is of great importance for warranting the structural integrity.

Without losing generality, a three layer Al-epoxy-Al bonded structure with disbond defects was studied, as illustrated in Figure 1(a). In this three layer bonded waveguide, two 300 mm × 300 mm aluminum plates measuring 1 mm in thickness were bonded using an epoxy film (Hysol PL7000) with a uniform thickness of 0.2 mm. Artificial disbond defects were introduced by placing Teflon inserts between one Al plate and the epoxy sheet adhesive, forming unbonded surfaces. A photograph of the specimen is shown in Figure 1 (b). The size of the defect is 20 mm × 20 mm and 40 mm × 40 mm for the disbond denoted by D2, and D4, respectively. The piezoelectric coatings were fabricated on the surface of the three layer bonded structure using the following method.



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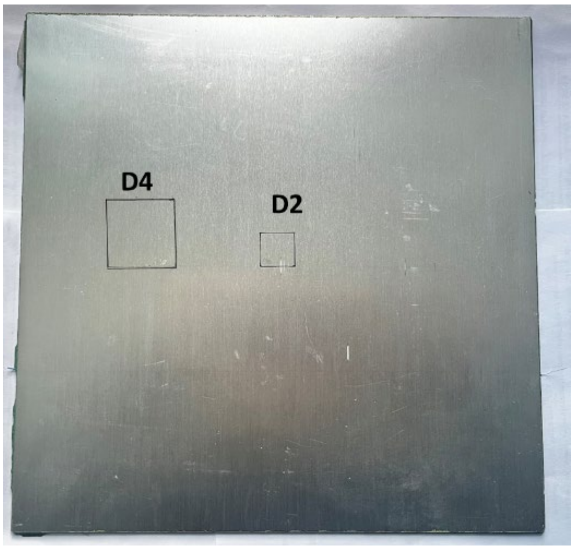

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Figure 1. (a) Schematic illustration of Al-epoxy-Al bonded structure with disbond defects; (b) photograph of the prepared structure with disbonds

2.2 Fabrication of Polarized PVDF-TrFE Coatings

The materials PVDF-TrFE (72/28, Solvay, Belgium), acetone and DMF (N, N-Dimethylformamide) with no further purification were used for the fabrication of piezoelectric coatings on the surface of the multilayer bonded structure.

The fabrication technique for PVDF-TrFE coatings and the effects of various processing parameters on the piezoelectric properties of the film was previously investigated by the authors, as reported in Li *et al*[28], and the optimized processing technique was adopted. The PVDF-TrFE powders were dissolved in a mixed solvent of DMF and acetone at a concentration of 5 wt%, and stirred by a magnetic stirrer for 10 hours. Then, 3 ml of the solution was sprayed on the surface of the structure using an airbrush, after which the structure was placed in a vacuum plate to evaporate the solvent and form the PVDF-TrFE coatings with thickness around 80 μm. These coatings were further annealed at 135 °C for 1 hour to improve the crystallinity. For electrical measurements, the silver paste was brushed on the surface of the PVDF-TrFE coatings with the aid of a shadow mask to fabricate top electrodes, and the structure served as the ground electrode owning to its conductivity. Subsequently, the PVDF-TrFE coatings were in-situ polarized by a corona discharge at 20 kV to enable the piezoelectric property. The preparation process is schematically shown in Figure 2.

