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QUANTITATIVE EVALUATION OF LOCAL PLY ANGLE ROTATION IN CARBON FIBER REINFORCED PLASTICS USING LASER-ULTRASUND

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ABSTRACT

Wrinkles in carbon-fiber reinforced plastics (CFRP) dramatically reduce the performance of a composite structure. Because they do not produce large echoes, detecting these defects remains challenging for conventional techniques.

Recent developments in laser-ultrasound (LU) have enabled non-contact high-resolution imaging of CFRPs. Due to LU's broad bandwidth and point-like optical detection, it is now possible to image CFRP structures with sub-ply resolution.

In this paper, we show that LU can image variations in ply orientation in composites. To improve the signal to noise ratio (SNR) and track wrinkled plies, tilt-filtering (TF), a local cross-correlation based method, is proposed. It can perform coherent spatial signal averaging taking into account the shape of neighboring layers. In addition, local ply angle is a straightforward output of the proposed processing, which can be used as a direct indicator of wrinkle severity.

Keywords: Laser ultrasound, CRFP, wrinkles, tilt filter, ply angle

NOMENCLATURE

LU	laser ultrasound
CRFP	carbon-fiber reinforced plastic
MA	moving average
TF	tilt filter
SNR	signal to noise ratio
STCC	short-time cross-correlation

1. INTRODUCTION

Wrinkling of carbon fiber reinforce plastics, defined as any variation of fiber orientation from the anticipated direction [1], [2] can significantly reduce the performance of the structure [3]–[6], reaching as much as a 40 % tensile strength drop [3]. Detecting wrinkles remains challenging for modern NDT techniques, since imaging these defects requires sub-ply resolution. X-Ray computed tomography (CT) can provide such resolution, revealing the orientation of individual plies [7]; however, this method is limited to small samples that can be rotated within the X-ray beam.

Significant effort has been applied to develop classic contact US methods for ply orientation imaging. By carefully gating US signals, C-scans were obtained that could reveal in-plane fiber alignment [8]. This procedure was extended using the 2D Fourier transform to process C-scans [9]. More recently, processing based on the phase of the analytical signal to follow ply orientation has been proposed [10], [11].

Modern LU systems can potentially enhance such methods to identify and quantify wrinkles. Because these systems have 3 times better axial resolution than conventional US transducers with the same characteristic frequency [12], sub-ply resolution can be obtained. Previously, we have shown that a kHz-rate LU scanner with a fiber-optic Sagnac interferometer on receive can detect not only large defects accurately, but can also help visualize pores and single layers within composite structures [12], [13], as well as evaluate heat damage [14]. Here we use this scanner to investigate wrinkles.

Starting with high-resolution LU images of a CFRP structure with significant wrinkles, we also introduce tilt filtering (TF) as a signal-processing tool to improve image quality in these complex structures. This scheme uses short-time cross-correlation to identify local time shifts between adjacent signals defining local ply orientation. Based on these time shifts, waveforms can be averaged along the ply direction to improve image quality while simultaneously producing maps of ply orientation to quantitatively characterize wrinkles.

2. MATERIALS AND METHODS

2.1 Tilt filter

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High signal to noise ratio (SNR) is required in US signals to reveal CRFP structural details. A common method to improve SNR is to collect a number of waveforms from a single location. For LU scanners operating at high repetition rate, however, stationary signal averaging can produce significant local heating and damage the structure. To avoid this, spatial signal averaging from a dense measurement grid can be used. In the moving average (MA) approach, the resulting A-scan is calculated as a weighted sum of spatially adjacent signals.

A MA filter over a wrinkled region may not improve SNR and, for large wrinkles, can actually reduce SNR. Averaging neighboring waveforms shifted by ply waviness also can blur images, removing wrinkle-related information. To overcome this problem, we use tilt filtering (TF), a method based on short-time cross-correlation (STCC) between neighboring signals. It estimates local ply rotation angle and averages neighboring signals along the fiber direction to preserve true structure.

2.2 Experimental setup

The experiments were performed in a fully non-contact way using the LU setup described in detail in Ref. [15]. The composite sample presented in figure 1 was fixed to a translation platform and scanned with 0.05 mm lateral resolution in both X and Y directions. Incident pump-laser pulses were delivered along an axis inclined approximately 40° from the sample normal to focus the probe-laser beam at the same point on the sample surface as the detection beam. The laser spot size at the sample surface was about 2 mm, resulting in a laser fluence of about 60 mJ/cm2, well below any damage thresholds for composite material illumination.

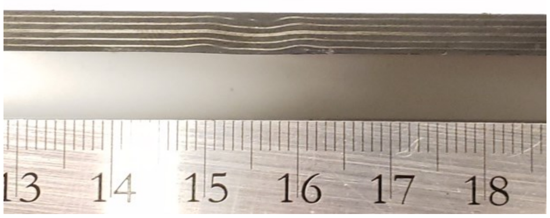

FIGURE 1: CROSS-SECTION OF THE WRINKLED AREA OF THE SAMPLE INVESTIGATED IN THIS STUDY.

