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Numerical and Experimental Investigation of Focused Ultrasonic Wave Interaction with Out-of-Plane Fiber Waviness in CFRP Laminates

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ABSTRACT: Quantitative characterization of non-uniform out-of-plane fiber waviness in carbon fiber reinforced polymer (CFRP) laminates remains a significant challenge in ultrasonic testing-based nondestructive evaluation (NDE). To elucidate the distinctive interaction mechanisms between a focused normal-incidence ultrasonic wave and embedded wrinkle defects, this study presents a systematic numerical and experimental investigation. Two-dimensional multi-physics finite element models are initially developed to reveal the wave scattering features induced by both convex and concave waviness. The models explicitly account for both the geometric variation of fiber waviness and the accompanying resin-rich and resin-poor zones. In addition, immersion ultrasonic pulse-echo C-scan and pitch-catch A-scan experiments are conducted to validate the numerical predictions. The C-scan approach, employing a focused ultrasonic beam incident on the top surface of the composite plate, enables the successful imaging of spatially varying, successive convex and concave waviness regions. Analysis of the pulse-echo A-scan responses reveals that the temporal signals obtained from convex waviness exhibit greater similarity to those from pristine laminates than those generated by concave waviness. Furthermore, shifts in the resonance frequencies effectively capture local changes in the effective ply thickness caused by waviness-induced geometric variations. The experimentally obtained scattering patterns show remarkable agreement with the simulation results, highlighting the additional lateral scattering phenomena associated with convex waviness. These results demonstrate that the wave scattering features induced by non-uniform out-of-plane fiber waviness can serve as reliable indicators for wrinkle detection. Furthermore, the findings of this work provide valuable insights for the development of more effective ultrasonic inspection strategies for characterizing out-of-plane fiber waviness in CFRP laminates.

KEYWORDS: Ultrasonic testing; fiber waviness; carbon fiber reinforced polymer; wave scattering; nondestructive evaluation; numerical simulation

1 Introduction

Carbon fiber reinforced polymer (CFRP) composites are widely used in mechanical, automotive, aerospace, marine, and civil engineering applications [1]. They offer not only a high strength-to-weight ratio but also exceptional mechanical properties, such as high stiffness and strong corrosion resistance [2]. However, manufacturing imperfections may arise during fabrication [3], among which fiber waviness is one of the most common defects. Fiber waviness can occur due to factors such as fiber misalignment during layup, residual stresses generated during curing, or thermal expansion mismatch between the fiber and matrix constituents [4]. Consequently, these defects can significantly degrade the overall structural properties and performance of CFRP laminates.

Depending on the orientation, fiber waviness can be generally classified as in-plane and out-of-plane [4]. Out-of-plane fiber waviness exhibits wrinkle-like distortions extending through the laminate thickness direction. It is reported that such wrinkles are often prone to form in regions with internal radii, where reduced consolidation pressures may occur due to the bridging of the vacuum bag during the manufacturing process [5]. In contrast, in-plane fiber waviness is characterized by fiber undulations within the laminate plane [6]. Furthermore, based on their geometric configurations, waviness can be categorized as uniform or non-uniform, with the latter often referred to as graded waviness [5]. This study focuses on embedded non-uniform out-of-plane fiber waviness [7], which cannot be directly observed from the external surface and is therefore more challenging to detect compared to surface-visible waviness defects.

A wide range of nondestructive evaluation (NDE) methods have been proposed for the inspection of out-of-plane fiber waviness in CFRP laminates, including micro-CT X-ray imaging [8,9], eddy current testing [10,11], microwave imaging [12], shearography [13], and ultrasonic testing [14–16]. Among these techniques, ultrasonic testing offers several advantages, such as high sensitivity to internal defects, deep penetration capability, and relatively low inspection cost. For example, Chakrapani et al. [17,18] employed ultrasonic Rayleigh waves to quantify out-of-plane marcel defects in thick composites based on variations in time-of-flight measurements. However, their capability to resolve deeply embedded waviness is limited, particularly in thick composite laminates with complex internal architectures. On the other hand, most existing studies have focused on utilizing bulk waves to evaluate wrinkle characteristics across structural cross-sectional slices. Pain and Drinkwater [19] extracted the average scattering matrix associated with fiber waviness using a contact ultrasonic array. Later, Larrañaga-Valsero et al. [20] compared the full matrix capture (FMC)/total focusing method (TFM) approach with phased array and single-element immersion techniques, demonstrating that the FMC/TFM method provides improved diagnostic performance for waviness detection. More recently, further improvements in wrinkle imaging efficiency and noise reduction have been achieved through the gradual phase shift migration algorithm applied to FMC data processing [21].

In addition to experimental investigations, numerical approaches have also been employed to elucidate the mechanisms of interaction between incident ultrasonic waves and out-of-plane fiber waviness. Zhang et al. [22] conducted finite element simulations showing that fiber waviness and thick resin-rich layers can disturb the wave-propagation path and cause wave-vector deviation in interply reflection signals. In addition, Liu et al. [23] numerically discovered that the echo signals from conventional single-sided B-mode scanning gradually attenuate and deviate significantly in the presence of wrinkle defects. To address this challenge, they proposed a double-sided inverse-variance weight-synthetic phase B-mode imaging method for more accurate characterization of wrinkle defects. These numerical modeling approaches provide useful insights into the mechanisms of wave-waviness interaction, which are often difficult to capture through experimental measurements alone.

