Ultrasonic Defect Inspection and Characterization for Wavy Composites

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Abstract

Multiple types of defects, including delamination, waviness and resin rich layers may be produced during the composite manufacturing process and service life, which will increase the risk of structural failure and introduce the challenge for defect detection and characterisation. In this study, delamination within wavy composites was inspected with improved signal-to-noise ratio (SNR) by using the optimised wave frequency from simulation results. Dependence of defect (i.e., waviness, resin rich layer and delamination) indication in the B-scan on the inspection frequency was simulated from CIVA® software. Results from both simulation and experiment demonstrated that B-scan images obtained from longitudinal waves at different frequencies can characterise delamination from waviness and resin-rich layers. Through both numerical simulation and experimental investigation, proper guidance for ultrasonic inspection of aerospace composite structures with complex geometry and layout is proposed in this study.

Keywords: Composite, Delamination, Waviness, Ultrasound Testing, Defect Characterisation

1 Introduction

Carbon fibre reinforced polymer (CFRP) composites are increasingly utilised in high-performance structural applications [1-2]. Fibre wrinkling and waviness, porosity and ply misalignment can progress during the fabrication process of CFRP composites and have the potential to form delamination, debond, and crack defects [3].

For aerospace composite structures with complex shape (e.g. composite fan blade and aerofoil), fibre wrinkling has a high chance to convert to either in-plane or out-of-plane waviness. During the service life of composite structures, static and dynamic stresses, together with impact forces can cause layers to separate and generate a small gap between composite layers (i.e., delamination), which typically reduces the structural strength. The existence of multiple types of defects within composite structures increases the risk of structural failure and also poses a challenge for defect detection and characterisation.

To maintain the service life of composite structures and reduce the potential failures, non-destructive techniques, including eddy current [3], X-ray computed tomography (CT) [4-5] and ultrasonic testing [6-11] are widely used to detect and characterise different defects in composite materials. Among them, ultrasonic testing (UT) is a prevailing technique for detection of surface-breaking, near-surface and sub-surface defects in composite structures.
Reported research has demonstrated the capability of ultrasound in detection of delamination [6], porosity [9] and fibre orientation (in-plane [7] and out-of-plane waviness [11]) in the composite structures with reliable results. Wave features like wave attenuation and frequency shift can be used to identify delamination and porosity inside the composites. To evaluate fibre orientation, wave attenuation or phase shift of ultrasound during propagation in the composite must be mapped with position information (B-scan and C-scan). Despite promising potential applications, delamination within wavy composites is seldom reported to be evaluated with high signal-to-noise ratio (SNR). Efficient UT methods are required for detection and characterisation of delamination and waviness in composite structures.

In order to extract wave features for defect characterisation within composite structures, wave interaction with delamination, waviness and resin rich layers must be fully understood. When ultrasonic waves, both longitudinal and shear, interact with delamination, due to acoustic impedance difference between air within delamination and composite material, waves will be reflected at the interface and sometimes even undergo mode conversion. Wave refraction and scattering occur when the wave is propagating through waviness region. Smith [11] conducted analytical modelling to investigate the interaction between the ultrasound and ply-drop composite plies. With the optimisation of frequency and bandwidth, the ultrasound instantaneous phase can lock onto the resin-rich layers and provide the out-of-plane layer orientation. According to the different interaction patterns of ultrasound at different frequencies with delamination and waviness, delamination within wavy composite could be detected with improved SNR and even identified by using optimized waves.

In this study, delamination within wavy composites was inspected with improved SNR by using the optimised ultrasound from simulation results. Wave interaction of ultrasound at varied frequencies with single type defects (waviness, resin rich layers and delamination) and delamination under wavy composite was simulated in CIVA® software. To validate the simulation results, waviness and delamination (represented by side-drilled holes, SDHs) were detected with desirable wave frequencies. SNR from both simulation and experiment was compared to verify the feasibility of the proposed method of the defect detection and characterisation in the composite structures.