Acquired signals were first deconvolved and low-pass filtered as described in [15]. The signal bandwidth was then reduced to 10.5 MHz. Next, signals were time-gain corrected (TGC) to compensate for exponential loss assuming an attenuation coefficient of about 2.7 cm^{-1}.

3. RESULTS AND DISCUSSION

A raw B-scan image obtained using the LU system is presented in figure 2a. It shows the front wall signal generated by laser-induced thermal expansion, all layers of the structure, and finally the back wall. Even in this raw image, composite waviness is evident in the central part of the B-scan.

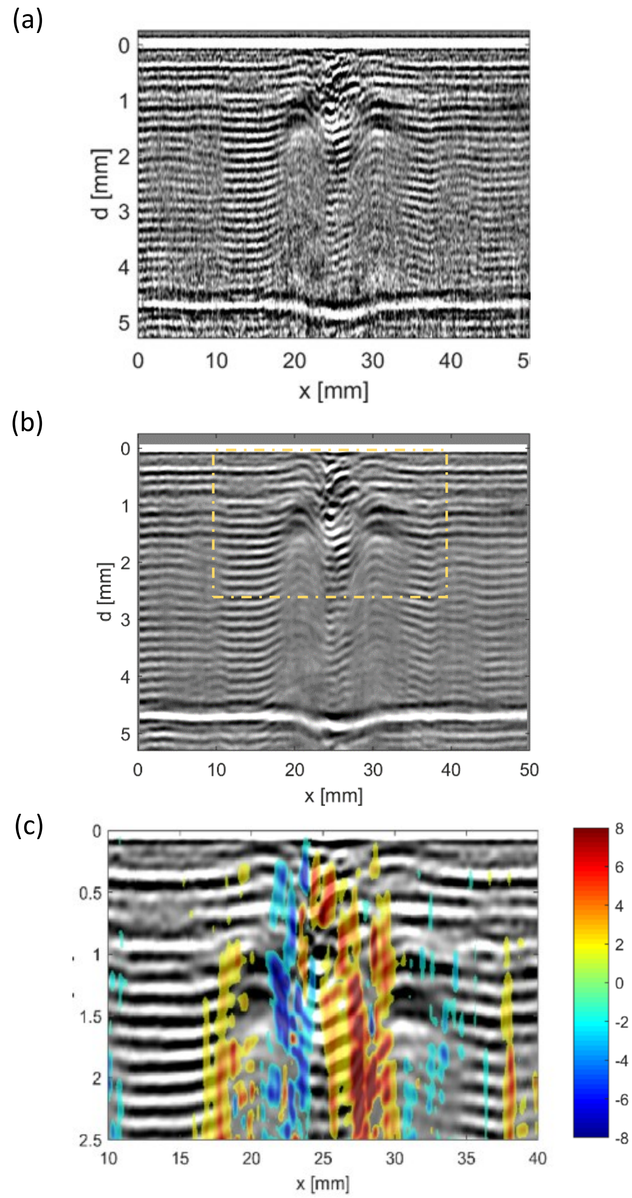

FIGURE 2: RAW B-MODE IMAGE OF THE WRINKLED CRFP SAMPLE (a); PROCESSED USING TILT FILTER (b); ZOOMED AREA OF THE PROCESSED IMAGE WITH SUPERIMPOSED LOCAL PLY ROTATION IN DEGREES (c).

Measured data were tilt filtered using the method described above. The algorithm calculated the correlation coefficients and time-lags between the signals used to reconstruct the tilt-filter B-mode image presented in figure 2b. SNR is significantly increased compared to original image in figure 2a. Clearly, wrinkles are highlighted by the filtration procedure.

In the last step, the local ply rotation angle estimated from correlation analysis was superimposed on the tilt-filtered B-scan image (figure 2c). This zoomed image contains information on both ply distribution and waviness in the area highlighted in figure 2b. Rising plies result in positive rotation angles, whereas descending plies lead to negative ones.

4. CONCLUSION

Ultra-broad signals generated and acquired by a high-speed LU scanner provide sub-ply resolution that can be used to image wrinkles in CRFP structures.

A moving average method conventionally used to improve SNR causes incoherent summation of signals reflected by wrinkled plies and, therefore, reduces signal SNR in wrinkled areas. To overcome this problem, we used tilt filtering to average along fiber directions and reduce image blur in wrinkled areas. In addition, local ply angle is a straightforward output of the method. Rotation angle estimates can identify regions with significant wrinkling and, potentially, produce a quantitative damage index related to wrinkle severity.

In this study, we applied the proposed TF method to a single B-scan, i.e. in 2D, because wrinkles were aligned nearly perpendicular to the B-scan in the elevational direction. If the orientation of wrinkles is not known *a priori*, the proposed TF method can be easily extended to all three dimensions.

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