It should be noted that most existing studies focus on uniform or artificially introduced waviness defects [19,24], which are highly idealized and may not adequately represent the accidental or spatially varying nature of fiber waviness encountered in practical composite structures. Consequently, a knowledge gap still exists regarding the interaction mechanisms between ultrasonic waves and embedded non-uniform out-of-plane fiber waviness. This research investigates the generation, propagation, interaction with both convex and concave waviness, and reception of normal-incidence focused ultrasonic waves, whose effectiveness has been demonstrated in previous studies [20,23]. In particular, the directivity-dependent scattering behavior induced by wrinkle defects is examined through both numerical simulations and experimental measurements. To the best of the authors' knowledge, the scattering characteristics associated with embedded non-uniform out-of-plane fiber waviness under focused ultrasonic inspection have not yet been systematically investigated in existing ultrasonic NDE studies. The findings of this work may

provide valuable insights into designing effective ultrasonic inspection systems for the characterization of out-of-plane fiber waviness in CFRP laminates.

The remainder of this paper is organized as follows: [Section 2](#) introduces the research methods employed in this study, including finite element modeling (FEM) and ultrasonic experiments. [Section 3](#) illustrates the numerical and experimental results regarding waviness-induced pulse-echo responses and scattering behavior. Finally, some conclusions and future work are drawn in [Section 4](#).

2 Methods

2.1 Finite Element Modeling

Finite element simulations are initially carried out using COMSOL Multiphysics to elucidate the generation, propagation, interaction with out-of-plane fiber waviness, and reception of focused ultrasonic longitudinal waves. In this study, both convex and concave waviness profiles are considered, with corresponding numerical models displayed in [Fig. 1a,b](#), respectively. The lower CFRP plate has a thickness of 6.4 mm and consists of 32 plies with a layup sequence of $[\pm 45/90_2/0/90_3/0/90_2/\pm 45/90/\pm 45]_S$. Specifically, the thicknesses of each fiber ply and resin interlayer are 0.18 and 0.02 mm, respectively. The material properties of the 0° ply are adopted from the experimental data reported in Ref. [25], while the material properties of the resin layer are obtained from Ref. [22]. [Table 1](#) summarizes the material properties of the 0° ply, resin layer, backing layer, and matching layer. The focused transducer is modeled using the COMSOL built-in PZT-5H piezoelectric material properties. The water environment between the matching layer and the composite plate is assumed at room temperature, with a sound speed of approximately 1500 m/s.

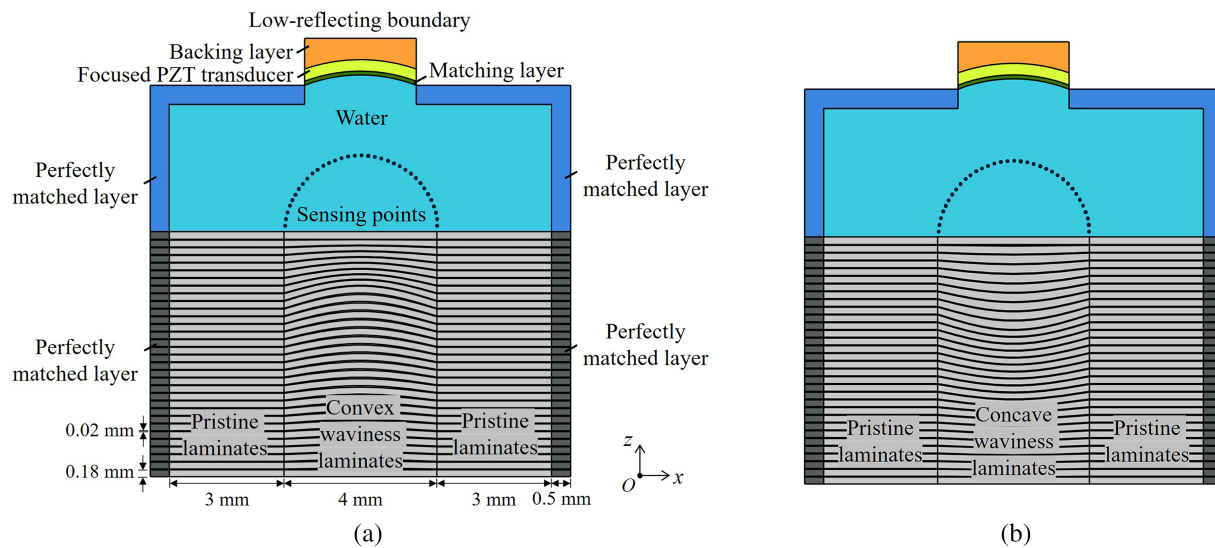


Figure 1: Two-dimensional finite element models of normal-incidence focused ultrasonic wave propagation in a CFRP plate with non-uniform out-of-plane fiber waviness: (a) Convex waviness laminates; (b) Concave waviness laminates.

Table 1: Material properties used in FEM.