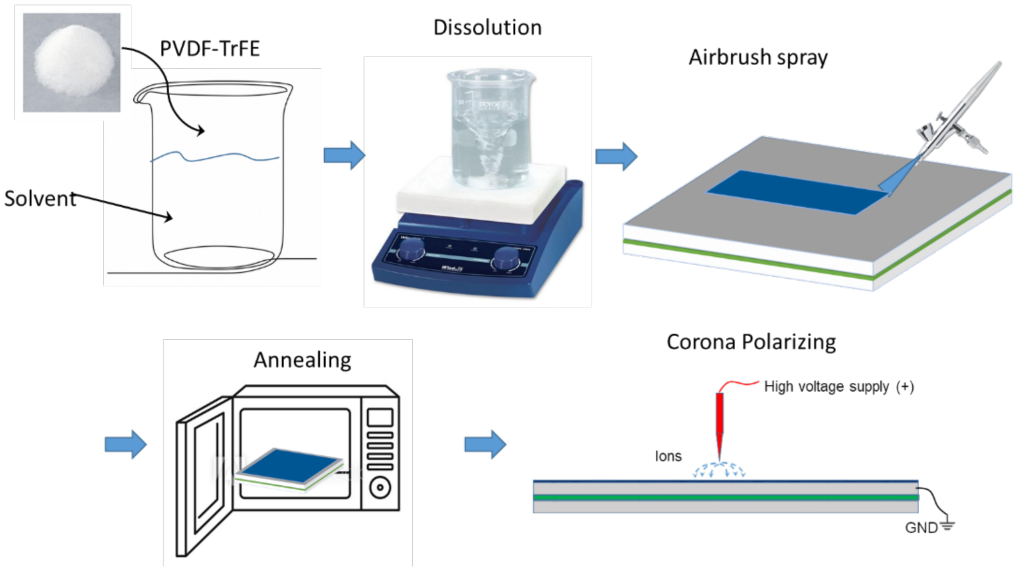


Figure 2. Schematic illustration of the in-situ fabrication of PVDF-TrFE film on the bonded structure

The effective piezoelectric coefficients of the PVDF-TrFE film were measured with a laser scanning vibrometer. A unipolar 1 kHz AC voltage of 20 Vp-p was applied onto the eletrodes and the region with and without electrodes were scanned as shown in Figure 3. It can be observed that the effective piezoelectric coefficient d_{33} value of the fabricated coating is ~18 pm/V.

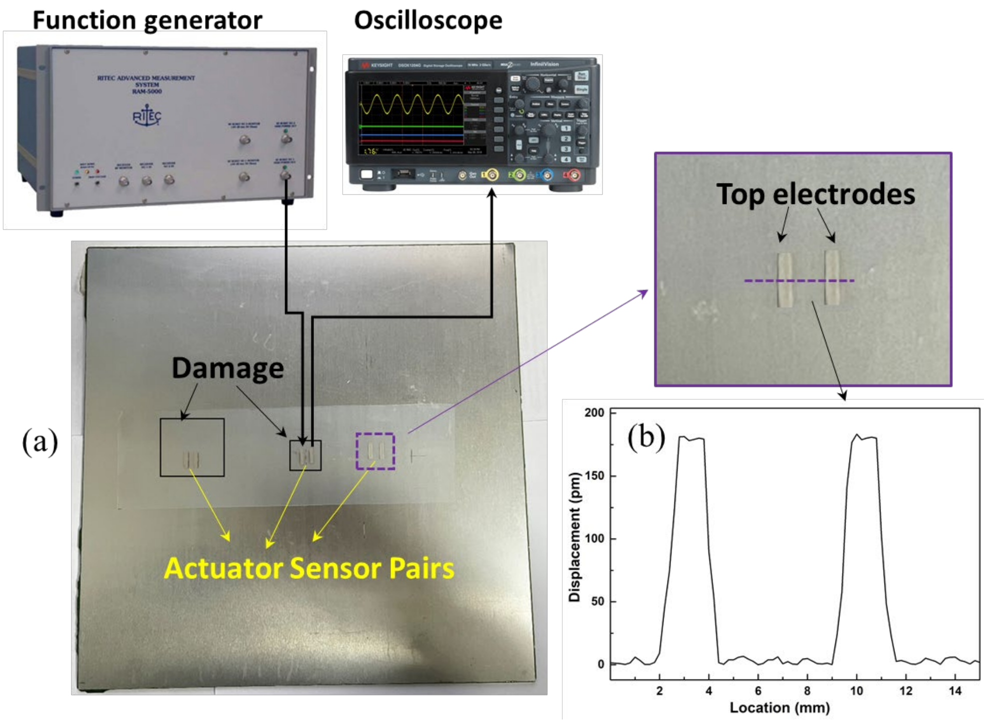


Figure 3. (a) Photograph of the multilayer bonded structure with piezoelectric coating on the surface acting as actuators and sensors; (b) the effective piezoelectric coefficient of piezoelectric coatings measured with laser scanning vibrometer

2.3 ZGV Waves in Adhesively Bonded Multilayer Structure

To calculate the dispersion curves of phase and group velocity of propagating modes in Al-epoxy-Al (see Figure 4), one-dimensional semi-analytical finite element method (SAFE) [16, 34] which is a powerful numerical method to obtain dispersion curves and mode shapes of GUW in cross section of arbitrary shape is adopted. The material parameters are listed in Table 1. In the SAFE method, the wave propagation can be depicted in an analytical form, and the displacement vector is written as

$$u_j\left(x,y,z,t\right)=U_j\left(x,y\right)e^{i\left(kz-\omega t\right)} \tag{1}$$

In which k is the wavenumber, ω is the angular frequency, t is the time variable and the subscript j=1,2,3. The function U_j denotes the mode shape in the cross-section of the waveguide, and it is incorporated in the model by a two-dimensional FE discretization.