2 Wave propagation in multi-layer composite material

During manufacturing of aerospace composite structures with a complex shape and a ply drop layout (e.g. composite fan blade and aerofoil), fiber wrinkling can easily convert to either in-plane or out-of-plane waviness due to uneven pressure and heating. These defect types are depicted in Figure 1(a). As a consequence, the resin flow is blocked in the wavy region and
thick resin layers form between the fiber layers. The inter-ply reflection signature becomes unpredictable due to wave scattering at the waviness profile. Furthermore, an unstable reflection intensity from uneven resin layers at the location of in-plane and out-of-plane waviness, further increases the difficulty of signal interpretation. Figure 1(b), obtained from optical microscopy, shows thin resin layers (approximately 10 µm) between fiber layers. These resin layers cause inter-ply reflections between the front-wall and the back-wall echoes, when ultrasonic wave propagates in composites. At each interface, for example the interface between layer 1 and 2 as illustrated in Figure 1(b), provided the incident ultrasonic spatial pulse length larger than the ply thickness, there is significant interference to the ultrasonic signal from the neighboring layer 3. This interference is more complex in a typical multi-ply composite. Besides that, the inter-ply reflection will be stronger at resonance if the ultrasonic wavelength matches the odd number of layer thickness.

2 Numerical simulation

In order to understand wave propagation in composite materials, numerical models of composite samples were built in CIVA® software. Firstly, as shown in Figure 2 (a), wave interaction in a flat composite sample with parallel layers and uniformly distributed resin layers was simulated. Influence of wave frequency on the delamination reflection and inter-ply reflection was investigated. For the wavy CFRP sample with three SDHs as depicted in Figure
2 (b), the interference of out-of-plane waviness on wave propagation was studied. In addition, inter-ply reflection from the resin layers under different frequencies was simulated.

![Numerical models built in CIVA®](image)

**Figure 2:** Numerical models built in CIVA® for (a) flat CFRP sample with one SDH and (b) wavy CFRP samples with three SDHs and out-of-plane waviness

### 3 Experimental validation

The experimental setup for composite inspection, consisting of ScanMaster ultrasonic immersion testing system (LS-50), Olympus ultrasonic probes (3, 5 and 10 MHz) and fixtures, is shown in Figure 3. Raster scanning with a 0.2 mm pitch was conducted at the same water path as the probe focus depth (2 inches).

![Experimental set-up](image)

**Figure 3:** (a) Experimental set-up for immersion ultrasonic testing of composite samples and (b) wavy CFRP sample

To overcome the intensive wave attenuation in composite and to suppress system noise, the time-corrected gain (TCG) was used to improve SNR. A-scan signals were captured with a wide-band filtering and further processed with stationary wavelet transform (SWT) in MATLAB®. Surface following technology (i.e., applying the delay laws to keep the water path
constant) was adopted to compensate for system vibration during the mechanical scanning. B-scan images for both defective regions with/without SDHs were comparatively constructed for defect identification and characterization.

4 Results and discussion

In this section, results from simulation and experiment are to be comparatively discussed. Influence of probe frequency on inter-ply reflection and influence of out-of-plane waviness on wave propagation will be concluded from the comparison. Numerical B-scan images for flat CFRP sample as depicted in Figure 2 (a) under increasing frequencies are shown in Figure 4. Inter-ply reflection is observed to increase with increasing frequency from 3 MHz to 10 MHz and decrease afterward. This is because that inter-ply reflection reaches its maximum when ultrasonic frequency matches the ply resonance (around 10 MHz).

![Figure 4](image.png)

Figure 4: Numerical B-scan images for the flat CFRP sample under different frequencies: (a) 3 MHz, (b) 5 MHz, (c) 10 MHz and (d) 15 MHz

Experimental B-scan images for the flat sample obtained from different frequencies are comparably shown in Figure 5. Note that time varied gain was used to compensate for wave attenuation at different depth. However, in general, the reliance of inter-ply reflection on the probe frequency is similar with the numerical predicated results.
To further investigate the influence of thick resin layers and out-of-plane waviness on the wave propagation, numerical simulation and experimental validation were conducted on the wavy composite sample as shown in Figure 3(b). The relevant numerical and experimental B-scan images are shown in Figure 6 and 7, respectively. From simulated B-scan images, it can be seen that defect reflection decreases with increasing frequency. Inter-ply reflection from thin and thick resin layers demonstrates different frequency reliance pattern due to different ply resonance. In addition, delamination indication in the deeper position is more prone to be affected by thick resin layers and out-of-plane waviness.
5 Conclusion

In this study, the wavy thick composite sample was investigated using numerical simulation and experimental ultrasonic measurements. The effect of the thick resin layers and waviness on the wave propagation was revealed with the dedicated numerical model built in CIVA®. Waviness and thick resin layers were found to introduce additional inter-ply wave scattering, which acts as noise to SDH and delamination reflection signals, causing difficulties in characterization based only on SNR. Making use of different defect reflection magnitude dependence on the ultrasonic frequency, internal defects can be characterized and differentiated from the thick resin layers experimentally. The experimental results were in close agreement with numerical simulation.

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References