Material	E_x (GPa)	E_y (GPa)	E_z (GPa)	G_{xy} (GPa)	G_{xz} (GPa)	G_{yz} (GPa)	ν_{xy}	ν_{xz}	ν_{yz}	ρ (kg/m ³)
CFRP (0° ply)	173.22	13.32	13.32	6.26	6.26	5.01	0.204	0.204	0.329	1640
Resin layer	4.67	4.67	4.67	1.70	1.70	1.70	0.370	0.370	0.370	1301
Backing layer	10.42	10.42	10.42	3.95	3.95	3.95	0.318	0.318	0.318	6580
Matching layer	21.28	21.28	21.28	8.41	8.41	8.41	0.266	0.266	0.266	2280

The non-uniform out-of-plane fiber waviness is introduced within the central region of the CFRP plate, while the two lateral regions are modeled as pristine (wrinkle-free) laminates. Particularly, the plies are locally compressed toward the top surface for convex waviness (Fig. 1a), whereas they are correspondingly stretched for concave waviness (Fig. 1b). Besides, the thickness of each resin interlayer varies with the local fiber curvature, thereby mimicking the resin-rich and resin-poor regions formed around the waviness defect. The focused PZT transducer is modeled by a curved strip to facilitate acoustic focusing at the top surface of the composite plate. A backing layer with a low-reflecting boundary condition [26] is incorporated to absorb backward-propagating wave energy, and a matching layer is deployed to enhance acoustic transmission into the water domain. Consequently, the numerical model accounts for the fully coupled interactions among acoustic, structural, and piezoelectric fields. The outer boundaries of both the water domain and the laminates are constructed as perfectly matched layers (PMLs) to suppress boundary reflections and prevent contamination of the scattered wave field [27]. In addition, a series of sensing points is distributed within the water domain to record the scattered acoustic pressure responses induced by the wrinkle defect.

It should be noted that the finite element models are constructed based on the plane-strain assumption. Such a 2D approximation assumes negligible structural geometric and material variations along the y -direction. Moreover, in practice, a focused beam generated by a finite-aperture transducer exhibits 3D diffraction effects, leading to reduced focal intensity and modified scattering amplitudes compared with an idealized 2D representation. Therefore, the 2D model may overestimate the scattered-wave amplitude near the focal region [28].

The excitation waveform is a Gaussian-modulated sinusoid signal centered at 7.5 MHz. This frequency is tailored based on the ply resonance theory [29]

$$f = \frac{c}{2h} = \frac{2850 \text{ m/s}}{2 \times 0.2 \text{ mm}} = 7.125 \text{ MHz} \quad (1)$$

where c denotes the longitudinal wave velocity in the composite ply and h stands for the ply thickness. Accordingly, the time step is determined to provide twenty sampling points per cycle of the excitation frequency, and the mesh size is set to one-tenth of the acoustic wavelength in water [30]. These parameters are sufficient to ensure the computation accuracy. Furthermore, Eq. (1) implies that the resonance frequency would become higher when it comes to the convex waviness case due to the decreased effective local thickness, whereas it shifts lower for the concave waviness owing to the increased effective local thickness.

In this study, the severity of non-uniform waviness is defined based on the most distorted ply, namely the 11th ply in Fig. 1a and the 10th ply in Fig. 1b. Fig. 2a depicts the corresponding waviness profiles. The waviness is characterized by the following formulation

$$z = \begin{cases} a \cos\left(\frac{\pi x}{l}\right), & \text{Convex waviness} \\ a \left[1 - \cos\left(\frac{\pi x}{l}\right)\right], & \text{Concave waviness} \end{cases} \quad (2)$$

where a stands for the waviness height and l represents the waviness width. In addition, the aspect ratio γ can be defined as [18]

$$\gamma = \frac{l}{a} \quad (3)$$

Accordingly, the aspect ratio considered in the numerical simulations renders 10. It can be noted that the waviness condition becomes more severe as γ decreases. Besides, the waviness angle, which describes the variation of fiber orientation in the xz plane, can be expressed as [23]

$$\theta = \arctan \frac{dz}{dx} = \pm \arctan \left[\frac{\pi a}{l} \sin\left(\frac{\pi x}{l}\right) \right] \quad (4)$$

where -1 corresponds to the convex waviness case, and $+1$ corresponds to the concave waviness case. Fig. 2b illustrates the corresponding angle details. Thus, the maximum waviness angle occurs at the two ends of the waviness region. In numerical models, such variations in ply angle are implemented by introducing a locally rotated coordinate system within the corresponding ply. Therefore, the non-uniform out-of-plane fiber waviness constructed in this research captures not only interply thickness variations but also changes in ply angles and localized resin-layer thickness. In contrast, the ply orientations (i.e., 0° , $\pm 45^\circ$, and 90°) are established with respect to the global coordinate system.

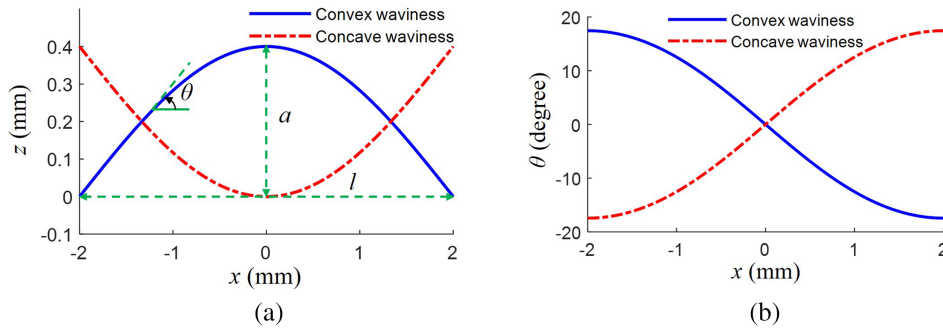


Figure 2: Waviness diagrams: (a) Profile; (b) Angle.