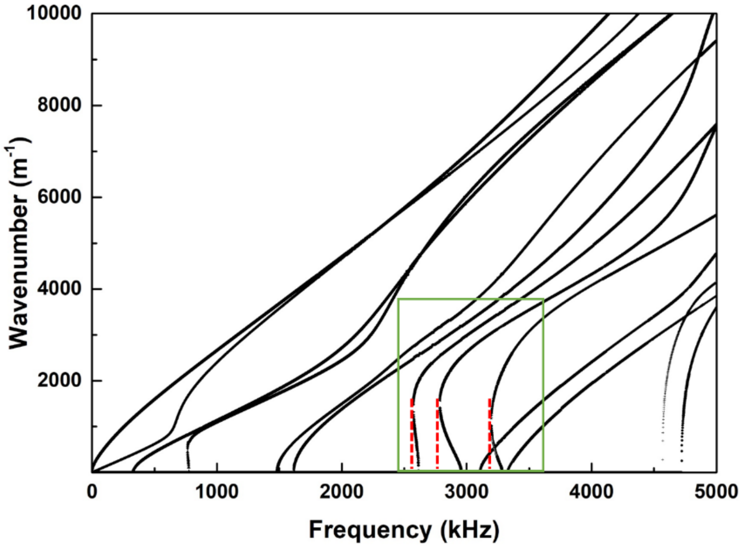
With Eq. (2), the dynamic equilibrium equation of the waveguide for general anisotropic media can be written as

$$C_{ikjl}\frac{\partial U_j}{\partial x_k \partial x_l}+I\left(C_{i3jk}+C_{ikj3}\right)\frac{\partial\left(kU_j\right)}{\partial x_k}-kC_{i3j3}\left(kU_j\right)+\rho\omega^2\delta_{ij}U_j=0 \quad (2)$$

with summation over the indices $j=1,2,3$ and $k,l=1,2$. The coefficients C_{ikjl} denote the stiffness moduli and δ_{ij} is the Kronecker symbol. Equation (2) depicts an eigenvalue problem, and in the commercial FEM code[35], the eigenvalue problems can be generally expressed in the following form

$$\nabla\cdot\left(c\nabla U+\alpha U-\gamma\right)-\beta\nabla U-aU+\lambda d_a U-\lambda^2 e_a U=0. \quad (3)$$

In the above, the expressions for all matrix coefficients can be referred to Predoi et al[16]. By finding the eigenvalues of Eq. (3) for a given angular frequency, all the wave numbers k can be obtained, each of which represents a propagating mode at the given frequency. By finding the eigenvalue solutions over the desired range of frequencies, full dispersion curves can be obtained, as displayed in Figure 4. It is clear that three ZGV modes are present at frequencies of 2.57 MHz, 2.78 MHz and 3.2 MHz, respectively, which can be simultaneously excited by the PVDF-TrFE transducers on the surface of the structure. The corresponding wavelength of the three ZGV modes are 4.4 mm, 4.2 mm, 6.2 mm, respectively.



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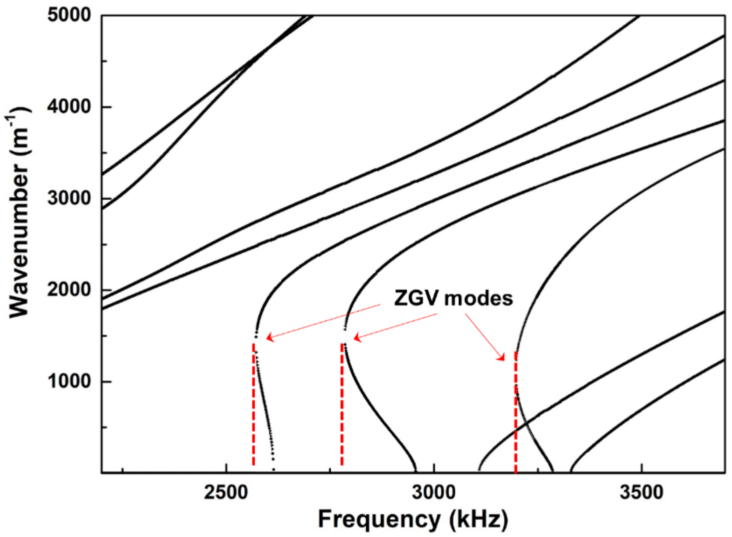


(b)

Figure 4. (a)The dispersion curves of Lamb waves in an intact three layer bonded structure; (b) the zoom-in view of the rectangular part in (a)

Table 1 Property parameters for the Al-Epoxy-Al structure

Part	Elastic modulus (GPa)	Poisson's ratio	Density (kg/m^3)
Aluminum 6061	68.9	0.33	2780
Epoxy	3.8	0.402	1104

The disbond defect can be modeled with unbonded surfaces between the adhesive and the adherend, which transmit no shear stress. In this scenario, the waveguide includes three regions, *i.e.* the intact bonded region denoted R_1 (Al-epoxy-Al), the upper part of disbonded region denoted R_2 (Al), and the lower part of disbonded region denoted R_3 (epoxy-Al), as denoted in Figure 5. In these three regions, guided waves propagate with different characteristics in terms of phase/group velocity dispersion curves and wave structure in the thickness direction.