2.2 Experiments

In order to validate the numerical modeling results, immersion ultrasonic experiments were conducted. The wrinkle specimen was provided by the Inspection Development Group of Northrop Grumman. Fig. 3 shows the top (Fig. 3a) and side (Fig. 3b,c) views of the CFRP sample. The specimen is 6 mm thick and has the same layup as the numerical model. A strip of tape was adhered to the top surface to enhance visual contrast with the waviness defect. It also serves as a fiducial marker that allows precise measurement of the distance between the waviness and the tape edge in both the physical sample and the scan images. Two tight-radius corners exist in the xz plane of the sample, extending along the y direction. The wrinkle region is located near one of these corners, and its trajectory is not parallel to the y axis. To be specific, it is closer to the corner on the left side (Fig. 3b) and nearer to the tape boundary on the right side (Fig. 3c). It can be observed that the non-uniform out-of-plane fiber waviness consists of continuous convex and concave patterns. In addition to the wrinkle defect, a 45° ply overlap can be noticed near the top surface, which may have been introduced during the fabrication process.

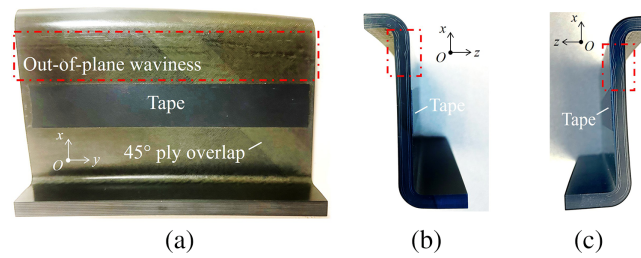


Figure 3: Out-of-plane fiber waviness CFRP sample: (a) Top surface with an adhesive tape; (b) Left view; (c) Right view.

Fig. 4 depicts the microscopic images of the out-of-plane wrinkle defects observed on both sides of the CFRP sample. The images show that the waviness defects are oblique, as the most distorted fibers are not aligned with the z -direction. The aspect ratio γ was characterized to be approximately 11 for the wrinkle defects located in the 0° plies on both sides of the specimen. It should be noted that this experimentally characterized aspect ratio ($\gamma \approx 11$) introduces a slight discrepancy from the aspect ratio adopted in the numerical simulations ($\gamma = 10$). However, selecting $\gamma = 10$ enables more efficient and robust implementation of the non-uniform wrinkle geometry in the numerical model while maintaining close agreement with the experimentally observed defect morphology. In addition, resin-rich layers can also be noticed, predominantly between the $\pm 45^\circ$ plies.

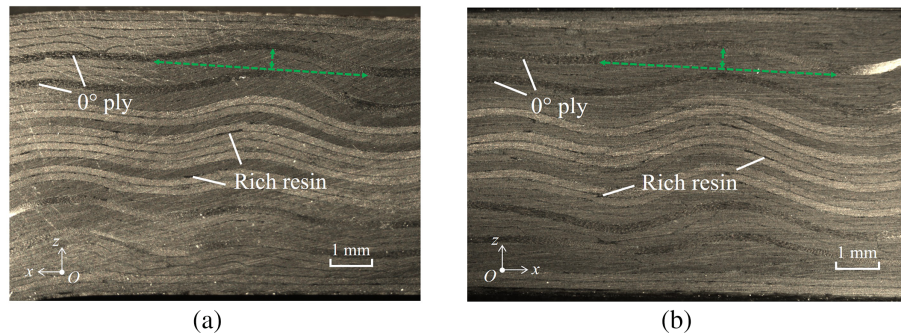


Figure 4: Microscopic images of out-of-plane fiber waviness defects: (a) Left view; (b) Right view.

Two types of immersion ultrasonic experiments were carried out to fully capture the wave scattering characteristics induced by non-uniform out-of-plane fiber waviness. Fig. 5a presents the first C-scan experimental setup, which operates in pulse-echo mode using a single transducer as both transmitter and receiver. The transducer has a center frequency of 10 MHz, a diameter of 0.5 inch, and a focal length of 6 inches. It should be noted that this transducer is also capable of capturing the response of the frequency component illustrated in Eq. (1) owing to its 6 dB frequency bandwidth [21]. The focal point was positioned on the top surface of the CFRP plate. A UT340 pulser/receiver system from UTEX Scientific Instruments Inc. was used for the immersion experiments. The excitation amplitude was set to 100 V, and a 10 dB gain was applied in the receiving mode. A rectangular area of 6 inches $\times$ 3 inches was scanned with a spatial resolution of 0.05 inches in each of the x and y scan directions, and the sampling rate was 125 MHz.

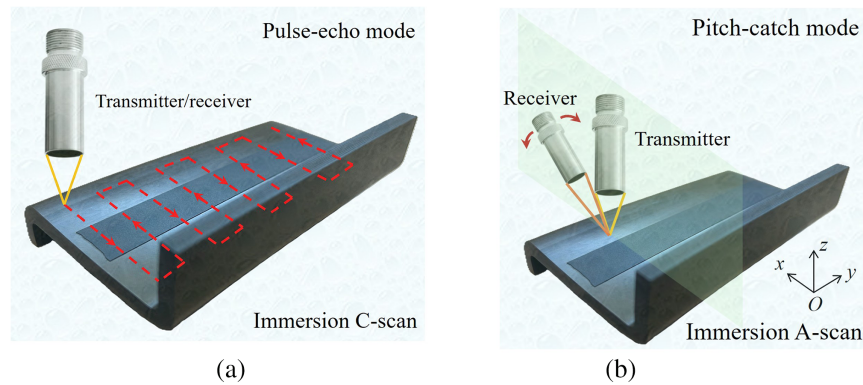


Figure 5: Diagrams of experimental setup: (a) Immersion C-scan for waviness imaging; (b) Immersion A-scan for waviness-induced scattering investigation.