Applying the same method as described above, the dispersion curves for the region R_2 and R_3 can be obtained (see Figure 6), and it can be observed that the dispersion curves in these two regions remarkably deviate from those in the intact region. Only one ZGV mode is present at the frequency of 2.64MHz for the R_3 region and 2.82MHz for the R_2 region. It can be envisioned that the energy spectrum of the dynamic responses dominated by the ZGV modes vary dramatically between the intact region and the defect region. This serves as the cornerstone for the defect detection in the adhesively bonded multilayer structures.

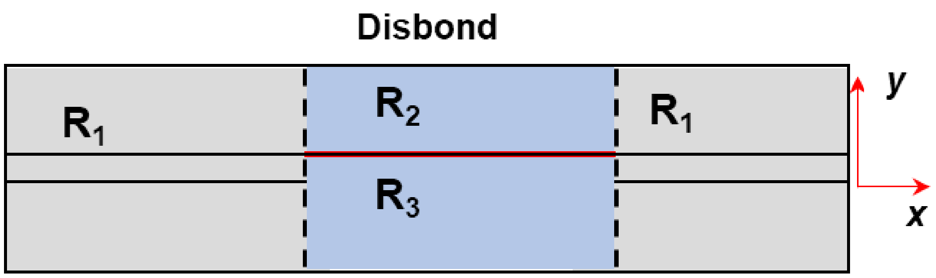
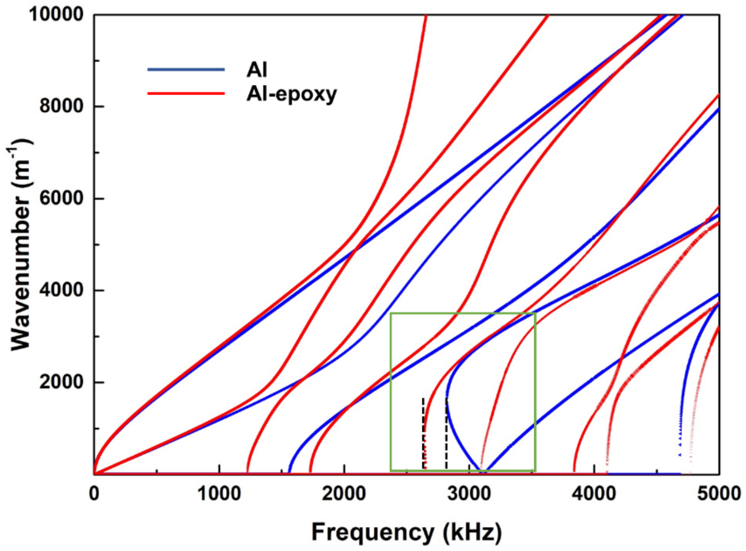


Figure 5. Schematic illustration of the three layer bonded structure bearing a disbond defect



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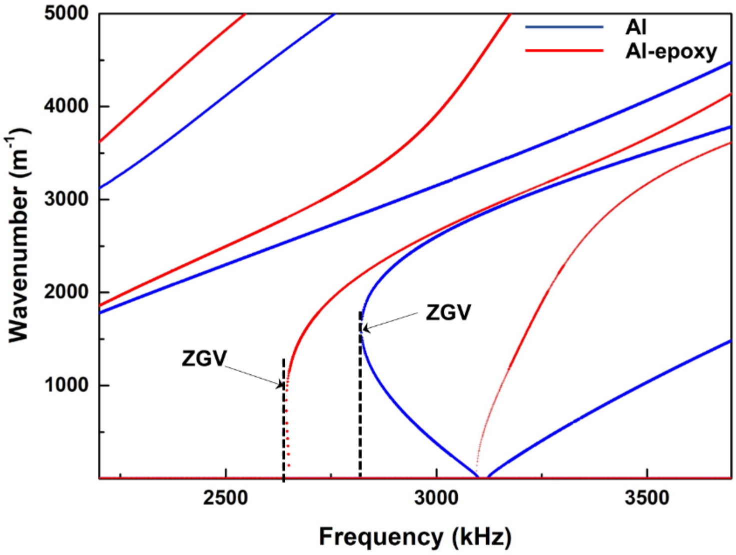


(b)

Figure 6. (a)The dispersion curves of Lamb waves in intact three layer bonded structure; (b) the zoom-in view of the rectangular part in (a)

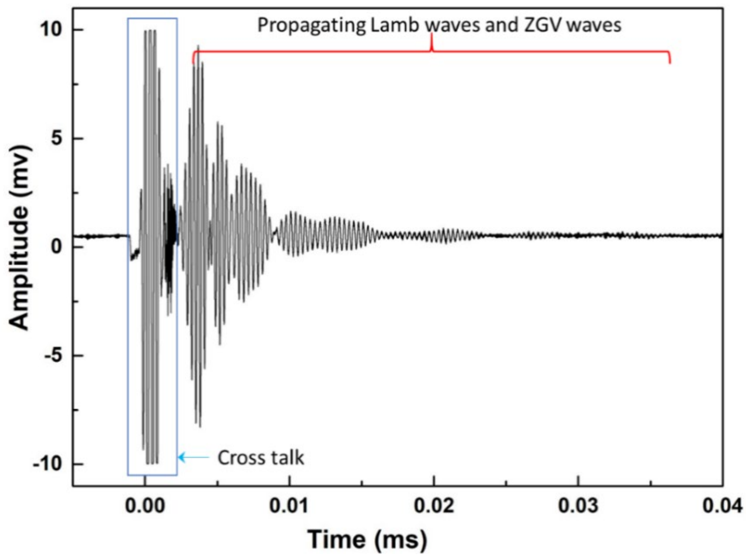
3. Results and Discussions

To excite and capture the ZGV waves, several pairs of electrodes with a size of 2 mm×10 mm were fabricated on the upper surface of PVDF-TrFE coatings in the intact and defect regions. Considering that the amplitudes of incident signals fed into the sensors (~ 300Vpp) for wave excitation exceed the allowable range of the oscilloscope, one of the electrodes in each pair was used for the excitation and the other one for acquisition to guarantee the measurement precision of ZGV waves. The distance between the electrodes was 6 mm, as shown in Figure 3. The sensing pairs are located near the center of each defect, and considering that the wave features remain the same in the defect region, and thus the proposed method is effective even when the sensing pairs are located near the boundaries of defects. A ten-cycle Hanning-window modulated sinusoidal tone burst with a central frequency of 3 MHz was generated using a computer controlled system (Ritec® 5000 SNAP) and fed into the electrodes of the PVDF-TrFE coatings to excite the waves in the structure. The acquired waves signals were recorded via an Oscilloscope. In order to increase the signal-to-noise ratio, the received signals were averaged for 512 times. To obtain the energy spectrum of the captured wave signals, the Short Time Fourier Transform (STFT) was adopted here, which was implemented using a signal processing tool Matlab(R2019b)/stft. To retain sufficient details in both time and frequency domain, a temporal window equivalent of three incident wave periods was selected to intercept acquired signal for FFT.

Figure 7(a) displays the wave signals obtained by the PVDF-TrFE transducers in the intact region, and it can be observed that the dynamic response which lasts for a long period of time before it become too weak to be detected is generated. This indicates the generation of ZGV waves which are constrained in the local region. The ZGV wave signals presented here (Fig. 7a) are the first instance of ZGV wave measurement in a contact and in-situ manner. Considering that multiple-cycle excitations can be applied on the PVDF-TrFE coatings for wave incidence, local resonance of ZGV waves can be generated, and thus the waves induced by the PVDF-

TrFE coatings can be much stronger that those by conventional non-contact methods. This is beneficial for the improvement in the immunity to measurement noises.

The corresponding spectrum obtained via the STFT are shown in Figure 7(b). It is clear that in the intact region, three ZGV waves are synchronously excited around the frequency of 3 MHz. The frequencies of three ZGV modes are 2.87MHz, 3.05MHz and 3.25 MHz, respectively, which are slightly different from the theoretical predictions. This slight difference might be caused by the variation in the properties of adhesive/adherend layer or the bonding strength between the adhesive and adherend layer. The coincidence between the theoretical predications and experimental results indicates the perfect suitability of the PVDF-TrFE coatings for the measurement of the ZGV waves.