Fig. 5b shows the second immersion A-scan experimental setup, which operates in pitch-catch mode using two transducers. The transducer used in the C-scan experiment served as the receiver, while the transmitter was a 10 MHz probe with a 0.5-inch diameter and an 8-inch focal length. The focal points of both transducers were aligned at the same spot on the top surface. To compensate for the relatively weak scattered signals near the plate, a 50 dB gain was applied in the receiver. The position and angle of the receiver were controlled using a two-dimensional gimbal, enabling measuring scattered waves in the xz plane on both sides of the transmitter. Due to geometric constraints of the setup, scattering angles ranging from 30° to 70° , with an increment of 5° , were achieved on each side of the transmitter. In addition, measurements were performed at two representative locations corresponding to the pristine region and the convex waviness region.

3 Results and Discussions

3.1 Normal-Incidence Pulse-Echo

The piezoelectric transducer generates a normally incident longitudinal wave, which propagates through the water medium and gradually focuses on the top surface of the CFRP plate. Upon entering the plate, partial reflections take place, propagating toward the transducer and producing front-wall echo signals. When the incident wave interacts with the waviness defect, more complex wave phenomena arise, including transmission, reflection, refraction, scattering, and mode conversion [22]. Fig. 6 displays the reflected and scattered wave components in the water domain. Front-wall echo patterns can be noticed in both the convex and concave waviness cases. For the convex waviness case (Fig. 6a), additional backscattered wave patterns are evident on both lateral sides of the front-wall echo. In comparison, no obvious lateral backscattering is found in the concave waviness case (Fig. 6b). Instead, the dominant scattered components are concentrated near the normal-incidence direction and follow the front-wall echo. It can be inferred that these scattered wave components originate from the interaction between the incident wave and the curved waviness interfaces. Physically, the convex curvature tends to defocus the backscattered waves, resulting in a broader angular distribution, while the concave curvature focuses the backscattered waves toward the transducer, leading to energy concentration near the normal-incidence direction. Subsequently, the front-wall echo, together with the scattered waves, is received by the transducer, forming the pulse-echo signal. From the snapshots, it can be seen that the PMLs perform effectively, as no apparent wave reflections from the water boundaries are observed.

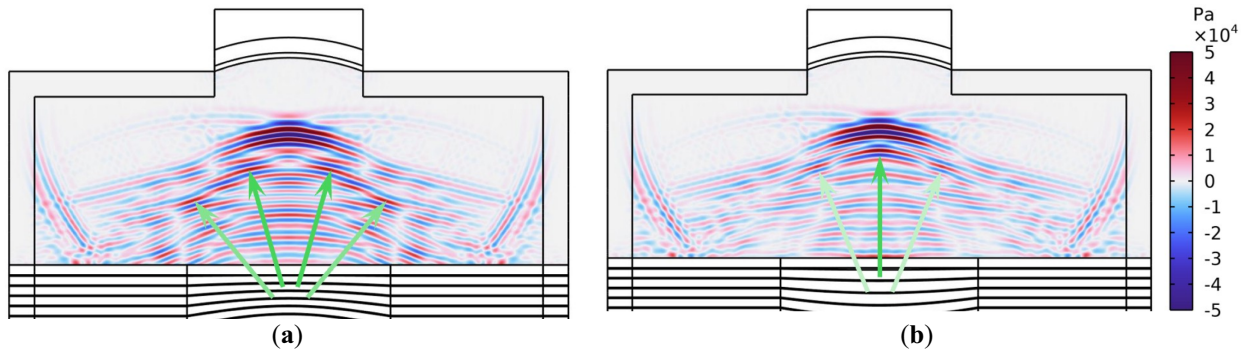


Figure 6: Simulated acoustic pressure snapshots captured at 5 μ s: (a) Convex waviness case; (b) Concave waviness case.

Fig. 7 presents the simulated pulse-echo signals. The initial response belongs to the excitation pulse, followed by transducer ringing. Then, the transducer picks up the front-wall echo. For the pristine case, the convex waviness case, and the concave waviness case, the first three main crests exhibit consistent phase behavior. However, beyond this region, the backscattered wave components lead to a noticeable phase shift in the time-trace signals (see the zoomed-in view). Specifically, the subsequent wave crest in the convex waviness case (i.e., at approximately 6.4 μ s) occurs slightly earlier than that of the pristine case, whereas the corresponding crest in the concave waviness case is slightly delayed relative to the pristine response. Such time-of-flight (ToF) features between successive voltage peaks can be extracted to reconstruct the laminate interfaces [16]. Moreover, the phase information of the signal may also be utilized to quantitatively characterize the waviness profile [23]. Overall, the waveform of the convex waviness case remains more consistent with that of the pristine case compared to the concave waviness case, as evidenced by the Pearson correlation coefficients (0.94 vs. 0.84). In addition, an interesting observation is that more pronounced interlaminar reflections and scattering signals between the front-wall and back-wall echoes are detected in the concave waviness case, especially at 8 μ s.

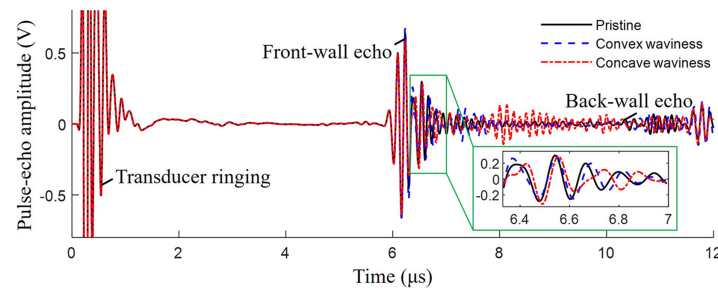


Figure 7: Simulated pulse-echo signals.

Fig. 8 presents the experimental C-scan results. The scanned plate boundaries are clearly delineated and correspond well with the specimen displayed in Fig. 3a. In addition, the rectangular tape region and the 45° ply overlap are distinctly identified. The convex waviness is represented by red regions (high amplitude), whereas the concave waviness appears in yellow. Notably, the trajectory of the concave waviness agrees well with that shown in Fig. 3a, i.e., exhibiting distortion as it crosses the 45° ply overlap. It should also be noted that another concave waviness feature near the left boundary ($x = 6$ mm) is seemingly detected. However, it is partially merged with the plate boundary in the vicinity of the tight-radius corner. The two points #S1 and #S2 are selected for the experimental scattering investigation discussed in Section 3.2.

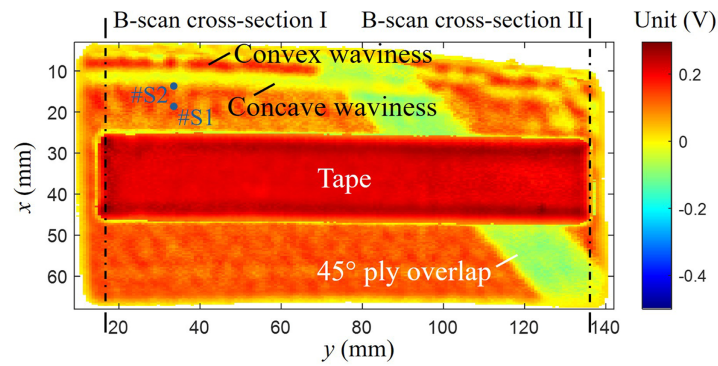


Figure 8: Experimental C-scan image.

Two representative B-scan cross-sectional images are presented in Fig. 9, with their locations indicated in Fig. 8, i.e., cross-section I is positioned near the left boundary, whereas cross-section II is located near the right boundary. The tape region in B-scan images appears as a step lower than the surrounding areas, which results from the implementation of a follower gate on the main wave package [31]. As shown in Fig. 9a, the continuous convex and concave waviness profiles are clearly visible in a region far from the left boundary of the adhesive tape. In contrast, for cross-section II in Fig. 9b, the waviness pattern progressively extends to the tape region, highlighting the spatial variation of cross-sectional waviness along the y direction. Furthermore, the bottom surface of the CFRP plate seems slightly curved, as inferred from the ToF of the back-wall echo.

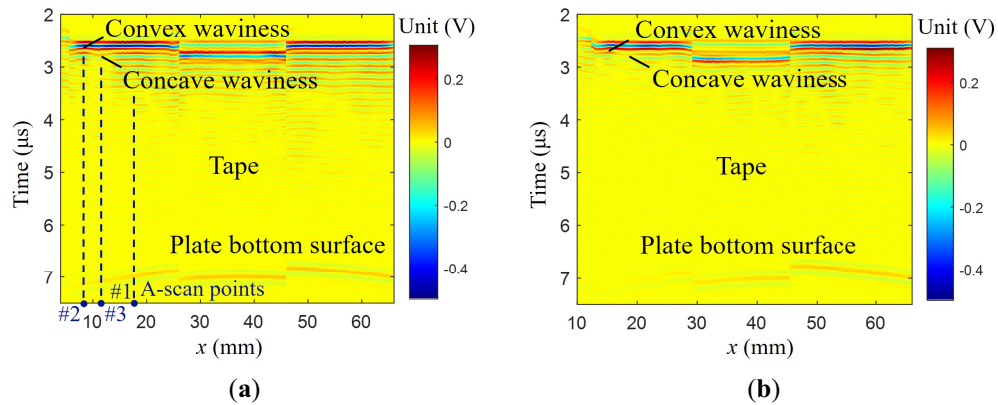


Figure 9: Experimental B-scan images: (a) Cross-section I; (b) Cross-section II.

Three representative points are selected from Fig. 9a. To be specific, point #1 corresponds to the pristine region, point #2 to the convex waviness, and point #3 to the concave waviness. Fig. 10 presents the associated A-scan time-domain signals, where the initial excitation responses have been excluded for clarity. The front-wall echo appears at approximately $2.5 \mu\text{s}$. For the pristine case, the subsequent echoes behind the front-wall echo exhibit a distinctive resonant behavior, reflecting nearly uniform wave interaction between the plies across the thickness direction. The immersion C-scan experiment was conducted twice under identical conditions to reduce the influence of measurement randomness. The root-mean-square deviation (RMSD) of the two A-scan signals at point #1 renders 0.0096, demonstrating reasonable repeatability of the experimental measurements.

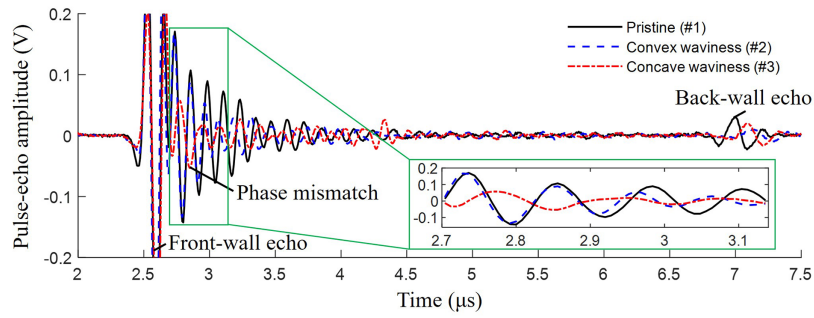


Figure 10: Experimental A-scan time-trace signals.