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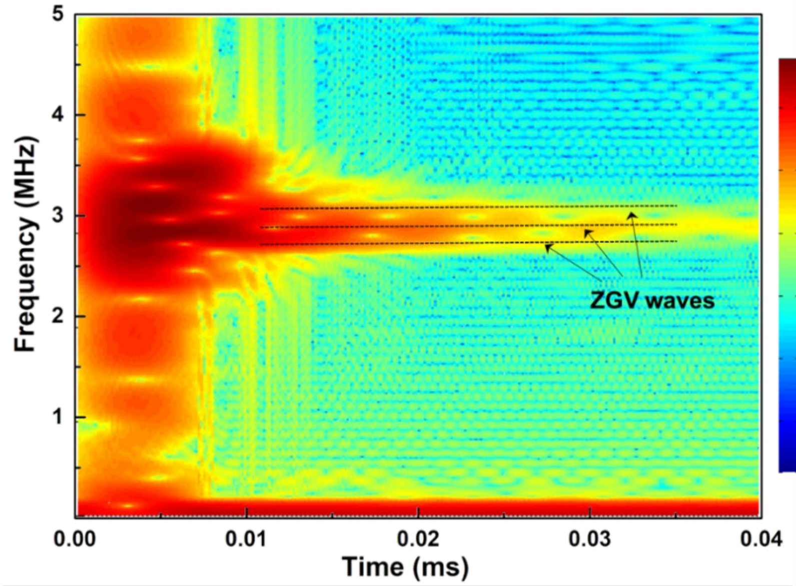
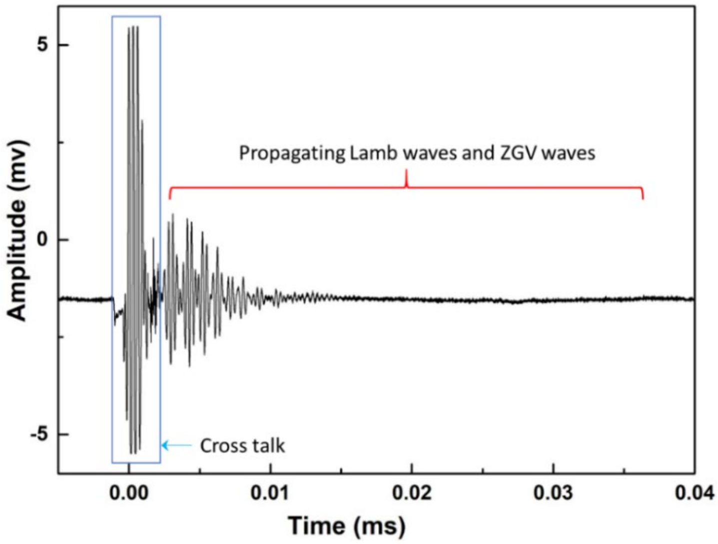


(b)

Figure 7. (a) The signals acquired via the sensor in the intact region; (b) spectrum of the signal in (a) obtained via STFT processing

The spectrum of the waves acquired from D2 defect region is displayed in Figure 7, and the attenuation of the three modes is clearly observed. This is attributed to the fact that the wavelengths of ZGV waves are slightly greater than the defect size and thus the interaction of ZGV waves with the defect causes strong wave reflections and mode conversions. This leads to the remarkable energy transfer from the local resonance to the wave modes which feature a non-zero energy velocity and thus propagate away from the defect region, causing the attenuation of ZGV waves.



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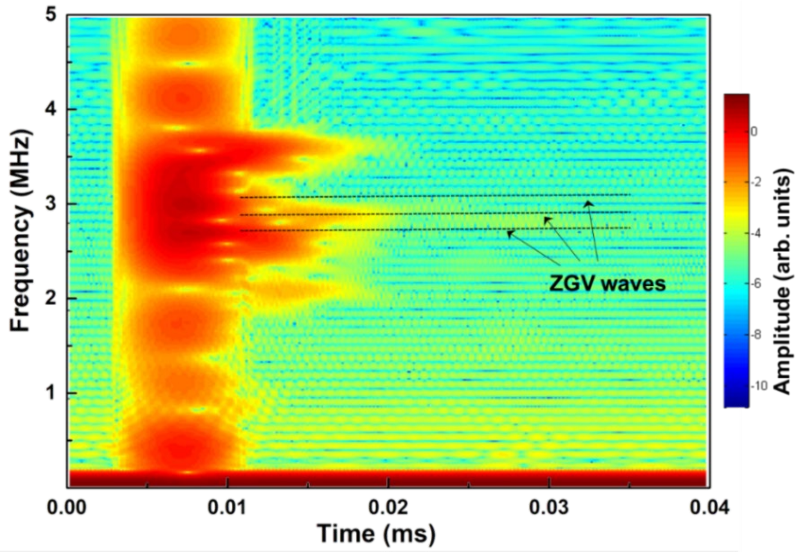