A closer inspection of the zoomed-in signals reveals that the convex waviness case shares similar amplitude and phase characteristics as those of the pristine region, with a Pearson correlation coefficient of 0.88. In contrast, the concave waviness case shows a remarkable deviation from the pristine response, with a corresponding Pearson correlation coefficient of 0.78. This trend is consistent with the simulation results. For the specimen considered here, the normal-incidence pulse-echo configuration demonstrates higher sensitivity to concave waviness, which explains the distinct color mapping assigned to this region in Fig. 8. In particular, an obvious wave crest can be noticed in the pulse-echo signal of the concave waviness case at approximately 4.3 μs , indicating the enhanced localized interlaminar reflections and scattering. This observation coincides with the numerical findings presented in Fig. 7. Furthermore, the back-wall echo remains clearly detectable in all cases. However, these three signals exhibit different ToF values, reflecting slightly variations in the local thickness of the specimen.

Fig. 11 shows the corresponding frequency spectra of the three experimental A-scan signals. It can be clearly noticed that the resonance frequency for the convex waviness case is higher than that of the pristine case, whereas the concave waviness exhibits a lower resonance frequency. This trend complies with the ply resonance theory illustrated in Eq. (1), which relates the resonance frequency to the effective local thickness variation induced by waviness. It can be noticed that the resonance frequency of the concave waviness case, i.e., approximately 7.14 MHz as shown in Fig. 11c, was successfully captured by the 10 MHz focused probe. This observation confirms that the 7.5 MHz frequency adopted in numerical simulations lies within the effective operating bandwidth of the experimental transducer and is therefore physically reasonable for comparison. These results further demonstrate that the use of a comparatively broadband transducer enables capturing the frequency shifts associated with various waviness-induced local geometrical variations, thereby allowing the identification of waviness-dependent resonance features.

3.2 Waviness-Induced Scattering

Fig. 6a has illustrated the simulated wave scattering behavior in the water domain. A more conventional approach to characterizing such scattering features is through the use of a directivity-dependent diagram [32], which presents the angular distribution of wave propagation in a manner analogous to describing directional characteristics in anisotropic media [33]. In this study, the directivity plot captures the maximal amplitude of the scattering wave as a function of angle. In the immersion A-scan experiments, two representative points, i.e., #S1 and #S2 indicated in Fig. 8, are chosen to represent the pristine and convex waviness cases, respectively. It should be noted that point #S2 is located near the end of the concave waviness. Thus, it can reasonably be considered to lie within the convex waviness region. The center of the convex waviness region was not selected for capturing the wave scattering features because it is located adjacent to

the front tight-radius corner of the specimen. Unavoidable boundary reflections in this region may interfere with the scattered wavefield and affect the accurate characterization of the wave scattering behavior.

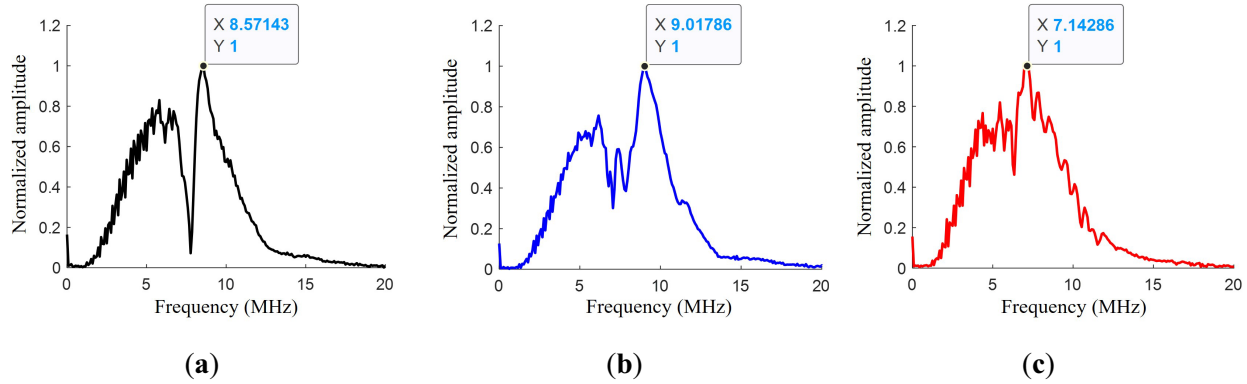


Figure 11: Frequency spectra of the experimental A-scan signals: (a) Pristine (#1); (b) Convex waviness (#2); (c) Concave waviness (#3).

Fig. 12 shows a comparison between the numerical and experimental scattering directivity patterns. The horizontal line means the top surface of the CFRP plate, and the focused normal-incidence ultrasonic wave comes from the 90° direction. To highlight the primary scattering features, the amplitude data in the angular range of 70° – 110° are excluded from the directivity plots due to saturation in this region. It is observed that even in the pristine case, the scattered amplitude does not monotonically decrease from 90° toward 0° or 180° . Notably, side lobes can be found in the angular ranges of 30° – 0° and 150° – 180° , which are likely attributable to multiple scattering and mode conversion effects approaching the near-horizontal directions. The experimental results, as shown in Fig. 12c, exhibit similar side-lobe features, confirming the validity of the numerical predictions. A noticeable difference between the numerical and experimental results is observed in the angular locations of the maximum scattering amplitudes. In detail, the numerical simulations predict the strongest scattering around 15° and 165° , whilst the experimental measurements indicate peak scattering at approximately 40° and 155° .