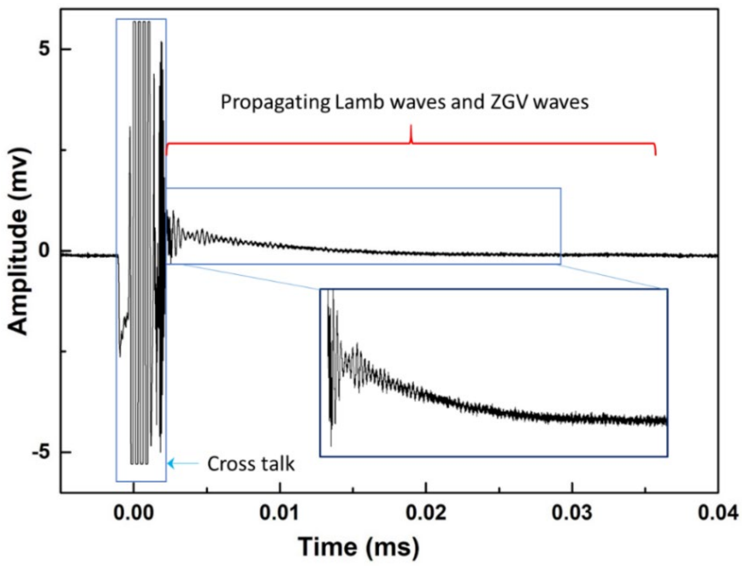
(b)

Figure 7. (a) The signals acquired via the sensor in the D2 region; (b) spectrum of the signal in (a) obtained via STFT processing

Figure 8 shows the spectrum of the waves acquired from D4 defect region, and it can be seen that only one ZGV mode with a frequency of 3 MHz dominates the response in the defect region. This is because the size of the defect is much larger than the wavelength of the ZGV waves, which guarantees the formation of the local resonance in the Al layer.

The above results indicate that the presence of defect leads to remarkable changes in the ZGV wave features. When the defect size is comparable with the ZGV wavelength, significant attenuation is induced by the wave-defect interaction, and when the defect size is larger than the ZGV wavelength, new ZGV modes can be formed within the defect region which is linked with the structural features of the defect region.

It is worth noting that the results from the intact and defect region corroborate perfectly with the theoretical predictions, validating that the lightness and flexibility of the PVDF-TrFE coatings impose negligible influence on the local resonance induced by ZGV waves. This justifies the effectiveness of the PVDF-TrFE transducers for the excitation and sensing of ZGV waves. Therefore, the combination of the PVDF-TrFE transducers and ZGV wave-based method can pave a new way for the health monitoring of the structures, tackling the challenges for the existing method when applied to complex structures.



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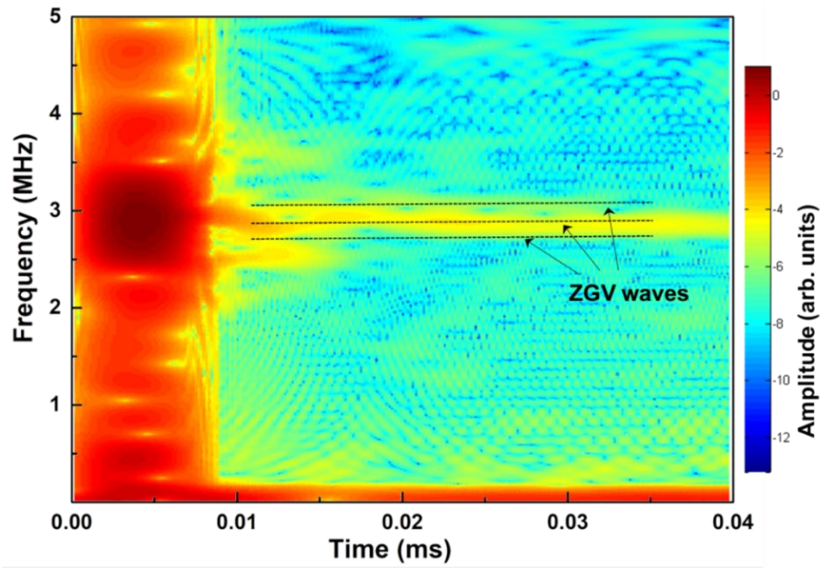

(b)

Figure 8. (a) The signals acquired via the sensor in the D4 region; (b) spectrum of the signal in (a) obtained via STFT processing

It is also noteworthy that the proposed method can enhance the robustness of the health assessment. This is attributed to the fact that the evaluation of the spectrum of ZGV waves does not entail a precise measurement of the absolute amplitude of the waves, which is a pre-requisite for numerous existing methods. As displayed in Figure 9, the amplitude of wave signals obtained from the D4 case is much lower than that in the D2 case, which is caused by the variation in the coupling conditions between the coatings and the host structure, the polarization degree and low uniformity of fabrication. Despite these uncertainties, the spectrum analysis clearly demonstrates a contrast phenomenon, a.k.a., the ZGV waves manifest outstanding dominance in the D4 case while the ZGV waves can barely be distinguished from the noise. This enhancement indicates the immunity of the proposed method to the interference related with the sensor bonding degradation and non-uniformity of fabrication, which are great concerns for conventional methods.