For the convex waviness case, additional scattering features are identified in both the numerical and experimental results, as illustrated in Fig. 12b,d, respectively. Specifically, the numerical results reveal enhanced scattering amplitudes along the 30° , 50° , 130° , and 150° directions, which align with the snapshot displayed in Fig. 6a. The experimental measurements confirm the presence of additional scattering components along 45° and 135° . It should be noted that such discrepancies in scattering directivity between the numerical and experimental results may stem from the differences between the idealized finite element model and the actual waviness morphology. Although the established numerical models adopted a similar aspect-ratio to that of the CFRP sample, accurately reproducing the complex practical waviness geometry, including local irregularities and twisted fiber orientations (see Fig. 4), remains challenging. These findings suggest that the scattering features induced by the non-uniform out-of-plane fiber waviness can serve as reliable indicators for detecting the existence of a waviness defect.

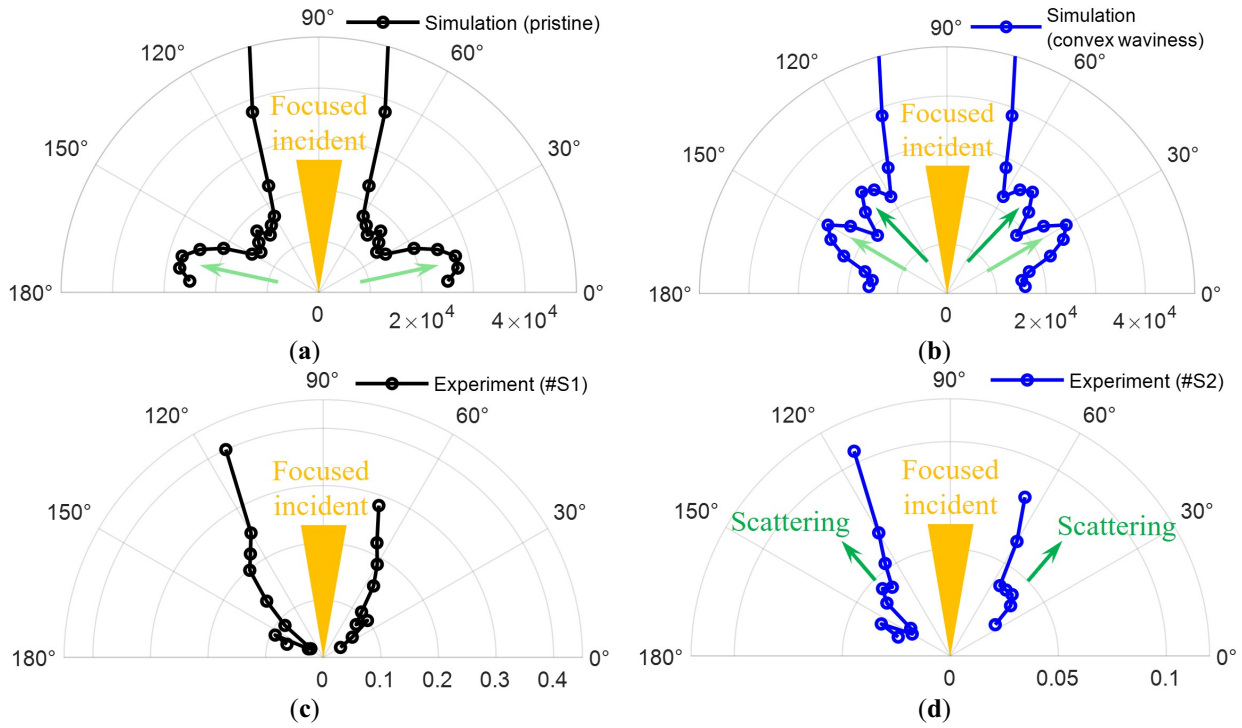


Figure 12: Scattering directivity patterns: (a) Simulation result of the pristine case; (b) Simulation result of the convex waviness case; (c) Experimental result of point #S1; (d) Experimental result of point #S2.

4 Concluding Remarks and Future Work

This paper presented a systematic numerical and experimental investigation of the interaction mechanisms between a focused normal-incidence ultrasonic longitudinal wave and embedded non-uniform out-of-plane fiber waviness in CFRP laminates. The wave scattering characteristics induced by both convex and concave waviness defects were disclosed, and remarkable agreement between the numerical simulations and experimental measurements was achieved.

The tailored two-dimensional finite element models revealed additional lateral wave backscattering features during the interaction between the focused wave and convex waviness. These additional scattering features can be effectively exploited for waviness detection. In contrast, the scattered wave components induced by the concave waviness mainly concentrate near the normal-incidence direction and behind the front-wall echo. Variations in amplitude and phase observed in the time-domain pulse-echo signals between the pristine and waviness cases provide useful indicators for characterizing the waviness profile. The immersion C-scan experiments successfully visualized the spatially varying and continuous convex and concave waviness defects. In addition, the detected resonance frequency shifts effectively captured the localized variations in effective ply thickness induced by the waviness geometry. These findings provide invaluable insights into the development of effective ultrasonic inspection systems for detecting wrinkle defects in CFRP laminates.

Future work will include comprehensive parametric studies considering different waviness geometries, aspect ratios, and three-dimensional morphological variations to further evaluate their influence on ultrasonic wave scattering behavior. It should also be noted that the present study focuses on imaging the non-uniform out-of-plane fiber waviness located near the top surface. Thus, future work will aim to develop

advanced ultrasonic techniques capable of characterizing waviness throughout the full thickness of the composite plate.

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