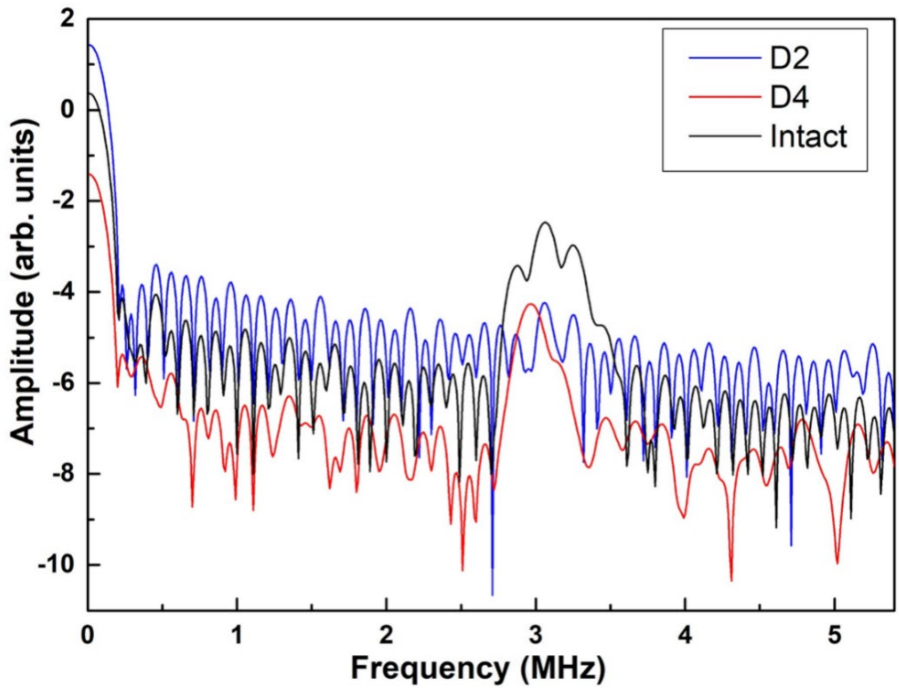

Figure 9. The spectrum at 0.015ms extracted from the STFT result of signals acquired via the sensors in the intact, D2 and D4 regions

The proposed method does not entail a repetitive scrutiny of the propagation of waves when applied to different structures with various geometrical features (*e.g.* rivet holes, stiffeners, thickness variation), which is time-consuming and challenging considering the sheer number of structures. This indicates that the proposed method can be applied in engineering practice with great convenience, featuring a potentially general applicability to the structures from various industries.

The reliability of the proposed method will be further enhanced by improving the performance of sensors used for the wave excitation and receiving, and the sensor embedment in the adhesive layer will be investigated as well in the future work. It is clear that compared with methods based on traditional propagating guided wave modes, the detection distance of the proposed ZGV wave-based method is limited. Therefore, the proposed method is suitable for the monitoring of key sites which feature stress concentration. A number of PVDF-TrFE sensors are required to fulfill the monitoring of a large region.

4. Conclusions

Targeting at the in-situ health monitoring of the emerging complex structures, an approach featuring a conjunction of the ZGV wave-based method and flexible piezoelectric coatings is proposed. In this approach, the in-situ deposited and polarized PVDF-TrFE coatings were fabricated to obtain thin and flexible transducers to act as both actuators and sensors for the generation and sensing of ZGV waves. On this basis, a defect characterization method based on the ZGV waves was established. The experimental examinations validated the efficiency and reliability of the thin and flexible PVDF-TrFE coatings for the generation and sensing of the ZGV waves. With the obtained ZGV waves, the disbond defects in the adhesively bonded multilayer structures were characterized. Using the proposed approach, the ZGV waves are measured in a contact manner for the first time. Compared with conventional non-contact measurement of ZGV waves, the proposed approach features a remarkably improved reliability, convenience for narrowband excitation, immunity to measurement uncertainty and capability of in-situ monitoring. The conjunction of ZGV waves and piezoelectric polymer-driven sensors can advance the ZGV wave-based methods towards the in-situ health monitoring of complex structures which are emerging in diverse industries.

Acknowledgements

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